The Economics of Adapting Fisheries to Climate Change



OECD

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Foreword

Scientific findings indicate that aquatic climate change impacts are becoming more apparent and will continue to have a profound effect on the productivity of fisheries and the distribution of fish stocks around the world. However, there is a great deal of uncertainty associated with climate change in a fisheries context, particularly with respect to when it will occur, what kind of changes will take place and the extent of the impact it will have on aquatic ecosystems and fisheries. While global models exist and provide some indication of the magnitude of impacts, much work needs to be done at the local level in terms of understanding how fish stocks will react to changes in their environment, as well as how ecosystems will change. From a social and economic point of view, it is clear that the effects of climate change will result in the redistribution of costs and benefits for the fisheries sector and for coastal communities, but how much, when and to whom these benefits and costs will flow are less clear. In this regard, there is a need for fisheries policy makers to develop strategies and decision-making models to adapt to climate change under uncertainty, while also taking into account social and economic consequences.

As a complementary exercise to the various other international events on climate change that generally have had a scientific focus, the OECD Committee for Fisheries held a Workshop on the Economics of Adapting Fisheries to Climate Change on 10-11 June 2010 in Busan, Korea, as part of its Programme of Work for 2009-2010. The main objective of the Workshop was to provide a forum for policy makers, economists, biologists, international organisations, the private sector and non-governmental organizations to examine the economic issues, policy challenges and institutional frameworks and responses to adapting to climate change. This publication, the outcome of the Workshop, highlights actions that are needed to respond to climate change: strengthening the global fisheries governance system, a broader use of rights-based management systems, ecosystem protection, industry transformation, ending perverse subsidies and a focus on demand for sustainable seafood. Policy makers will also need to consider how to ensure sustainable aquaculture production as part of adaptation strategies, and how to develop adaptable and flexible fisheries and aquaculture policies within a broader oceans management framework.

The Workshop brought together over 100 participants, ranging from policy makers, fisheries managers, economists and biologists. The two-day Workshop consisted of six sessions which included expert presentations and plenary discussions and focussed on identifying the key economic issues, challenges and possible impacts in relation to climate change and the fisheries; explored adaptation policy measures and options; selected case studies on national adaptation strategies in the fisheries sector; policy issues regarding trans-boundary and high seas stocks as well as climate change adaptation challenges facing developing countries. The Workshop concluded with a panel session on the political economy aspects of developing and implementing climate change adaptation strategies for fisheries, especially with regard to managing expectations and working collaboratively with stakeholders.

Acknowledgements

The OECD Fisheries Policies Division expresses its appreciation to all participants for contributing to the success of the Workshop on the Economics of Adapting Fisheries to Climate Change. The Workshop and the publication of these proceedings were made possible through the generous financial support of the governments of Korea (Ministry for Food, Agriculture, Forestry and Fisheries (MIFAFF) and the Organizing Committee for EXPO 2012 Yeosu Korea) and the Canadian Government (Fisheries and Oceans Canada). The OECD would in particular like to thank Mr. Tae-Puong Chang, Minister of MIFAFF, for hosting a working dinner, and Mr. Yong-Jae Ha, Vice-Minister of MIFAFF for his welcome address that initiated the Workshop. Thanks are also extended to the Brazilian Minister of Fisheries and Aquaculture, Mr. Altemir Gregolin, who addressed the Workshop participants.

The OECD also gratefully acknowledges the Workshop Chair, John Davis, for leading the discussions, all the speakers for presenting studies on climate change adaptation issues or national approaches, and the authors of the papers included in this volume.

The Workshop was organised by Sungbum Kim and Carl-Christian Schmidt (OECD) with continuous collaboration from Il-Jeong Jeong, Kihwan Kim and Hyo-Jung Jung from MIFAFF. Karine Ravet and Emily Andrews-Chouicha provided substantial administrative support. The publication has been prepared and edited by Emily Andrews-Chouicha, Karine Ravet, Sungbum Kim, Saba Khwaja, and Carl-Christian Schmidt from the OECD and Sally Hinchcliffe (Consultant).

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Acronyms and Abbreviations

ACIA	Arctic Climate Impact
AOGCMs	Atmosphere-Ocean Global Circulation Models
BEST	Bering Sea Ecosystem Study
C	Carbon
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CCRF	FAO Code of Conduct for Responsible Fisheries
CFP	Common Fisheries Policy
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
COFI	OECD Committee for Fisheries
COP	UNFCC Conference of the Parties
CO_2	Carbon dioxide
CO_3^{-2}	Bicarbonate concentration
CPUE	Catch per unit of effort
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CZCS	Coastal Zone Color Scanner
DfID	Department for International Development (U.K.)
DIC	Dissolved inorganic carbon
DWFF	Distant water fishing fleets
EAF	Ecosystem approach to fisheries
EAM	Ecosystem approach to management
EBFA	Ecosystem-cqsed fishery assessment approach
EEZ	Exclusive economic zone
EFZ	Exclusive fishery zone
ENSO	El Niño Southern Oscillation
ERAEF	Ecological risk assessment for the effects of fishing
ERI	Ecosystem risk index

ESD	Ecologically sustainable development
F scenarios	Fishing mortality scenarios
FAM	Fishery assessment methodology
FAO	Food and Agriculture Organizaton
FHS	Fish habitat system
FMPs	Fishery management plans
FRCC	Fisheries Resource Conservation Council
FRI	Fishery risk index
FSQ	UN Fish Stocks Agreement
GCM	Flobal Circulation Model
GDP	Gross domestic product
GEF	Global Environmental Facility
GESAMP	Group of Experts on the Scientific Aspects of Marine Pollution
GHG	Greenhouse gas
GIS	Geographical Information System
GLOBEC	Glocal Ocean Ecosystem Dynamics Program
HABs	Harmful algal blooms
HadCM3	UK Hadley Centre model
ICCAT	International Commission for the Conservation of Atlantic Tunas
ICES	The International Council for the Exploration of the Sea
IFRAME	Integrated fisheries risk analysis method for ecosystems
IOTC	Indian Ocean Tuna Commission
IPCC	Intergovernmental Panel on Climate Change
IPOAs	International Plans of Action
IPWEA	Institute of Public Works Engineering Australia
IQ	Individual operator quota
ISF	Industrial sustainability framework
ITQ	Individual transferrable quota
IUU	Illegal, unreported or unregulated fishing
IVQ	Individual vessel quotas
LDC	Least Developed Countries

LOSC	UN Convention on the Law of the Sea
MAC	Management Advisory Committees
MCCIP	Marine Climate Change Impact Partnership
MCS	Monitoring, control and surveillance
MEY	Maximum economic yield
MOU	Memorandum of Understanding
MPA	Marine Protected Area
MRS	Marine resource system
MSC	Marine Stewardship Council
IPCC	Intergovernmental Panel on Climate Change
IPOAs	International Plans of Action
IPWEA	Institute of Public Works Engineering Australia
IQ	Individual operator quota
ISF	Industrial sustainability framework
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LDC	Least Developed Countries
LOSC	UN Convention on the Law of the Sea
MAC	Management Advisory Committees
MCCIP	Marine Climate Change Impact Partnership
MCS	Monitoring, control and surveillance
MEY	Maximum economic yield
MOU	Memorandum of Understanding
MPA	Marine Protected Area
MRS	Marine resource system
MSC	Marine Stewardship Council
MSE	Management strategy evaluation
MSY	Maximum sustainable yield
MTL	Man trophic level
NAO	North Atlantic Oscillation

NAPAs	National adaptation programmes of action
NEAFP	North East Atlantic Fisheries Commission
NEP	Northeast Pacific Program
NGO	Non-governmental organisation
NM	Nautical miles
NPCREP	North Pacific Climate Regimes and Ecosystem Productivity
NPP	Net primary productivity
OECD	Organisation for Economic Co-operation and Development
ORI	Objective risk index
P/B	Production/biomass ratio
NEP	Northeast Pacific Program
PA	Precautionary approach
PACFA	Global Partnerships for Climate, Fisheries and Aquaculture
PDO	Pacific Decadal Oscillation
PICES	North Pacific Marine Science Organization
PIPs	Policies, institutions or processes
POPs	Persistent organic pollutants
ppm	Parts per million
ppmv	Parts per million by volume
PRSP	poverty reduction strategy process
Q/B	Ponsumption/biomass ratio
QSR	Quality Status Reports
REDD	Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
RFA	Regional fisheries arrangement
RFMO	Regional fishery management organisation
RFMS	Regional Fisheries Management Committees
SD	Systems Dynamics
SeaFIC	Seafood Industry Council
PIPs	Policies, institutions or processes
POPs	Persistent organic pollutants
PPM	Parts per million

PPMV	Parts per million by volume
PRSP	Poverty reduction strategy process
Q/B	Consumption/biomass ratio
QSR	Quality Status Reports
REDD	Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
RFA	Regional fisheries arrangement
RFMO	Regional fishery management organisation
RFMS	Regional Fisheries Management Committees
SD	Systems Dynamics
SeaFIC	Seafood Industry Council
SEAFO	South-East Atlantic Fisheries Organisation
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SOM	Self-organising mapping
SRI	Species risk index
SST	Sea surface temperature
TAC	Total allowable (or annual) catch
UNCED	United Nations Conference on Environment and Development
UNCLOS III	Third United Nations Conference on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
UNFSA	United Nations Fish Stocks Agreement
WTO	World Trade Organization

Chair's Summary

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Introduction

Recent scientific findings, including the 2007 Intergovernmental Panel on Climate Change report (IPCC, 2007) indicate that the global effects of climate change are becoming more evident. Climate change is likely to influence fisheries and aquaculture production in various ways. For capture fisheries, climate change affects fish productivity and distribution through changes in recruitment, growth rates and mortality rates, as well as in the migratory patterns of some stocks. From an economic point of view, these changes will result in losers and winners, between regions or countries as well as within national jurisdictions. With respect to aquaculture production, climate change may necessitate changes in the species composition farmed in some areas depending on tolerability of the species to temperature and other changes. Other possible impacts of climate change on aquaculture include changes in feed composition and supply as well as changes in the type, scope and extent disease outbreaks in fish farms. For both sectors, relocation of aquaculture production sites, wild harvest landing sites (e.g. ports), and fish processing facilities may be required due to extreme weather events, changing stock distribution and location relative to markets.

The expected changes in the fisheries and aquaculture sectors caused by climate change will require enhanced adaptability and flexibility in fisheries and aquaculture policies in order to be able to quickly and effectively respond as circumstances evolve. While there will continue to be a great deal of uncertainty associated with the interactions between climate change and fisheries and aquaculture over the next several years, fisheries policy makers should now turn their attention to the development and implementation of climate change adaptation strategies. These strategies must also expressly consider social and economic consequences and the distribution of impact across time and between stakeholders. More specifically, fisheries policy makers will need to consider the following fundamental questions when developing climate adaptation strategies: What policy options are available? How should decisions be made? When should actions be taken? How do we build support for the changes required?

Against this backdrop, the OECD Committee for Fisheries (COFI) hosted an international workshop entitled "The Economics of Adapting Fisheries to Climate Change" on 10-11 June, 2010 in Busan, Korea to address these challenges and provide insights to policy makers. Adaptation to climate change was the primary focus of this Workshop in order to allow for a fulsome discussion on this topic. COFI nevertheless recognizes the importance of mitigation strategies as part of a comprehensive response to climate change, and further work in this area is warranted.

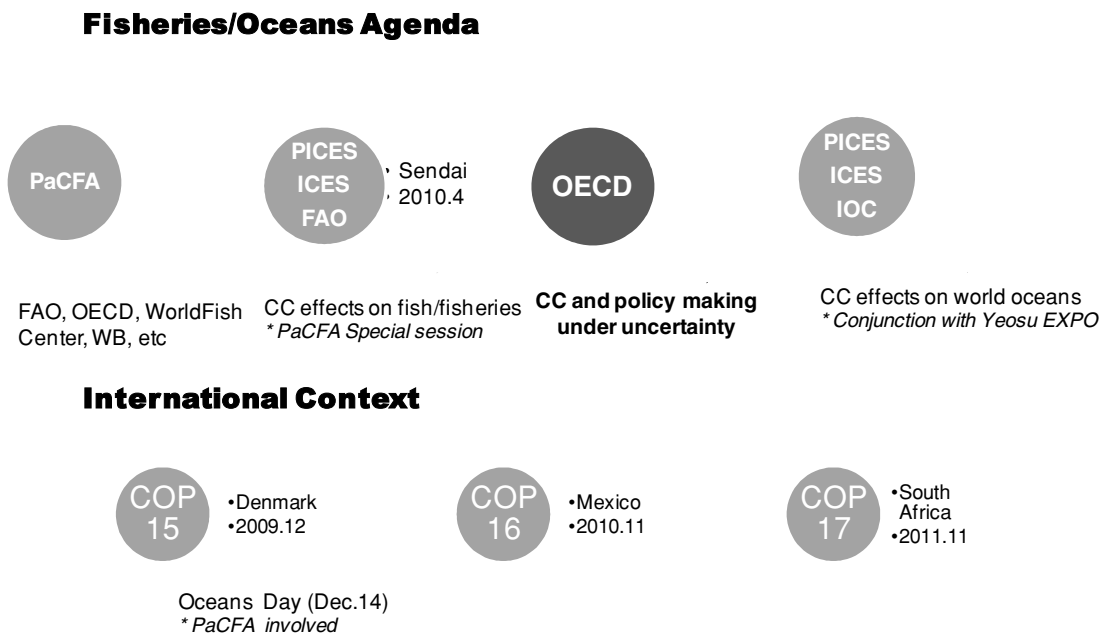
The Workshop was designed to provide guidance to fisheries policy makers in terms of when to implement policy changes or develop new policies or approaches to adapt to climate change impacts. Furthermore, it was conceived to allow for an examination of the "tools" in the fisheries manager's "toolbox" in terms of their suitability in the face of climate change, as well as to develop an understanding of the economic, social and environmental information that can underpin decisions on climate change adaptation. The Workshop findings included in the Chair's summary are intended to inform governance considerations that are important to national and international efforts to manage and conserve aquatic resources while adapting to the effects of climate change, as well as other pressures that influence fisheries resources, whether they be natural or man-made. Specifically, the objectives of the Workshop were to:

- Improve the understanding of the interaction between climate change and fisheries and aquaculture from economic, social and institutional perspectives, in light of risk and uncertainty;
- Identify key policy issues that should be taken into consideration when developing fisheries and aquaculture strategies to adapt to climate change;
- Explore the fisheries policy tools that will increase flexibility in adapting to climate change;
- Analyze the possible social and economic consequences of the management strategies to help fisheries decision-making; and,
- Provide fisheries policy makers with insights on developing climate change adaptation strategies and when to make decisions under uncertainty.

Context

As an organization mandated to provide a setting where governments compare policy experiences, seek answers to common problems, identify good practice and coordinate domestic and international policies, the OECD has a particular role to play in the global discussions on climate change and fisheries. Specifically, the OECD's role and expertise regarding economic and policy analysis, coupled with the COFI's analytical work regarding to fisheries economics, management, policy development and governance will assist in shedding light on the economic and institutional aspects of climate change. While the science around climate change is relatively advanced in a number of areas, there are significant gaps in knowledge and particularly a need for informed policy-making, strengthened governance structures, and international cooperation based on sound economic analysis. The OECD Workshop was designed to fill that gap. Figure 1 illustrates the how this Workshop complements and contributes to other international fisheries and climate change conferences.

Figure 1. Role of the OECD COFI in the global discussions on climate change and the fisheries sector



The Workshop agenda was structured to build towards a comprehensive consideration of the subject of fisheries adaptation to climate change, reviewing the status of scientific knowledge, uncertainty, and fisheries management and governance challenges in order to adapt to climate change. The fisheries management toolbox was also examined, from the perspective of whether or not existing tools are available to develop effective climate change adaptation strategies for the fisheries and aquaculture sectors. In addition, a number of presentations addressed the ecosystem approach, economic implications, and the strategies being employed by various nations to adapt fisheries and aquaculture to the impacts of climate change. There was also an emphasis on adaptation strategies in both developed and developing nations, including an assessment of their respective vulnerability to adapting to climate change impacts. A follow-up session dealt with the political economy of adapting fisheries to climate change with views from the large-scale fishing industry, NGO's and policy makers. Finally, a Panel Session with active involvement of the Workshop participants brought together key findings and insights, with a view to developing key considerations for policy makers.

The growing awareness of the importance of these issues, the shift towards embracing the "Green Growth" paradigm, and the urgency of these matters, offers considerable impetus to move forward, particularly if market forces are harnessed to ensure appropriate reduction in greenhouse gas emissions and more generally in support of green growth and sustainable management practices for aquatic resources. In this context it is important to ensure that the right incentive structures are built.

This Chair's Summary is intended to summarize key insights and major findings of the Workshop and not to repeat all the rich content of the papers presented by speakers. Readers are encouraged to refer to the complete volume of the Workshop Proceedings for further information.

Climate Change and Fisheries Adaptation Issues and Strategies: Current State of Play

The opening presentations examined science, uncertainty, and fisheries management and governance challenges in the context of climate change in order to set the scene for the workshop. Key findings of a recent large-scale ICES, PICES and FAO symposium on the subject held in Sendai, Japan in April 2010 were outlined by a representative of ICES. The Sendai Conference illustrated that while there is a considerable body of science, this information tends to be patchy, with a bias towards developed countries. It also demonstrated that the Ecosystem Approach to Fisheries (EAF), which incorporates multiple and interactive factors, offers the best potential for understanding and responding to climate change impacts on fisheries.

Several participants raised the comparative carbon-related costs of fishing relative to those of other food-related activities such as raising cattle. It was pointed out that many fisheries and aquaculture activities do not contribute significantly to greenhouse gas emissions and that a good case in this regard can be made for such activities compared with more traditional and environmentally costly forms of food production. Panellists concluded that this perspective does not appear to be widely known and may be an important marketing, certification and policy-related point for consideration. Accordingly, there may be benefits in developing and promulgating comparative data of this type for policy-makers.

Workshop participants agreed that clearly, it is very important that fisheries managers and policy makers find effective ways of managing uncertainty and incorporating it in management practices and governance arrangements. In managing both fisheries and those individuals and organizations that conduct fishing, we are dealing with coupled marine socio-ecological systems. One cannot separate the natural science from the social science aspects; in that regard, our systems and processes must take both into account in order to develop effective management and governance structures to deal with the adaptation of fisheries to climate change impacts. During the workshop, it emerged that uncertainty can be grouped into four categories[1]:

- Observational uncertainty, where the current state of system is not known.
- Model uncertainty, in that models are not perfect.
- Process uncertainty, where there is a lack of understanding of the system.
- Policy uncertainty, where scientific and economic information and advice are inadequately applied.

Workshop participants argued that the ocean has always been variable and that stock collapses are most likely a combination of environmental effects and overexploitation. Climate change is superimposed upon natural variability, with resultant fluctuations in stocks (which may be major or minor in nature) and possible irreversible changes.

A session at the workshop was devoted to the political and economic aspects of developing and implementing fisheries adaptation strategies to climate change, especially regarding stakeholder involvement and expectations. Linked to this is the question of governance and how policy-makers and managers deal with competing interest groups and effect policy change in the face of varying positions. At issue are questions of local, regional, national and international governance, established interests of large and small-scale fishing operations, national and individual self-interest, the effectiveness of

governance systems and processes, and how to build consensus to make needed changes for sustainable use of fisheries resources and adapting fisheries to the impacts of climate change. While it was recognized that many fisheries management tools that incorporate uncertainty exists, they may not be effectively applied due to implementation challenges associated with political, social, economic and financial factors.

From a commercial fishing sector perspective, it emerged that changes in fish stock location and abundance presents major challenges, as do the costs of fossil fuels and refrigerants and impacts of incentives to discourage the use of those products. For example, there have been major changes in composition of the New Zealand charter fleet in recent times and major decreases in mid-water landings of a number of species. As fish stocks move and distribution and abundance change, there will be significant issues with respect to access and allocation between affected States and their commercial stakeholders, possibly resulting in situations where national and local community interests may clash.

From a fisheries policy maker's perspective, the need for strengthening already existing good fishery governance practices, including implementing an ecosystem approach to fisheries management, rebuilding fish stocks and applying a participatory approach, was stressed. Lessons can be learned from applying traditional knowledge, involving fishers and building on practices supported by those individuals[2]. While not extensively discussed, the need for adequate fisheries data in light of climate change may be an important consideration given that many fisheries management practices are based on historical, single species data sets. If the ocean changes beyond our historic scientific experience, managers and scientists may have a weakened foundation for making predictions and assessing which management actions to take, and also in terms of developing ecosystem strategies.

The experiences of OECD countries as well as non-member economies in identifying climate change impacts on fisheries, developing adaptation strategies and addressing social and economic issues were presented. A number of developed nations are actively anticipating, designing and implementing actions to deal with expected climate change impacts on fisheries. In contrast, developing countries are affected by their limited capacity despite the overall importance of the fisheries as a source of food protein. Fisheries on the high seas and those for straddling stocks face unique challenges, as fish move across national boundaries. The following paragraphs identify the state of play at the national and international level, and in some cases illustrate how nations are seeking ways in which to deal with the four types of uncertainty identified earlier.

The EU is currently instituting measures that seek to address both process and policy uncertainty in particular. This is being undertaken through the appointment of a European Commissioner for Climate Action, the establishment of a Commissioner's Group on Climate Change, and an Inter-service Group on Adaptation to Change to explore integration of adaptation policy into policy development. A comprehensive EU climate change adaptation strategy is under development and is intended to harmonize EU fisheries management policies and procedures.

In the United Kingdom, the government is developing an approach for climate change adaptation which considers the impact of increased ocean temperature, sea level rise, ocean acidification and changes in storm intensity and ocean circulation with resultant impacts on fish species distribution and abundance. Adaptation approaches are being designed with the goal of securing sustainable and stable fish biomass, alongside a viable and economically healthy fishery. The core elements of the strategy include building trust

between fishers, scientists and government, while also ensuring resilience in marine ecosystems. The incorporation of an ecosystem- based approach to marine management is crucial in this regard. The UK also places a strong focus on reducing reliance on government transfers to the sector and instead focussing on market incentives. To this end, the UK government is examining approaches that would allow fishing enterprises greater flexibility and incentives to self-adjust as required, without significant government intervention. Further detail on the UK's fisheries climate change adaptation strategy are provided in a separate chapter in this volume.

In Korea, indications of changing ocean conditions have included the appearance of sub-tropical species and toxic jellyfish, and there have been significant changes in the distribution and abundance of major fish species. In response, Korea has instituted the comprehensive Marine and Fisheries Policy in 2007 and the National Action Plan for Climate Change in 2009. These two policies incorporate climate change initiatives, including strengthening resource management for emerging warm water species while taking advantage of new harvest opportunities, developing farming technologies for new species (e.g. tuna), and creating marine parks to protect fish habitat and spawning grounds.

Similarly, Chinese Taipei has experienced significant changes in distribution and abundance of fish stocks in recent years. There have been declines in key fisheries linked to climate change effects, with the resultant impacts on fishers and the fishing industry. Typhoon-induced floods have had major impacts on the aquaculture industry through facilities damage and escapes of cultured fish. Major reductions in fisheries catches are projected to occur. Adaptation strategies are under development in Chinese Taipei that are intended to include specific adaptation measures to supplement current management practices.

The workshop also identified the divergence in approaches and highlighted the varying levels of capacity between developing and developed countries in adapting to climate change. In many developing countries, marine and freshwater fisheries are an important source of protein and national food security, as well as crucial to the livelihoods of parts of the population. Some are land-locked countries with a dependence on freshwater fisheries and aquaculture. Accordingly, as global climate change impacts intensify and affect freshwater availability and food security issues, impacts on fisheries and aquaculture may be severe

It emerged that developing nations appear to be the most vulnerable to the effects of climate change on fisheries, and many lack the capacity to adapt and cope with these impacts. In this vein, a global study on the effects of climate change conducted by the UK QUEST project explored the vulnerability of countries was presented. This study used an indicator-based approach based on exposure, sensitivity and adaptive capacity of the societies and noted that vulnerabilities were especially high in developing countries. African countries, former Soviet countries and landlocked countries were identified as most vulnerable.

As a way forward in the Pacific, a number of adaptation strategies to restore and sustain the food production potential of the coastal fisheries of Pacific Island nations were proposed: applying an EAF, increasing access to tuna for subsistence fishers with low-cost, inshore Aggregating Fish Devices, storing and distributing tuna and by-catch from industrial fleets to urban areas; and developing pond aquaculture. The debate about sharing experiences and building capacity among nations was illustrated by the example of "The Blue Economy Initiative" of the Korea 2012 Yeosu EXPO. This program is

intended to institute a capacity-building program where resources will be devoted to developing countries in order to deal with problems in the field of marine and fishery affairs, including climate change impacts.

The Workshop also addressed management of fisheries and aquaculture in the ocean area beyond national jurisdictions in a world where climate is changing. Participants generally agreed that major steps have been made in addressing international agreements and regulatory arrangements for high seas fisheries through initiatives such as the UN Fish Stocks Agreement, FAO Compliance Agreement, and the FAO international Plan of Action. However, given the size of the ocean and limited enforcement capacity, it was concluded that illegal activities are largely state failures that result from either a lack of capacity or lack of will. While the international legal framework to effectively manage fish stocks and adapt to climate change exists, further work on implementation (e.g. enforcement) is required.

Changes in fish distribution resulting from variations in ocean conditions will likely affect fish stock sharing arrangements between countries regarding straddling or migratory stocks, creating a need to develop incentives for those countries that may receive smaller shares as a way to ensure conservation. However, one provocative comment raised during the discussions was that future changes in fish abundance on account of climate change may not be as dramatic as what was seen in the 70s and 80s as a result of overexploitation. As such, we may be able to draw on past fisheries management measures that were effective in rebuilding or managing depleted stocks.

Key Messages for Fisheries Policy Makers

Climate change will impact fish species in uncertain ways relative to their current range of distribution or historical patterns, and some species within an ecosystem may shift in one direction (e.g. north), while others move in the opposite direction (e.g. south). This may result in changes in ecosystem structures themselves, as species that have traditionally cohabited within certain geographical ranges may move apart, altering predator/prey interactions for example. Resilient fisheries management regimes are required in order to provide a buffer against this uncertainty.

At issue is the effectiveness of fisheries organizations and existing governance structures and their ability to ensure conservation and sustainability while being adequately flexible so as to deal with change. It is clear, that climate change impacts, in association with natural variation and the various factors that affect fish stocks and the ecosystems they inhabit, will add uncertainty to fisheries management and pose a challenge to our efforts to conduct sustainable fisheries, feed a growing global population, and put in place effective international fisheries organizations and arrangements. Fostering initiatives to address key gaps in natural and social scientific knowledge associated with fisheries adaptation to climate change including specific impacts on major target species, shifts in ecosystem dynamics related to climate change, public awareness and decision-making and incentives to policy change and good fisheries management governance arrangements and practices will be essential. Based on the discussions and findings of the workshop, the following section outlines the main messages to be considered by fisheries policy makers in adapting to climate change challenges in the fisheries and aquaculture sector.

The fisheries toolbox to adapt to climate change already exists, but stronger and more flexible governance frameworks are needed

The consensus of the Workshop is that effective array of management tools exist to allow us to adapt to the impacts of climate change on fisheries, although governance itself appears to be the weak link. It was highlighted that evolving, responsible, and resilient fisheries management approaches require a contextual and participatory governance framework characterized by flexible and adaptive operational and strategic fisheries decision making. Often, emphasis is placed on examining the causes of stock collapses, but rarely do we look at and capitalize on the lessons learned from stock recovery. However, it was agreed that it is possible to strengthen fisheries management systems to be more adaptive to climate change through a flexible management framework that explicitly considers uncertainty.

In this regard, there is a need to avoid "institutional mal-adaptation" which refers to a governance structure that assumes the ecosystem is static, rather than a structure that recognizes that for example, fish distribution will evolve over time. For instance, in cases where species managed under a quota system move between pre-determined zones and the fishers cannot "follow the fish" to an area where they do not hold quota is evidently problematic. Designing an enabling framework and developing markets for trading domestic and international quotas were raised as options in this regard. Another case in point refers to marine protected areas; such geographically based tools require some inherently flexibility so as not to be rendered redundant as species migrate to more suitable climates. Participants emphasized that an important role for governments include identifying and removing institutional barriers, periodically reviewing protection measures to see if they are still applicable and ensuring that they do not dilute incentives for fishers to adapt to climate change, as well as addressing ongoing concerns such as discards, while also building trust between fishers, scientists and governments.

Furthermore, "coping strategies" will need to be developed as aquatic conditions change and the ecosystem responds. In the short term, this may include tuning fishing intensity, gears, times, areas, target species, etc. and using the appropriate methods in the fisheries management toolbox. In the longer term, adapting to climate uncertainty will require political reform leading to effective governance arrangements, and the will and capacity to enforce the required management actions. In this regard, marine spatial planning (or aquatic spatial planning) and integrated ocean management is an important element in developing strategies to respond and adapt to fisheries climate change.

The economic effects of climate change will depend on specific conditions of a fishery or coastal community and need to be taken into account in developing adaptation strategies

Economic effects are influenced by a number of factors, including value of catch (e.g. productivity, size, species distribution, markets, etc), costs of production (e.g. new investment and energy consumption), employment, community economies (reach of the market for seafood and their flexibility in responding to changes in supply and prices), redistribution of benefits and costs among stakeholders, and long-term profitability and ability to account for a range of possibilities. Economic effects depend on the context of a situation and may be positive or negative. Economic vulnerability of a business or an individual is related to the level of exposure to change, response capability, and level of dependence on the fish species or group of species in question.

In addition, there is an inherent contradiction between stability and flexibility and that managing portfolios of fisheries (e.g. multi species approach) may promote more resilience for fisheries and fishing enterprises than managing single stock managing individual fishery units.

Involving stakeholders and communicating with them in designing and implementing climate change adaptation strategies are essential

The need to consider the human dimension of fisheries management and the need for stakeholder engagement, including literacy and capacity, was also emphasized. In particular, the need to engage the public (the fisheries resource users) as well as the broader set of stakeholders in order to anticipate social and economic impacts, explore options, make the necessary choices and implement effective policies was highlighted. Inclusion of local and traditional knowledge is an important element of this approach. Effective engagement will facilitate the necessary social, economic and political policy changes required to adapt. Failure to do this may cause the often competitive and sometimes antagonistic relationships between competing interests to persist and frustrate effective change and governance. Accordingly, there is a need to better communicate with a broader set of stakeholders and the public with respect to fisheries, global food and water security issues, and the impact of climate change in order to facilitate awareness, establish priorities and develop the needed political and societal support for adaptation.

There is a need to think about how to communicate and implement overarching good governance principles of fisheries management and incorporate climate change impacts while doing that. In this way, the focus would be less on climate change per se, but would be considered as part of the complexity and uncertainty to be addressed as part of fisheries management. An important part of building understandings and effecting policy change is the need to inform people about anticipated impacts so that choices can be made. This will require more engagement of economists and social scientists to assist the public in gaining understanding and in facilitating change based on human behavioural patterns. Understanding the natural science and the biology and oceanographic implications will not be sufficient to achieve the necessary changes. The social-ecological relationships will need to be addressed as well.

New arrangements for international fisheries management to deal with stock migration and conserve the stocks are required

A continued focus on efforts and initiatives to elucidate, foster and develop adaptive, flexible international arrangements, agreements, organizations, and cooperation to address the fisheries climate change adaptation challenge and to promote effective stewardship, conservation and good governance of aquatic resources is essential. The changing distribution of fish stocks and altered abundance in the face of climate change will require a renewed focus on developing and/or adapting international fisheries agreements that address fish stock migration between EEZs, and treaties governing the distribution of shared stocks amongst countries. Strengthening regional fisheries management organizations will also be key to managing fish stocks as they migrate on the high seas, with the added urgency posed by stress on the stocks due to exploitation as well as climate change impacts.

Some changes in species abundance, distribution or ecosystem composition may be irreversible; these shifts will put international arrangements and treaties under stress. As a

result, innovative incentive structures and adaptation strategies will need to be considered, including side payments to countries that would offset reductions in their fish catches; greater flexibility regarding fishing in adjacent zones and in foreign EEZs; the advent of new technology; creating and accessing new markets or introducing new products; and, increased flexibility to deal with supply changes in relation to market demand.

Sustainable aquaculture production, the Ecosystem Approach to Fisheries management and strong science are core elements of a fisheries adaptation strategy

Sustainable aquaculture production may be one solution to supplement stagnating/declining capture fisheries or those affected by climate change. Sustainable aquaculture has the potential to help address global food security challenges and may be particularly important for developing countries where fish forms a very important component of the diet. Aquaculture may offer flexibility in dealing with challenges associated with climate change such as water scarcity, storms, temperature, choice of adaptive species, etc. Technological developments to increase the ability to adapt fish cages and installations to prevent storm damage, techniques for dealing with temperature stress, breeding technology innovations, genetic engineering, improved food sourcing away from reliance on fish meal, and reduced antibiotic use would be key elements of ensuring sustainable aquaculture production. A simpler governance model compared to wild fisheries, in which property rights for aquaculture sites and stocks are clearly assigned, was also considered a benefit.

There was strong consensus that adoption and implementation of the ecosystem approach is a very important strategy as it is only this approach which can incorporate all elements which are necessary to deal with the complexities of natural systems and the impact of climate change. This however, is a major task and often ecosystems are not well understood and our ability to manage fisheries stocks on a multi-species basis is not well developed.

While there is considerable scientific work being done, the global view on climate change impacts on fisheries is patchy and not fully understood. There is a need for more comprehensive science, particularly with respect to fisheries of developing countries, and a focus on key stocks and areas of concern which will vary geographically in sensitivity to climate change. Aligning global estimates of climate change to the local scale and accordingly downscaling predictions to the local level remains a challenge and must be addressed as is assigning a priority to further elucidating the biological, social and economic impacts of climate change on fisheries and aquaculture.

Developing countries are especially vulnerable to climate change, calling for knowledge transfers and capacity building

For developing countries, there is an urgent need for anticipating and understanding the expected impacts, developing adaptive capacity, particularly for knowledge transfer, capacity building, and effective technology transfer from developed countries. Furthermore, small developing countries with coastal or artisanal fisheries may be significantly impacted by distant water fishing nation activities which may change with climate change influences. Considerable research and development efforts are needed in this area to ensure that other human activities and uses (e.g. urbanization, population

growth, and agriculture) are not negatively effecting water quality, fisheries productivity or aquaculture potential. In short, a focus on the specific problems of developing nations and their lack of capacity to deal with fisheries climate change adaptation and need for assistance from developed countries is required.

Future research and considerations

This Workshop covered a vast and complex topic of global proportions with strong implications for the fisheries and the aquaculture sector, and with major elements of an economic and social nature. Global water security issues and their impact on fisheries and aquaculture, including in the freshwater environment, are major challenges. Effective water use and water conservation initiatives, anticipating and coping with storms, floods, drought, snow-pack depletion, coastal sea level changes, and impacts on freshwater ecosystem integrity are topics for important research and policy development. These issues have both a natural science and a social science dimension in terms of choices that must be made with respect to global water security issues, including those related to the fisheries sector. In this regard, future work on climate change and the fisheries should also consider the following aspects.

- **Mitigation Strategies**: There is a major difference in the costs and benefits of adaptation and mitigation activities respectively. The costs and benefits of *adaptation* are more likely to be local in nature, and can thus strain countries with limited capacity and resources to implement adaptation measures. In contrast, the costs of *mitigation* are more likely to be local, while the benefits are often diffuse and experienced on a global scale. Research to assess the various approaches and strategies regarding mitigation of the effects of climate change (e.g. carbon sequestration in the oceans; increasing fuel efficiency for fishing vessels) for fisheries and aquaculture is required. In addition, the scale and scope of socio-economic sensitivities of fisheries to climate change, including the associated fishing communities, may be assessed in terms of their resilience to respond to the effects of climate change. Such work would help identify if the fishery can adjust autonomously or whether targeted transitional policies (e.g. additional capacity building or economic development) are needed.

- **Integrated marine management:** There is a call for a more a comprehensive approach to examining the cumulative impacts of the various human activities in the ocean. This may include shipping, oil exploration, fishing, tourism, etc. Holistic management plans may be based on an assessment of the impacts on the marine environment of human activities and the interactions between them. Elaboration of the necessary elements of a governance structure that adopts such an integrated approach would enable strong institutional frameworks within which to deal with climate change.

- **Freshwater fisheries management:** There is a need for more emphasis on climate change impacts on freshwater fisheries which will affect many of the most vulnerable countries with a strong dependence of fisheries for food security. The ocean has always been a highly variable ecosystem and variation in abundance and distribution of fish stocks has always challenged fisheries managers, with considerable uncertainty present which must be accounted for. In many locations around the world, changes in fisheries related to phenomena in the ocean are being observed, particularly changes in fish distribution and abundance. Changes are also happening in freshwater water bodies, and these must equally be considered in the development of climate change mitigation and adaptation strategies.

Notes

1. See the Chapter entitled "Dealing with Uncertainty: Implications for Fisheries Adaptation" by Dr. R. Ian Perry for additional information the authors classification of uncertainty.
2. For further information, please refer to the Proceedings of the OECD Workshop on the Economics of Rebuilding Fisheries (OECD 2010).

PART I
SETTING THE SCENE

Chapter 1

Fisheries management and governance challenges in a climate change

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Most (84%) of the warming due anthropogenic climate change has been transferred to the oceans. This chapter outlines the causes and consequences of climate change and summarise future projections for ocean temperature rise, coral bleaching events and ocean acidification, and the associated uncertainties. This review largely focuses on marine ecosystems, as three quarters of capture fisheries landings come from the seas. However, it also presents key issues and examples from freshwater fisheries, as these fisheries provide important livelihoods and fish protein for some of the world's poorest people. While the physical and biological effects of climate change are increasingly well understood, particularly for well-studied temperate shelf ecosystems, relatively little is known of the likely impacts for ecosystems elsewhere and their associated fisheries. Overall, on balance, climate change appears to have impacts on fish ecology and fisheries, but the strength and direction (positive or negative) of the effects vary from place to place. The social and economic effects are less clear; however it is likely that the economies of countries with the lowest levels of adaptive capacity will be most vulnerable to the effects of climate change on capture fisheries and less able to anticipate and capitalise on any advantages of climate impacts. Despite the uncertainty surrounding the direction and degree of the impact of climate change on marine and freshwater ecosystems, and the associated fisheries and fishing communities, the options for policy makers are relatively clear. Policy makers can respond by pursuing mitigation strategies (reducing CO^2 emissions), building socio-ecological resilience and capacity to enable fishing communities to cope with and adapt to the opportunities, challenges and potential dangers presented by climate change, and by integrating the management of natural resource sectors in a portfolio approach.

Overview of global warming relevant to fisheries

Climate change causes, observations and projections

We briefly summarise the technical background to climate change including its causes, against the recent historic patterns of climate variation, and outline the wider changes in physiochemical and oceanographic processes, namely: carbon dioxide (CO2) concentrations, temperature increase, sea level rise, rainfall and runoff, hazards and storms, ocean upwelling, primary production, oxygen depletion, acidification, and coral reef degradation. We highlight the areas of consensus and where possible, highlight areas of uncertainty and debate.

Carbon dioxide concentrations

Atmospheric CO2 concentrations oscillated between 200 and 280 parts per million (ppm) over the 400 000 years before the industrial revolution. Current atmospheric concentrations are now approaching 380 ppm, representing a 33% increase on recent historic levels, largely as a result of emissions from industry and changes in land use practices. Estimates of future atmospheric and oceanic CO2 concentrations, based on the Intergovernmental Panel on Climate Change emission scenarios and general circulation models, suggest that by the end of the century CO2 levels could be over 800 ppm (Prentice *et al*., 2001).

Atmospheric and oceanic temperature rise

Climate model simulations show that the estimated temperature variations during the past two millennia prior to the Industrial Revolution can be explained plausibly by estimated variations in solar radiation and volcanic activity during the same period (National Research Council, 2006). It is widely accepted that at least part of the earth's 0.6 °C warming during the last 100 years is due to emissions of greenhouse gases caused by human activities (IPCC, 2001; National Research Council, 2006). It can be said with a high level of confidence that global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries (Mann *et al*., 1998, 1999; National Research Council, 2006).

The temperature rise over the last 50 years is broadly accounted for by anthropogenic forcing due to increases in greenhouse gases (mainly CO2 and methane), with some minor cooling caused by sulphate particles in the atmosphere from a concurrent increase in sulphur dioxide emissions, and some natural forcing from volcanoes (Houghton *et al*., 2002). The scientific consensus is that most of the observed warming over this period was due to human activities (Houghton *et al*., 2002). During the present century, the world is expected to continue warming, by between 1.4 and 5.8 °C (Houghton *et al*., 2002). The range in values reflects the range of different climate models and emission scenarios used to provide projections. There is strong consensus that warming will be no less than 1.4 oC over the next century, but there is greater uncertainty in the upper boundary of the projected temperature increase (Kerr, 2004). Land masses are projected to warm more than oceans, with high latitudes being most affected (Royal Society, 2002).

The oceans are warming as a result of human-induced climate change (Barnett *et al*., 2005b). Observations show approximately 84% of the change in energy content of the Earth system (oceans, atmosphere, continents and cryosphere) over the last 40 years has

gone into warming the oceans (Levitus *et al*., 2005). There is considerable variation in the penetration of warming among ocean basins, with greatest penetration in the deeply convecting North Atlantic Ocean, and less heat penetration occurring in North Pacific and south Indian Oceans (Barnett *et al*., 2005b). Importantly, these findings are relatively robust, the uncertainties in the models used are too small to affect the conclusion attributing the historic ocean warming signal to anthropogenic forcing, at least for the temperature-driven part of the signal (Barnett *et al*., 2005b).

Sea level rise

Sea-level has already risen by 10 to 20 cm during the 20th century, largely due to thermal expansion, and is predicted to rise by between 9 and 88 cm by 2100 based on the Intergovernmental Panel on Climate Change's full range of 35 climate projection scenarios (Church *et al*., 2001). The largest contributions to sea level rise are estimated to come from thermal expansion of ocean water (288 cm) and the melting of mountain glaciers and icecaps (106 cm), with smaller inputs from Greenland (24 cm) and a negative sea level lowering contribution from Antarctica (-74 cm) (Church *et al*., 2001; Raper and Braithwaite, 2006). There is a high degree of uncertainty in projected sea level rise, particularly in the strength of positive feedback which might accelerate the loss of glaciers which might result in sea level rise of several meters by 2100 (Hansen, 2007). Rising sea levels could lead to inundation of low-lying countries and many islands.

Precipitation, glacial melt and run-off

Model projections generally show increased precipitation and water availability in the high latitudes and in the tropics and less precipitation in the sub-tropics (southern Africa and Mediterranean) (Scholze *et al*., 2006). In other subtropical regions there is little consistency among model projections. The predicted precipitation changes will significantly affect surface water access across 25% of Africa by the end of this century (de Wit and Stankiewicz, 2006). Climate change will cause earlier season peak flows and reductions in flow overall, due to reduced snowfall and melting glaciers (Barnett *et al*., 2005a). In a warmer world, less winter precipitation falls as snow and the melting of winter snow occurs earlier in spring (Arnell, 1999). Even without any changes in precipitation intensity, both of these effects lead to a shift in peak river runoff to winter and early spring, away from summer and autumn when demand is highest. Where storage capacities are not sufficient, much of the winter runoff will immediately be lost to the oceans (Barnett *et al*., 2005a). All of these physical changes in timing and volume of flows will have potential consequences for fish and fisheries production.

Hazards, storms and El Niño Southern Oscillation (ENSO)

The frequency of extreme events is likely to increase with climate change. These may have a greater impact than expected changes in the mean conditions. Extreme events include more intense precipitation events, increased frequency and severity of flooding and increased frequency and severity of El Niño Southern Oscillation events and extreme weather such as hurricanes and droughts (Goldenberg *et al*., 2001, Timmerman *et al*., 1999). Theory, observations and modelling provide evidence of a direct link between changes in sea surface temperatures and hurricane intensity (Emanuel, 2005). Globally, there is little sign that the frequency of hurricanes has increased with increasing sea surface temperatures, however there is a correlation between sea surface temperature and

power dissipation due to both longer storm lifetimes and greater storm intensities (Emanuel, 2005). There has been debate about the link between hurricanes and climate change (Pielke Jr. *et al*., 2005). However, a recent study shows that the observed increase in sea surface temperatures in hurricane-forming regions of the Atlantic and Pacific Ocean are a result of human-caused global warming (Santer *et al*., 2006). In 2010 a study published by US government researchers predicted an 18% decline in the number of hurricanes in a warmer world, but that future hurricanes will be fiercer and more destructive (Bender *et al*., 2010).

Ocean upwelling

The relationship between climate and the production of upwelling systems remains uncertain. On one hand stronger wind fields might lead to enhanced upwelling in eastern boundary currents, which could increase nutrient availability at the surface (Bakun, 1990). For example, upwelling in the California current system is positively correlated to temperature and has increased over the last 30 years (Pisias *et al*., 2001, Snyder *et al*., 2003). On the other hand, however, stronger thermal stratification and deepening of the thermocline in some areas could prevent upwelling of the cool nutrient waters associated with plankton production (Roemmich and McGowan, 1995).

Ocean primary production

The relationship between climate change and future ocean primary production is likely to be a key constrain on fish and fisheries production (Cushing, 1982; Dulvy *et al*., 2009; Chassot *et al*., 2010). Metabolic scaling theory suggests that the balance between primary production and respiration will be profoundly affected by temperature increase (López-Urrutia *et al*., 2006). While both production and respiration will increase with temperature, respiration will increase relatively more than production. These models predict that the epipelagic1 ocean biota will capture 4 gigatonnes less of C per year by 2100. This equates to 21% less CO2 being captured (López-Urrutia *et al*., 2006). At present there is considerable uncertainty in empirical measures of the effects of climate change on global primary production and in regional variation in these effects.

The declines in primary production predicted by metabolic theory are consistent with global observation datasets. Recent comparisons of two satellite datasets - Coastal Zone Color Scanner (CZCS, 1979-1986) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) ocean colour observations (1998-2002) suggest that global ocean annual primary production has declined more than 6% since the early 1980s. Nearly 70% of the global decadal decline occurred in high latitudes (Gregg and Conkright, 2002). In northern high latitudes, these reductions in primary production have corresponded with increases in sea surface temperature and decreases in atmospheric iron deposition to the oceans (Gregg *et al*., 2003). Satellite estimates indicate chlorophyll concentrations decreased in the northern high latitudes while chlorophyll in the low latitudes increased. Mid-ocean gyres exhibited limited changes (Gregg and Conkright, 2002) or declining concentrations (Antoine *et al*., 2005). There is further heterogeneity among regions. Sea surface warming in the North-east Atlantic is accompanied by increasing phytoplankton abundance in cooler regions and decreasing phytoplankton abundance in warmer regions (Richardson and Schoeman, 2004). Sea temperature increases have led to an 80% decrease in macrozooplankton biomass since 1951 in waters off southern California (Roemmich and McGowan, 1995). Global chlorophyll concentration increased following a strong El Niño year in 1998, until a La Niña in 2000 whereupon global chlorophyll

concentration decreased. These changes are largely attributed to changes in surface temperatures and stratification associated with the ENSO cycle and multivariate ENSO index (Behrenfeld *et al*., 2006).

An analysis of six coupled Atmosphere-Ocean Global Circulation Models (AOGCMs) indicates that primary production may increase in the future by very little, no more than 10% by 2050 relative to a pre-industrial state (Sarmiento *et al*., 2004). However, the level of confidence in this prediction is low, primarily due to large increases in the inter-tropical areas (Antoine *et al*., 2005). The AOGCMs predict a reduced area of permanently stratified low productivity waters in subtropical gyres (Sarmiento *et al*., 2004), which has already been observed in ocean colour estimates. At the same time this study suggested that there will be a 15% increase in the size of the ocean's most oligotrophic waters (that have chlorophyll concentrations <0.07 mg chl m-3) and this has been confirmed through analyses of satellite-derived ocean colour estimates (Polovina *et al*., 2008). Coupled ocean biogeochemical and GCM models predict climate change to lead to more nutrient-depleted conditions in the ocean surface favouring small phytoplankton at the expense of diatoms (Bopp *et al*., 2005).

Oxygen depletion

Hypoxia (low oxygen) is starting to become an issue of major concern for coastal waters around the world (Weston *et al*., 2008). However, little is understood of the possible impact of low oxygen zones on fish and fisheries. Dead zones in the coastal oceans have spread exponentially since the 1960s and have serious consequences for ecosystem functioning. The formation of dead zones has been exacerbated by the increase in primary production and consequent worldwide coastal eutrophication fuelled by riverine runoff of fertilisers. Enhanced primary production results in an accumulation of particulate organic matter, which encourages microbial activity and the consumption of dissolved oxygen in bottom waters. Dead zones have now been reported from more than 400 systems, affecting a total area of more than 245 000 square kilometres, and are probably a key stressor on marine ecosystems (Diaz and Rosenberg, 2008). Low oxygen is predicted to occur more regularly in the future as a result of climate change. In the North Sea, for example, waters are 2-3 ºC warmer and therefore contain less dissolved oxygen by 0.4 mg l-1; the period of stratification will last for longer, and summer storms that normally dissipate areas of hypoxia will likely decrease in the future (Weston *et al*., 2008). In the Kattegat, the Baltic Sea, and the Gulf of St. Lawrence, fish such as cod completely avoid low oxygen waters (Chabot and Claireaux, 2008). Furthermore, in the Baltic Sea cod eggs do not survive low oxygen conditions, and years with extensive hypoxia have been related to very poor stock recruitment for this species (Koster *et al*., 2005).

Ocean acidification

Rising atmospheric CO2 concentrations over the past two centuries have led to greater CO2 uptake by the oceans. In the past few decades, only half of the CO2 released by human activity has remained in the atmosphere; of the remainder, about 30% has been taken up by the ocean and 20% by the terrestrial biosphere. Based on the Intergovernmental Panel on Climate Change estimates of future atmospheric and oceanic CO2 concentrations, corresponding models for the oceans indicate that surface-water dissolved inorganic carbon (DIC) could probably increase by more than 12%, and the carbonate ion concentration would decrease by almost 60%, resulting in a corresponding

pH drop of about 0.3-0.5 pH units in surface waters by 2100 (Caldeira and Wickett, 2003). Ocean pH was around 8.3 after the last ice age, and 8.2 before CO2 emissions took-off in the industrial era (when CO2 in the atmosphere amounted to around 280 parts per million). Ocean pH is now 8.1, with an atmospheric CO2 concentration of around 380 parts-per-million (ppm). This is more acidic than the ocean has been for hundreds of millennia, and the rate of pH change is estimated to be 100 times faster than at any other time during the past 100 000 years. A key consequence is that the degree of saturation of seawater with aragonite2 and calcite, which is largely governed by bicarbonate concentration (CO3-2).

Undersaturation, particularly of aragonite, is predicted in near surface waters between 200-1000 m in the North Pacific, north Indian and east Atlantic Oceans within the next few decades (Feeley *et al*., 2004). The calcification rate of organisms across multiple taxa – from single-celled protists to reef-building corals – is expected to decrease in response to a decreased CaCO3 saturation state (Feeley *et al*., 2004). Coral reef calcification depends on the aragonite saturation state of surface waters. By the middle of the next century, an increased concentration of carbon dioxide will decrease the aragonite saturation state in the tropics by 30% (Kleypas *et al*., 1999). Acidification is likely to favour some phytoplankton species over others, particularly in the Southern Ocean, which may in turn influence the community structure of the higher trophic levels that are reliant upon phytoplankton as food and will also influence the cycling of elements, since processes and mechanisms differ between phytoplankton species (Hays *et al*., 2005). High pCO2 and lower pH will also affect the growth and reproduction of many benthic invertebrate species (see Fabry *et al*. 2008), including echinoderms, bivalve molluscs and some crustaceans. While understanding the effects of acidification on components of the life history of organisms has been the focus of laboratory scientists, the real question is: what are the population and community effects of acidification? Whole ecosystems already exist in the acidified deep water below the aragonite saturation horizon; the question is who will be the winners and losers as the undersaturated acidic waters shoal and influence shallower water ecosystems that support commercial fisheries and aquaculture.

Coral reef degradation

Rising sea temperatures are likely to have the greatest effects in the tropics, particularly on coral reef habitats. Tropical oceans have already warmed by 0.5-1 °C over the past 100 years (Hoegh-Gulburg, 1999). Elevated carbon dioxide levels and temperatures are likely to increase coral mortality through bleaching, ocean acidification and changing frequency and intensity of hurricanes (Hughes *et al*., 2003).

Coral growth and reef building processes occur only under conditions of low nutrients, warm waters >18°C, high light, and stable full salinity (Veron, 1993). Corals can be found in conditions other than these but do not form massive atoll and barrier reef structures. The temperature range under which reef building corals survive is wide (18-34 °C) but the variance is low, suggesting that coral are highly adapted to live within narrow temperature tolerances (Hoegh-Gulburg, 1999; Hughes *et al*., 2003). Overheated corals expel their symbiotic microalgae (zooxanthellae) and become pale or white. If the stress is prolonged the coral will die. Temperature elevation by 1 °C above the summer seasonal average is likely to cause coral mortality (Hoegh-Gulburg, 1999), accentuated by calm conditions in which coral receive more light (Sheppard *et al*., 2009). Temperature rises of this magnitude and greater are associated with ENSO events, which have

occurred with increasing frequency in the last two decades resulting in widespread coral bleaching and mortality (Glynn, 1996).

Bleaching could become an annual or biannual event for the vast majority of the world's coral reefs in the next 30-50 years without an increase in thermal tolerance of 0.2-1.0 °C per decade (Donner *et al*., 2005). In the western Indian Ocean the probability of repeated episodes of mass bleaching similar to that observed in 1998 will increase to a 50% chance of recurrence for the warmer months within 25-35 years (Sheppard, 2003).

Thermal bleaching along with fisheries exploitation, pollution and disease are the greatest threats to coral reefs (Newton *et al*., 2007; Hughes *et al*., 2003; Pandolfi *et al*., 2003). In 1998 the biggest ENSO-driven bleaching event killed between 10-16% of the world's corals (Goreau *et al*., 2000; Wilkinson, 2000). Mortality in some areas was higher: western Indian Ocean reefs lost as much as 46% of reef-building coral cover (Wilkinson, 2000). The degree of degradation has been higher on Caribbean reefs; it is estimated that fishing, hurricanes, bleaching and disease have resulted in a loss of 80% of Caribbean hard coral cover over the last three decades (Gardner *et al*., 2003). Even relatively pristine, well-managed reefs such as the Great Barrier Reef, Australia have been severely degraded; hard coral cover has halved from ~38% cover in 1964 to the current cover of ~21% in 2004 (Bellwood *et al*., 2004). Overall, it has been estimated that 30% of coral reefs have been severely damaged and close to 60% may be lost by 2030 (Wilkinson, 2000). The current annual rate of loss of coral cover is approximately 0.5-1.5% per year, based on estimates from the Caribbean (1.3% year-1) (Gardner *et al*., 2003) and the Great Barrier Reef, Australia (0.56% year-1) (Bellwood *et al*., 2004).

Ocean acidification poses a major threat to the world's coral reefs. A high profile paper in 2009 highlighted the deleterious effects of falling pH on corals across a huge swath of the Great Barrier Reef in Australia (De'ath *et al*., 2009). Reading the rate of growth recorded in coral skeletons, the authors found that calcification rates had declined by 14.2% since 1990, and they demonstrated that no equivalent phenomenon had been recorded within the past 400 years. Laboratory experiments have revealed that high CO2 is also a bleaching agent for corals (Anthony *et al*., 2008), and projections suggest that under the current rate of increase in CO2 emissions, (>1 ppm y-1) carbonate ion concentrations will drop below 200 μmol kg-1 and reef erosion will exceed calcification by the year 2040 (expected to occur at 450-500 ppm). The density and diversity of corals on reefs are likely to decline, leading to vastly reduced habitat complexity and loss of biodiversity, including commercially important fish and invertebrates (Hoegh-Guldberg *et al*., 2007). Added to this, a recent study on coral reef fish (Munday *et al*., 2009) has shown that larval fish reared in control seawater (pH 8.15) discriminated between a range of cues that could help them locate reef habitat and suitable settlement sites. This discriminatory ability was disrupted when larvae were reared in high CO2 waters. Larvae became strongly attracted to olfactory stimuli they normally avoided when reared at levels of ocean pH that could occur ca. 2100 (pH 7.8) and they no longer responded to any olfactory cues when reared at pH levels (pH 7.6) that might be attained later next century on a business-as-usual carbon-dioxide emissions trajectory. If acidification continues unabated, the impairment of sensory ability may reduce population sustainability of many reef fish species, with potentially profound consequences for marine diversity.

What are the latest projections and associated uncertainties?

Global surface temperature has been observed to have increased by 0.6 °C and global average sea level has already risen by 10-20 cm. Precipitation has increased in the northern hemisphere by 1% per decade, and the frequency of heavy precipitation events increased by 2-4% over the century. Arctic sea-ice thickness during late summer-early autumn has decreased by up to 40% and global snow cover has decreased by about 10% since 1960 (IPCC, 2001; Barange, 2002). In the past 200 years ocean uptake of CO2 has led to a reduction of the pH of surface seawater of 0.1 units, equivalent to a 30% increase in the concentration of hydrogen ions (Royal Society, 2005).

The predictions for the twenty-first century include an increase in the rate of global warming. Mean global surface temperature is predicted to increase by 1.4-5.8 °C by 2100. Warming will be most pronounced over land areas, particularly in high latitudes and in the cold season. Most models predict a weakening, but not shutdown, of the thermohaline circulation by 2100. Shutdown may occur beyond 2100. Sea level will rise by 9-88 cm by 2100. The Antarctic ice sheet will gain mass due to greater precipitation, but the Greenland ice mass will decrease significantly because of increased run-off and glacial melt. There is relatively high certainty that ocean pH will decrease (acidify) by 0.3-0.5 pH units over the next century (Royal Society, 2005).

There are some aspects of future climate change with which we have greater confidence than others. For example, we are more confident about increases in greenhouse gas concentrations and rises in sea-level than we are about increases in storminess, winds and waves, and the behaviour of the El Niño-Southern Oscillation (ENSO) (Allison *et al*., 2005). The main sources of uncertainty in the physical effects of climate change result from:

- Uncertainty over future CO_2 emissions (a consequence of human demography and development) and consequently atmospheric concentrations of greenhouse gases, as these will depend on societal choices.
- Incomplete knowledge about how the global climate system will respond to greenhouse gas forcing.
- Inherent variability because climate models are non-linear and thus tend to be sensitive to the starting conditions, which can create uncertainty at a later time.
- Variation in feedbacks among models associated with not knowing how the climate system reacts to unprecedented rates of greenhouse gas emissions or in knowing how clouds, forest, grasslands or particularly the world's oceans react to climate perturbations and how they feed back into the system.
- Reduced confidence in Global Circulation Model (GCM) results at the detailed spatial and temporal scales often required by planners and managers. One outcome of this uncertainty is that different climate models sometimes yield different regional climate responses to the same greenhouse gas emissions, producing an additional measure of uncertainty in future climate scenarios. This is particularly acute for precipitation, wind and storminess. While there is high certainty that precipitation will increase, particularly in the northern hemisphere, the effect will be less certain at smaller spatial scales.
- A key uncertainty is the degree to which short-lived mobile calcifying organisms will be able to respond to ocean acidification and higher pCO2 by altering their

distribution or adapting to lower saturation states. There is relatively low certainty of how complex second-order climate phenomena and extreme events, such as hurricanes, upwelling, ENSO are affected by climate change.

- The detailed response of ecological and socio-economic systems to the observed and predicted physical and chemical changes is less certain. While there is relatively high certainty that elements of climate change, such as temperature, have changed the growth, phenology, productivity and geographic distribution of some populations and species, it is less clear how climate change will affect ecological interactions such as the "match-mismatch" of consumers and resources. The greatest area of uncertainty is in the our understanding of the degree to which effects of climate change on physical and biological systems have translated into positive or negative effects on social and economic systems, such as fisheries.

How and where does global warming potentially impact on fisheries?

There are many different potential pathways through which climate change may influence fisheries and their contribution to local community livelihoods, national economies and global trade-flows and supplies of fishery products to consumers. Notwithstanding this complexity and uncertainty, it is increasingly recognised that climate change can impact local human communities through two broad pathways.

- Climate change, including ocean acidification, modifies the structure and function of the aquatic ecosystem, which in turn influences the productivity and spatial and temporal distribution of fisheries resources. This is likely to reduce access to livelihood opportunities and natural capital through changes in the fisheries productivity in some areas, but may well enhance opportunities elsewhere (especially at higher latitudes).
- The increasing frequency and severity of extreme events such as floods, storms and hurricanes will increase the vulnerability of fishing communities through damage to infrastructure, reduced opportunities to go to sea, and increasing threats to human health (Kovats *et al*., 2003; Adger *et al*., 2005b; Pascual *et al*., 2000).

While it is clear that both of these climate change pathways tend to result in generally negative impacts, Cheung *et al*. (2009b) suggests that climate change may lead to large-scale redistribution of global catch potential, with an average of 30-70% increase in yield of high-latitude regions, but a drop of up to 40% in the tropics. Changes in fish productivity will result in the larger, macro-scale impacts such as reduced contribution of fisheries to the national economy in some areas and reduced availability of fish as a source of dietary protein. These potential impacts are examined further below.

Climate effects on fisheries-relevant populations, species and ecosystems

Climatic variation has wide-ranging effects on the ecology of aquatic systems, by acting across ecosystems and propagating through trophic webs, over broad spatial and temporal scales (Harley *et al*., 2006; Stenseth *et al*., 2005). For exploited species, the various impacts of climate change include direct and indirect effects on individuals (Wood and McDonald, 1997), populations (Cushing, 1982; Beaugrand *et al*., 2002; Edwards and Richardson, 2004; Perry *et al*., 2005) and ecosystems (Feeley *et al*., 2004; Harvell *et al*., 2002; Schindler *et al*., 1996). These effects are likely to coincide with more general warming-related changes in habitat quality and productivity which are likely to

affect fished species and fisheries, e.g. coral reef loss (Hoegh-Gulberg, 2005; Graham *et al*., 2006). Recent reviews provide strong circumstantial evidence to suggest that ocean climate will have far-reaching effects on the dynamics of fish populations. However, knowledge of the underlying mechanisms and likely future trajectories is rather limited (see Rijnsdorp *et al*. 2009; Drinkwater *et al*., 2010). First, there is uncertainty about the future development of the ocean climate itself, as various aspects will be influenced such as circulation patterns, air and sea surface temperatures, frequency and intensity of storm events, precipitation patterns, pH and river run off. Second, fish have complex life cycles comprising several life history stages, differing in their sensitivity to climate effects (Graham and Harrod, 2009). We summarise the known effects of climate change at the individual and population scale on fish physiology, growth, reproduction, distribution and abundance, and known effects on assemblages, communities and ecosystems.

Physiology and metabolism: the acute response to thermal stress

Changes in temperature will have a direct impact on the physiology and metabolic processes of fish, which will in turn influence energy allocation, and consequently the life histories and demography of populations and species (Atkinson, 1994; Charnov and Gillooly, 2004). When faced with physiological stress, such as temperature change, individuals have four options: tolerate the stress, move or migrate, adapt physiologically or die (Schmidt-Nielson, 1973; Pörtner and Knust, 2007). Individuals are characterised by relatively narrow temperature and salinity tolerances, limiting their ecological habits and distribution (Wood and McDonald, 1997). Tolerances, such as to temperature variation, may change with season and age. A review of the upper and lower lethal temperatures of various marine fish species indicated that thermal tolerance changed markedly with latitude (Rijnsdorp *et al*., 2009). The range of tolerable temperatures was narrower in fish inhabiting high and low latitudes and wider for fish inhabiting intermediate latitudes. Furthermore in some species, egg and larval stages have been observed to have a narrower range of tolerable temperatures than other life-history stages (specifically juveniles) making these early life stages more vulnerable to changes in temperature (Portner and Farrell, 2008). Increases in temperature, changes in precipitation, and atmospheric gas concentrations resulting from climate change may benefit some species (e.g. in temperate regions) by increasing growth, reproductive capacity and metabolic efficiency. However, these benefits will only occur up to a point. As temperature increases beyond an individual's thermal optimum, the ability to extract oxygen from the water decreases, and energy is more likely to be diverted away from movement, growth and reproduction into maintenance metabolism, ultimately constraining the tolerance of individuals (e.g. Björnsson and Steinarsson, 2002).

Migration, movement, invasion and distribution changes

Individual fish that are unable to tolerate ambient conditions may migrate to locations with more thermally optimal habitats (e.g. MacCall, 1990; Blanchard *et al*., 2005b). Such individual-based decisions, combined with changing habitat size and quality, may result in geographic range expansion and invasions of new coastlines and sea areas and reductions in abundance and range size of others (Francour *et al*., 1994). Adult fish in particular may adjust their migratory patterns following food availability and become the targets of new fisheries as a result (Reid *et al*., 2001). In Europe, offshore fishes with southerly distributions are increasing in abundance and expanding their range into the North Sea and other northerly waters. Examples include John Dory (Zeus faber), red

mullet (Mullus surmeletus), anchovy (Engraulis encrasicolus), sardine (Sardina pilchardus) (Quero, 1998; Beare *et al*., 2004; MacKenzie *et al*., 2007) many of these are subject to new and emerging fisheries.

Considerable shifts in the geographic and depth distribution of Northeast Atlantic fish species have already been identified and linked to climate change (Perry *et al*., 2005). Southerly species increased their depth range, e.g. plaice (Pleuronectes platessa), or extended their range centres or range boundaries northwards. Northerly species contracted and retracted northwards. The rate of distribution change was greatest for species with faster life histories and smaller body sizes. Species and assemblages are deepening coherently as their preferred thermal habitat (isotherms) deepen (Dulvy *et al*., 2008). Similarly, the distribution of intertidal invertebrates is changing, with southerly limpets, topshells and barnacles increasing their range around UK coastlines (Mieszkowska *et al*., 2006). Northward range shifts associated with coastal warming were observed in Californian coastline invertebrates, with eight out of nine southern species increasing in abundance and five out of eight northerly species becoming less abundant since the 1930s (Barry *et al*., 1995; Sagarin *et al*., 1999). These changes reflect the impacts of both climate and fishing. For individual fish, tolerance to temperature change can vary significantly; indeed individual North Sea cod may tolerate temperatures considered too warm for optimal growth (Neat and Righton, 2007). This reflects the complexity of the impacts of future climate on species distribution.

Cheung *et al*. (2009) investigated the global patterns of climate impacts on marine biodiversity by projecting the distributional ranges of a sample of 1066 exploited marine fish and invertebrates up to the year 2050 using a dynamic bioclimate envelope model. These projections showed that climate change could lead to numerous local extinctions in the sub-polar regions, the tropics and semi-enclosed seas. Localised extinctions have also been projected at the edges of current ranges, including in freshwater and diadromous species (Brander, 2007; Drinkwater, 2005), and within the Mediterranean Sea (Lasram *et al*., 2010). Simultaneously, species invasion was projected to be most intense in the Arctic and the Southern Ocean. The authors suggested species turnovers of over 60% of the present biodiversity, with the potential for these ecological disturbances to disrupt ecosystem services and fisheries.

Building on this work Cheung *et al*. (2009) attempted to predict changes in catch potential of exploited marine fish and invertebrates under various climate change scenarios. Maximum catch potential declines considerably in the southward margins of semi-enclosed seas while it increases in poleward tips of continental shelf margins. Such changes are most apparent in the Pacific Ocean. Among the 20 most important fishing exclusive economic zone (EEZ) regions in terms of their total landings, EEZ regions with the highest increase in catch potential by 2055 include Norway, Greenland, the United States (Alaska) and Russia (Asia). On the contrary, EEZ regions with the biggest loss in maximum catch potential include Indonesia, the United States (excluding Alaska and Hawaii), Chile and China. Many highly-impacted regions, particularly those in the tropics, are socio-economically vulnerable to these changes.

Changing timing of ecological events

On land, increases in temperature are bringing forward the onset of springtime and delaying the onset of autumn. Similarly, in the sea biological events are happening earlier in the seasonal cycle, and there have been marked changes in the seasonal distribution and abundance of plankton (Richardson and Schoeman, 2004) and in the maturation of

fish (Morgan *et al*., 2010), their spawning (Sundby and Nakken, 2008) and fish larval abundance (Greve *et al*., 2005), for example. The timing of migrations and peak abundance of squid and fishes varies with the North Atlantic Oscillation (Sims *et al*., 2001, 2004). Change in migration phenology has been described for the flounder Platichthys flesus, which has been shown to undertake a spawning migration 1-2 months earlier when conditions are cooler. This may seem paradoxical at first, given our usual expectation that organisms will migrate earlier during warmer years. In the English Channel region however, freshwaters, estuaries and shallow marine environments are colder in winter than the deep offshore waters. Flounder make their annual winter migration to these warmer deep waters to breed, and the timing of migration appears to be triggered by the onset of low temperatures. Recently published evidence from ichthyoplankton sampling suggests that other winter breeding species in the English Channel region also spawn earlier in cooler years, while summer spawning fish tend to spawn later (Genner *et al*., 2010; Greve *et al*., 2005). Together this evidence suggests that fish spawning and migration phenology may be spatially variable and highly dependent on local differences in thermal regimes. For example, veined squid (Loligo forbesi) migrate eastwards in the English Channel earlier when water in the preceding months is warmer. Higher temperatures and early arrival correspond with warm (positive) phases of the North Atlantic Oscillation (NAO). The timing of squid peak abundance advanced by 120-150 days in the warmest years ("early" years) compared with the coldest ("late" years).

A key concern with changing timing of annual recurring life cycle events is that is will lead to a decoupling or mismatch between consumers and their prey resource. The degree of spatial and temporal overlap of the spring phytoplankton bloom with the timing and spatial distribution of the spawning of eggs into the surface waters strongly influences larval fish survival, and hence recruitment success (year class strength) of important fish species (Platt *et al*., 2003). The North Atlantic Oscillation (NAO) influences sea temperature and the timing of phytoplankton blooms and other ecological processes in the North Atlantic (Reid *et al*., 1998; Irigoien *et al*., 2000). Temperature-driven acceleration of egg development times may result in fish and zooplankton eggs hatching prior to the peak in abundance of their main food source - phytoplankton - resulting in a mismatch between trophic levels and functional groups (Edwards and Richardson, 2004). In the North Sea, phytoplankton blooms have generally advanced more in response to warming than have their zooplankton grazers (Hays *et al*., 2005).

Assemblage, community and ecosystem effects of climate change

The changing distribution and abundance of species is likely to affect the structure and function of communities and ecosystems. Recent analyses of changing fish distributions indicate that temperate fish communities are likely to be composed of increasing numbers of smaller-bodied species of southerly biogeographic affinity, with less contribution from larger-bodied species with boreal, northerly affinity (Blanchard *et al*., 2005a; Drinkwater, 2005; Perry *et al*., 2005). The change in relative contribution of southern and northern species to fish communities has been observed in the North Sea and the Bering Sea (Perry *et al*., 2005; Wang *et al*., 2006; Dulvy *et al*., 2008). This simplified summary of community and ecosystem change is relatively conservative; little is known of the effects of changing phenology on predator-prey relationships, and there is also uncertainty about overall effects of temperature and the other variables describing climate change on ecosystem properties such as production and turnover. Specific modelling studies for Australian waters (Brown *et al*., 2010) suggest increases in primary

production and hence ecosystem biomass. Overall, however, predicting the resulting response of populations to primary production change is complicated by predation and competition interactions.

Even though commercial finfishes may be less impacted by ocean acidification than is the case with commercial shellfish, in terms of direct physiological effects, they may be impacted by changes in the marine food-web. Larvae and juveniles of most fish are reliant on planktonic crustaceans which may or may not be impacted by future ocean acidification. As adults, many commercial fish species (e.g. haddock and plaice) are also reliant on bivalve molluscs or echinoderms which are predicted to decline in the future as a result of ocean acidification (Fabry *et al*., 2008).

Effects of changing aquatic ecosystems and fish ecology on fisheries

Climate change can affect fisheries ecosystems in complex and sometimes contradictory ways. This makes it difficult to assess net impacts. For example, freshwater lakes have been predicted to increase in productivity across trophic levels as a consequence of the effect of warming on metabolism and production (Regier and Meisner, 1990). However, the warming effect is often associated with other physical changes which can have countervailing effects, such as thermal stratification resulting from lighter winds. These may result in anoxic conditions or less intense upwelling and/or seasonal mixing, which may cause fish mortality or reduced primary productivity. This is not a comprehensive review and we have not considered open ocean ecosystems, but for a fuller treatment see Stenseth *et al*. (2005), Barange (2002), Brander (2006) and Lehodey *et al*. (2006).

Upwelling systems

Climate-sensitive upwellings of nutrient-rich waters support huge catches of sardines (Sardinops sagax) and anchovy (Engraulis mordax), primarily off Peru and Chile. Catches of small pelagic fishes have been as high as 11 million tonnes per year, representing more than 10% of world capture fish production (FAO, 2004). However, these show pronounced fluctuations often associated with ENSO effects on upwelling dynamics and productivity (Lehodey *et al*., 2006). The strength of upwelling off the South American coastline is strongly determined by the ENSO phase, with warm phases associated with a lower thermocline, which reduces phytoplankton production through inhibited upwelling of nutrients. As a result sardine move southward. However, anchovies are more constrained and become more accessible to fisheries as they aggregate in dense coastal pockets of colder water. During the 1972 El Niño, anchovies were so highly concentrated on the coast that 170 000 tonnes were caught on one day (Lehodey *et al*., 2006).

In coastal western Africa fisheries, catches of small pelagic fishes also track the strength of the upwelling pulses, which are largely driven by El Niño-like effects on eastern boundary current circulation and local wind stress (Binet *et al*., 2001; Binet, 1997). The frequency of ENSO events is projected to increase with global warming (Bakun, 1990). This has obvious implications not just for coastal fishers whose fishing range is constrained by technology and conditions, but also major industrial fisheries and export-derived incomes (see the sections below on the social and economic impacts of climate change).

Temperate shelf waters

Climate change is shifting target species northwards in the northern hemisphere (southwards in the southern hemisphere) and at the southerly extent of their range reducing the productivity and recovery capacity of some species. For example Atlantic cod (Gadus morhua) growth, recruitment, abundance and distribution are all strongly influenced by climate (Brander, 2000). Some important stocks, including those in the North Sea cod produce fewer recruits in years when winter sea surface temperature is warm (Planque and Fredou, 1999), whereas those at the northerly limit benefit from warm conditions and exhibit enhanced recruitment. During the late 1960s and early 1970s in the North Sea, cold conditions were correlated with a sequence of positive recruitment years in cod, haddock and whiting (Brander and Mohn, 2004) and subsequently high fisheries catches for a number of years to come. However, in more recent years, a warming climate has prevailed and year class strength has been weaker than average.

Extensive fishing may cause fish populations to be more vulnerable to short-term natural climate variability (O'Brien *et al*., 2000; Walther *et al*., 2002; Beaugrand *et al*., 2003), by making such populations less able to "buffer" against the effects of the occasional poor year classes. Conversely, long-term climate change may make stocks more vulnerable to fishing, by reducing the overall "carrying capacity" of the stock, such that it might not be sustained at, or expected to recover to, levels observed in the past (Jennings and Blanchard, 2004). Cook and Heath (2005) concluded that if the recent warming period were to continue, as suggested by climate models, stocks which express a negative relationship with temperature (including cod) might be expected to support much smaller fisheries in the future. In the case of cod, climate change has been estimated to have been eroding the maximum sustainable yield at a rate of 32 000 t per decade since 1980.

Older and larger cod have lower optimal temperatures for growth (Bjornsson *et al*., 2001) and the local distribution of cod is known to depend on depth and temperature (Ottersen *et al*., 1998; Swain *et al*., 2003). Blanchard *et al*. (2005b) used information on optimal temperatures for growth and suggested that in years when stock size is low, catches are largely confined to regions with near-optimal bottom temperatures. Conversely, when population size is high, catches are spread across a larger area including regions with suboptimal temperatures. The authors demonstrated that spatial extent of optimal habitat appears to have decreased from 1977 to 2002, reflecting a gradual warming of the North Sea. This is particularly worrying given that the remaining, highly aggregated, stocks would be especially vulnerable to over-harvesting.

Cod are known to be capable of moving large distances (approximately 1000 km), and hence could theoretically relocate to anywhere in the North Sea. However, a study by Neat and Righton (2007), based on observations of the temperature experienced by 129 individual cod (using data storage tags), suggested that in the summer most of the individuals in the south experienced temperatures considered suboptimal for growth. Cooler waters were easily within the reach of these cod and a small number of individuals migrated to areas that allowed them to experience lower temperatures, indicating that the cod had the capacity to find cooler water. Most however, did not, suggesting that cod could be trading between thermally optimal habitats and requirements for prey, shelter and reproduction.

Climate change-induced warming is expected to have adverse effects on some exploited invertebrates such as abalone (Haliotis spp.). Warm temperatures are known to increase the onset of withering syndrome, a fatal abalone disease, and to halt growth and

reproduction of red abalone (Vilchis *et al*., 2005). By contrast, year-class-strength in scallops around the Isle of Man are, on average, positively related to seawater temperature in the spring (Shephard *et al*., 2010). The gonads of adult scallops are also larger, indicating higher egg production, in warmer years.

Historic studies can be used to provide some information on the possible effect of climate change on fish stocks. Cod and halibut (Hippoglossus hippoglossus and Reinhardtius hippoglossoides) catch records in the Barents and White Sea from the 17th and 18th centuries suggests catches were much lower in cooler periods (Lajus *et al*., 2005). Similarly, Southward *et al*. (1988) suggested that sardine were more abundant in south-east England when climate was warmer (e.g. 1590 to 1640), whereas herrings were more abundant in cooler times (e.g. the "little ice age" of the late 17th century).

Despite all these expected direct effects of climate change on fisheries, Harley *et al*. (2006) note that abiotic changes and subsequent biological responses will be complex. They note that changes in ocean chemistry may be more important than changes in temperature for the performance and survival of many organisms. Furthermore, climatic impacts on one or a few "leverage species" may result in sweeping community-level changes. In turn, synergistic effects between climate and other anthropogenic variables, particularly fishing pressure, will likely exacerbate climate-induced changes. Indeed, in the short term, it is often effective management of fish stocks that is needed, to return the populations to relative health in the short term (Kell *et al*., 2005). A diversity of healthy stocks may then provide a greater buffer against the impacts of climate change on fish recruitment success and other direct and indirect impacts (Hilborn *et al*., 2003).

Coral reefs

Coral reef coasts provide diverse, productive and accessible open livelihoods centred on fisheries and aquaculture resources, which are particularly attractive and important for poor and migrant people (Whittingham *et al*., 2003). Variation in natural resource systems are expected to occur with increased frequency and increased intensity of shocks, such as bleaching events and hurricanes, and the degradation and loss of resilience of coral reefs e.g. associated with ocean acidification (Hughes *et al*., 2003; Bellwood *et al*., 2004). The diversity and abundance of reef fishes is correlated with the extent and architectural complexity of coral reefs (Friedlander and Parrish, 1998). The loss and degradation of coral reefs through climate change can be expected to reduce the abundance and diversity of fishes, with negative impacts for subsistence and artisanal fisheries that provide important livelihoods and a source of protein and micronutrients for coastal and island populations.

The acute short-term impacts of coral bleaching mortality have had a relatively minor impact on fish assemblages to date. Events such as the 1998 mass coral bleaching in the Indian Ocean have not been accompanied by obvious negative short-term bio-economic impacts for coastal reef fisheries (Grandcourt and Cesar, 2003; Spalding and Jarvis, 2002; Bellwood *et al*., 2006). However, a longer term study of Seychelles fish assemblages has indicated that responses may lag long after the coral mortality event, due to the loss in complex substrate that smaller fishes depend upon. Fish assemblage structure appears to be determined by the degree of bio-erosion and collapse of the dead reef architecture (Graham *et al*., 2006). The collapse of reef skeletons resulted in local extinctions, particularly of obligate corralivores, substantial reductions in species richness, reduced taxonomic distinctness, and a loss of species within key functional groups of reef fish, particularly planktivores, corralivores and herbivores (Graham *et al*., 2006), with reduced

recruitment success and potential population collapse (Graham *et al*., 2007). Following the loss of Caribbean coral cover there has been region-wide collapse in the complexity of reefs, due to disease-induced die-off of structure-forming Acropora corals in the later 1970s and the subsequent renewed phase of collapse following the 1998 ENSO bleaching event (Alvarez-Filip *et al*., 2009). This renewed phase of collapse coincides with the region-wide decline in reef fishes (Paddack *et al*., 2009). Coral reefs are already suffering from overfishing in many parts of the world (Newton *et al*., 2007), which, when combined with the effects of coral mortality and reef architecture collapse, can only further diminish coral reef fish productivity (Sadovy, 2005; Warren-Rhodes *et al*., 2003). The loss of fish productivity is anticipated to have substantial negative consequences for island and coastal communities (Whittingham *et al*., 2003).

Freshwater lakes

Freshwater lakes act as microcosms for the impacts of climate change in marine waters. At the most extreme, lakes such as Lake Chad can dry up in particular years. Impacts of climate change have been found in Lake Baikal, with significant warming of surface waters and long-term changes in the lake's foodweb, and corresponding increases in chlorophyll a and some zooplankton grazers (Hampton *et al*., 2008). In the deep African Rift Valley lakes, such as Lake Tanganyika, climate change has been associated with increases in surface water temperature, reduced vertical mixing of water, reduced primary productivity and reduced fish catch per unit effort, which has driven fishers to other lakes (Verburg *et al*., 2003; O'Reilly *et al*., 2003; Allison and Ellis, 2001). In Lake Tanganyika, the surface water temperature has risen over the last century. This has increased the stability of the water column, which along with a regional decrease in wind velocity has contributed to reduced mixing, decreasing deep-water nutrient upwelling and entrainment into surface waters. This has decreased primary productivity by about 20%, and decreased fish yields as a result (Verburg *et al*., 2003; O'Reilly *et al*., 2003). Water levels and surface areas of some large, shallow African lakes (such as Lakes Chilwa, Bangweulu and Chad) fluctuate with changes in ENSO (Jul-Larson *et al*., 2003). These fluctuations are mirrored by changes in fishing activity and catches (Allison and Mvula, 2002).

Rivers and estuaries

The impact of climate change on river fisheries and fisher livelihoods will vary among river basins according to regional differences in the forecasted effects on the water temperature, and on the hydrological regimes of rivers and their floodplains.

Increased temperatures have been shown to negatively affect the survival of juvenile summer chinook salmon (Oncorhynchus tshawytscha) in wide and warm streams, and positively affect survival in narrow cool streams of the Salmon River basin, Idaho (Crozier and Zabel, 2006). Stream temperatures in this basin have been increasing steadily since 1992. It has been argued that few North Atlantic fish species will be as intensely affected by climate change as Atlantic salmon (Stenseth *et al*., 2005; Jonsson and Jonsson, 2009). Whalen *et al*. (1999) reported that peak migration of salmon occurs later in spring for tributaries with lower temperature. Also, annual variation in the timing of peak migration of Atlantic salmon is related to variation in annual temperatures (McCormick *et al*., 1998). Low water flow in rivers can also have a deleterious effect on upstream migration of salmon returning from the sea to spawn (Solomon and Sambrook, 2004). Studying radio tagged salmon in four English rivers, they noted that when water

flows were relatively high, the majority of migrating adult salmon passed through estuaries and into the rivers with a minimum of delay. However, when river flow was low (drought years), most fish arriving from the sea did not pass quickly into freshwater but remained in the estuary or returned to sea for several months. Many fish subsequently failed to enter the river even when favourable flow conditions returned, possibly as a result of lost physiological opportunity (Solomon and Sambrook, 2004). Jonsson and Jonsson (2009) provided a detailed review of the likely effects of climate change on salmon and sea-trout, with particular reference to water temperature and river flow.

The effects on river hydrology, driven largely by changing patterns of precipitation and run-off, are currently difficult to predict with certainty at the river basin scale (McCarthy *et al*., 2001; Conway *et al*., 2005). This uncertainty propagates to our predictions of the impacts on river fisheries. In addition to the direct effects of climate change (e.g. increased atmospheric and water temperatures), climate change will have indirect impacts. Increased precipitation and evapotranspiration will change the hydrology of inland waters and rivers. In turn, anthropogenic impacts on water use and extraction will further impact downstream processes (see below).

Fisheries production in many Asian countries relies on rivers that arise in the Himalayan Mountains, such as the Indus, Brahmaputra, Ganga and Mekong. The effect of changes in the hydrological regime will vary amongst river basins, according to regional differences, although forecasts of these changes are often lacking. Climate change will cause earlier season peak flows and reductions in flow overall, attributable to reduced snowfall and melting glaciers (Barnett *et al*., 2005a). Changing timing of peak flows, higher summer temperatures and lower oxygen concentration are likely to reduce larval fish survival (Gibson *et al*., 2005) and thermally optimal habitat by 15-30%, particularly for cool and cold-adapted species (Mohseni *et al*., 2003).

Reductions in river discharge (water availability) stemming from climate change or increased water withdrawal tends to reduce freshwater biodiversity. In rivers with reduced discharge, up to 75% (quartile range 4-22%) of local fish biodiversity would be headed toward extinction by 2070 because of combined changes in climate and water consumption. This effect would be disproportionately high for the world's poorest countries (Xenopoulos *et al*., 2005). The consequences for river fisheries are uncertain and depend on the interaction of local rainfall and glacier melt profiles and the importance of dry versus wet season water levels for fish productivity.

Increased run-off and discharge rates might increase fish yield through more extensive and prolonged inundation of floodplains, such as in the Ganges Basin (Welcomme, 1985). Fish abundance and catches tend to be higher depending on the depth and duration of floodplain inundation in the wet season. In Bangladesh a 20-40% increase in flooded area could raise total annual yields by 60 000-130 000 t (Halls *et al*., 2006; Mirza *et al*., 2003). These elevated yields may not be realised as a key bottleneck to river fish populations is the amount of water remaining in the dry season, when the area of water remaining can be as low as 5% of the floodplain area (Halls *et al*., 2001; Halls and Welcomme, 2004). According to the available models, benefits may arise during the flood season, but these must be offset by reductions to yield predicted during the dry season. Increased peak flows associated with increased inland precipitation due to climate change is likely to increase the run-off of fertiliser and sewage into coastal waters. Increased nutrient loading may trigger algal blooms, leading to potential poisoning of fish and humans, and directly affect those countries farming fish in coastal waters (Anderson, 1997).

Estuaries and wetlands are productive and rapidly changing environments, but are less resilient to climate change because many native species currently live near their tolerance limits (Roessig *et al*., 2004). Global warming-induced changes in ocean circulation and river flows are anticipated to increase marine intrusion or freshwater plumes, increase eutrophication and lower oxygen levels and are predicted to destroy saltmarsh and intertidal habitats resulting in declines in native species and increases in invasive species (Roessig *et al*., 2004).

Climate hazard effects on coastal communities

Climate change has the potential to affect coastal and inland fisheries systems through increased risk of disaster and health problems. Over one third (37%) of the global human population lived within 100 km of the coast in 1994 and this proportion is expected to increase over time (Cohen *et al*., 1997). Globally, the number of fishers has increased considerably over the last two decades. Fisheries have emerged as one of the last refuges of the impoverished. With reduced opportunities and incomes in other sectors of the economy (often associated with climatic changes inland), fishing has been viewed as an attractive option, and this has contributed significantly to the overexploitation of marine resources and the deterioration of the coastal environment (Tietze *et al*., 2000). For example, in the 1970s and 1980s difficulties in the agriculture sector led to increases in small-scale fisheries in the Philippines and in Senegal during this period (Tietze *et al*., 2000). As more and more people enter fisheries, so they are faced with declining catches.

Sea level rise resulting from thermal expansion of the oceans and melting ice caps and glaciers may inundate almost 1 million km2 of coastal land, dependent upon the climate projection (Liu, 2000). This may destroy coastal habitats by inundating them faster than the ability of accretion and plant colonisation to create wetland habitats (Daniels *et al*., 1993). Sea level rise may reduce intertidal habitats, while the increased water column depth will also alter hydrodynamic coastal processes, affecting shoreline configuration and sedimentation patterns. This may be particularly severe in countries such as Bangladesh, Guyana, and low-lying coral islands in the Pacific and Indian Oceans (Dickson, 1989). The effects of sea level rise may be exacerbated by other anthropogenic activities, such as coastal development and mangrove forest clearance. These activities, which are done to support high export value shrimp farming in Asia, are reducing coastal defences, biodiversity and food security options of vulnerable countries and people (Adger, 2000; Danielson *et al*., 2005). As a result, new approaches to the design of aquaculture farms that utilise the protection provided by mangroves have been developed to reduce these impacts.

Sea level rise will interact with other climatic changes including changes in storm surge heights, resulting from increasingly strong winds and low pressure events, and increased frequency and severity of storms, flooding and hurricanes or cyclones. These events are likely to result in tragically increased loss of life among fishermen, lost fishing days, damage to the fishing gears and boats of coastal communities, and increased damage to infrastructure (Adger *et al*., 2005b). For instance, during Hurricane Gilbert in 1988, Jamaican fisherfolk lost 90% of their fish traps resulting in a huge loss of revenue and high cost of repairs, as well as resulting in the inability to resume fishing activities promptly after the disturbance (Aiken *et al*., 1992).

Increased flooding resulting from climate change is anticipated to increase the risks of water-borne infectious diseases. For example, ENSO events are often followed by an upsurge in cholera cases in Bangladesh coastal communities and malaria epidemics in

parts of South Asia and South America (Kovats *et al*., 2003; Pascual *et al*., 2000). Marine bacterial and fungal growth rates are positively correlated with temperature, increasing human, coral and fish disease risk (Harvell *et al*., 2002). Shifts in the range and impacts of diseases are likely to be exacerbated by other impacts of climate change on organisms whose metabolic resources are being diverted to deal with the stresses of increased temperatures. In tropical areas, the increased bleaching and disturbance of coral reef systems is likely to increase the risk of ciguatera poisoning - a tropical disease caused by ingesting a poison found in certain marine fishes (Wilkinson *et al*., 1999). These effects are often exacerbated in small coastal and riparian rural communities where systems for potable water, sewage and drainage may be limited (Badjeck *et al*., 2010).

Peperzak (2003) attempted to evaluate whether harmful algal blooms (HABs) are likely to occur more or less often over the next 100 years in the North Sea as a consequence of future climate change. Climate change is expected to lead to an increase in extreme precipitation events (intense rainfall), and this will result in sudden pulses of freshwater being released at the coast and hence intermittent salinity stratification. During such conditions, surface phytoplankton benefit from a decrease in salinity, greater availability of terrestrial nutrients, rapid increases in daily irradiance and higher water temperature, all of which are conducive to bloom formation. During recent years there has been an apparent increase in the occurrence of HABs in many marine and coastal regions around the world (Anderson *et al*., 2008). Increase in the prevalence and distribution of HABs may have a substantial human health impact, and serious economic effects due to closure of commercial fisheries, losses of fish in aquaculture facilities, public health sector costs, and related environmental and socio-economic disruption.

Identification of regions vulnerable to the economic impact of climate change on fisheries systems

The observed and anticipated impacts of climate change on biophysical systems will have significant potential impacts that themselves represent opportunities, challenges and potential dangers for societies and economies. Current scientific knowledge of impacts and vulnerabilities is based on models that rely on future socio-economic scenarios and interpretative reviews of location-specific case studies (Arnell, 2004; Smit and Pilifosova, 2001). A major recent advance is the development of a quantitative indicator-based implementation of the vulnerability assessment frameworks outlined in the Intergovernmental Panel on Climate Change and the Millennium Ecosystem Assessment (Kasperson *et al*., 2005; McCarthy *et al*., 2001; Turner *et al*., 2003). Allison *et al*. (2009) used such an indicator-based framework to assess the vulnerability of national economies of OECD and non-OECD countries to the impacts of climate change on fisheries systems.

Vulnerability can be defined as a combination of the extrinsic exposure of groups or individuals to a hazard, such as climate change, their intrinsic sensitivity to the hazard, and their capacity to modify exposure to, absorb, and recover from losses stemming from the hazard, and to exploit new opportunities that arise in the process of adaptation (Adger *et al*., 2005a; Brooks *et al*., 2005; Kasperson *et al*., 2005; O'Brien *et al*., 2005; Smit and Wandel, 2006). At sub-national and regional scales, vulnerability is regarded as a context-specific local property that varies by socio-economic grouping and geographically within and among countries (O'Brien *et al*., 2005; Metzger *et al*., 2005). However, vulnerability can be influenced by national policies within the context of larger (regional and global) and smaller scale (individual, community and district) processes.

Allison *et al.*'s approach to measuring vulnerability was used to identify those countries that have the greatest predicted exposure to climate change, high dependence on fisheries and low capacity to respond to social and economic change. Given the complex of inter-related climate variables through which fisheries may be affected (including water temperature, precipitation, evaporation, extreme events, changes to ocean currents), the underlying driver of all these changes – projected surface air temperatures for 2050 – was used as a proxy measure of climate change risk exposure. The approach assumes that warming-related impacts upon physical and biological variables affecting fisheries production and fishery operations will be greater in areas where projected surface air temperature increases above the landmass are greater. Sensitivity of the national economy to climate risk exposure was assessed as a composite index of dependence upon fisheries, calculated on the basis of national fishery landings and the contribution of fisheries to employment, production, dietary protein and export income. The index of the adaptive capacity combined human development indices (HDIs: health, education and governance) with size of economy (total gross domestic product), based on the assumption that countries with high levels of economic and human development have the resources and institutions necessary to permit adaptation.

Warming will be greatest for high latitudes, but overall the most vulnerable countries lay in the tropics. Surface temperature changes were predicted to be highest in northern parts of North America, Europe and Asia (Table 1.A1.1 in the annex). The OECD countries that would experience the highest land surface temperature changes included: Canada, Finland, Hungary, Japan, Korea, Portugal, Sweden, Turkey and the USA (Table 1.A1.1). Overall the most fisheries-dependent countries were found throughout Africa, Asia and the Americas. The most fisheries-dependent OECD countries included Iceland, which falls within the upper quartile, followed by Canada, Japan, Mexico, Norway, Portugal and Spain (Table 1.A1.1). OECD countries had the highest adaptive capacity with almost all countries falling within the upper quartile, apart from Turkey, Hungary and Mexico (Table 1.A1.1). The countries with the lowest adaptive capacity were concentrated almost exclusively in Africa and tropical Asia. Virtually all Saharan and sub-Saharan African countries, except Namibia, Botswana and South Africa, had low adaptive capacity. The Asian countries with lowest adaptive capacity were Pakistan, Bangladesh, Laos PDR and Nepal (Table 1.A1.1). As a result of the high adaptive capacity of OECD countries, almost all were among the least vulnerable to the socio-economic effects of climate change on their fisheries sectors. The most vulnerable OECD country was Turkey, due to relatively low adaptive capacity, high exposure to climate change and moderate fisheries dependence derived from a relatively high fisheries catches and number of fishers in the economically active population (Table 1.A1.1; Figure 1.A1.1). Those regions most vulnerable to climate-induced changes in fisheries were in the Western Sahel and Central Africa, north-western South America, and, in Asia, Yemen, Pakistan, Bangladesh and Cambodia.

The national economies of OECD countries appeared to have relatively low vulnerability to the effect of climate change on the fisheries sector. This was largely due to the relatively high capacity to cope with and respond to the future challenges and opportunities presented by climate change. It should be emphasised that this indicator-based analysis does not suggest that there will not be significant effects of climate to fish, fisheries and aquatic ecosystems among OECD countries (both positive and negative). Much of our knowledge of the impact of climate variability on fish, fisheries and aquatic ecosystems comes from OECD countries and suggest the environmental, economic and social impacts are potentially large. However, compared to many other parts of the world,

these countries have large, diverse economies and functioning social service provision that can help to reduce the social and economic disruption caused by climate-induced changes in employment and profitability in the fisheries. This analysis highlights the importance of building and maintaining social, economic and ecological resilience to ensure societies have the greatest opportunity to both cope with and take advantage of climate change.

Social, economic and environmental consequences of the impact of climate change on the fisheries sector

The effects of climate change on the environment have been considered in detail above. Climate change also has the potential to affect the food security and livelihoods of the world's 36 million fisherfolk and 1.5 billion consumers who rely on fish for more than 20% of their dietary protein and as a source of key micronutrients (see Badjeck *et al.*, 2010). Here we highlight some examples of how global climate change and climatic variation are associated with changes in the social and economic factors associated with fishers and fishing communities.

Social impacts of climate change

The impact of global warming on the fisheries sector in socio-economic terms is difficult to assess, not only because of the great uncertainty regarding the extent and rate of climate change, but also due to the uncertainty surrounding the impacts on bio-physical processes and how these propagate upwards through ecosystems to harvest or use ecosystem services. In addition to the effect of climate on natural resource systems, Arnason (2003) proposed that climate change may impact fisheries in at least two different ways: by altering the availability of fish to fishermen (direct impact) and by changing the price of fish products and fisheries inputs (indirect impact). This section focuses on the direct impact and the next section will provide examples of the indirect impact.

Changes in the availability of fish to fishers can occur through impacts of climate change and climate variability on stock distribution and abundance (Roessig *et al.*, 2004). Changes in the availability of fish products can affect total revenues and harvesting costs (net revenues) of fishermen, thus influencing the choice of target species. For example, the anticipated increased travel costs due to increased sea surface temperatures disproportionately caused a decrease in the number of boats targeting squid in a fishery off Monterey Bay, California (Dalton, 2001).

West Greenland's transition from a cod-fishing to a shrimp-fishing economy, *ca.* 1960-90, provides a case study in the human dimensions of climatic change. The southern town (Paamiut) was more specialised in cod fishing, with one of the largest fish processing plants in the North Atlantic. However, as the cod collapsed the human population declined due to out-migration. The climate- and overexploitation-driven declines in predatory cod resulted in increases in shrimp abundance (Worm and Myers, 2003). The more northerly town (Sisimiut) had less specialised fisheries pursuing multiple species, and once cod declined the fisheries focused on shrimp and the town grew rapidly in size as a result (Hamilton *et al.*, 2003). By contrast in Paamiut the small shrimp catches were insufficient to replace the large cod catches and support the large-scale industrial processing plant (Hamilton *et al.*, 2003). Two lessons were drawn from this example. First, socially important environmental changes result not simply from

climatic change, but from interactions between climate, ecosystem and resource usage. Second, environmental changes affect people differentially and through interactions with social factors. Social networks and cohesion (social capital) are important, in addition to skills (human capital), investments (physical capital), and alternative resources (natural capital): all shape how the benefits and costs are distributed. (Hamilton *et al.*, 2003)

Fish distribution shifts may have "knock-on" impacts upon commercial fisheries catches because changes in migration or spawning location affect the "catchability" of individual fish to fishing gears. Fish populations may move away from (or towards) the area where particular fishing fleets operate and/or where spatial restrictions on fishing are in place. Also species distributions may migrate across the boundaries where quotas belong to different nations. A notable example might arise as a result of quota allocations between a non EU country and the EU. If, for example, species such as mackerel or herring move away from the EU sector, then EU fisheries may no longer be able to catch their full quota within indigenous waters, and hence there will be difficult political negotiations between nations with regard to future access to key fish stocks (*e.g.* Sissener and Bjørndal, 2005). The converse happened in October 2009 when North Sea mackerel appeared to have moved away from the Norwegian Sector, resulting in disagreements over permissible catches by Norwegian boats in EU waters. Norwegian vessels were forcibly evicted from Scottish waters by UK fishery patrol vessels once they had caught their allotted quota (see Fishing News, 9th October 2009). At the same time Iceland and the Faeroe Islands unilaterally claimed quota for mackerel, since the species had migrated westwards and had attained high abundance in their indigenous waters. International law provides that coastal states have sovereign rights to manage fisheries in waters under their jurisdiction. More than 90% of the global fish catch is estimated to be taken within waters under the jurisdiction of particular coastal states. With climate change in the future, we might anticipate more territorial disagreements of this type.

Economic impacts of climate change

Here we address the second of Arnason's (2003) proposed impacts of climate change on fisheries sectors, *i.e.* indirect impacts on fishers due to changes in fisheries economics. Much of our knowledge of the economic impacts of climate change can be drawn from the effect of ENSO-induced climatic variability on fisheries targeting small pelagic plankton-feeding fishes.

The 1997/98 *El Niño* was the strongest in the last century. Chilean and Peruvian pelagic marine fish landings fell by 50% and 52%, respectively, and the value of their fish meal exports dropped by USD 8.2 billion. The share of world fish meal export market of these two countries decreased from 70% in 1997 to 49% in 1998. The pelagic marine fisheries were essential to both the Chilean and Peruvian economies. As almost 90% of the Peruvian and Chilean anchovy harvest was processed into fish meal, the huge reduction in exports caused a great deal of hardship in the already strained fishing industries and generated adverse long-term economic consequences (Caviedas and Fik, 1992).

A reduction in financial capital, for instance access to credits and loans, can also be observed as a consequence of climatic variability. In Peru, at the time of the 1997/98 *El Niño* event, a percentage of the catch was put into a recently privatised social security and health organisation for the industrial fishermen (Broad *et al.*, 1999). As a result of decreasing catches the agency's coffer quickly ran dry, leaving fishermen without a safety net and access to financial resources to cope with the difficult economic situation (Broad

et al., 1999). While infrastructure damages are recoverable, the time necessary for such endeavour can be critical for the fisheries sector and in countries where state assistance is minimal and financial capital limited the impact of extreme events could be damaging in the longer term.

Such patterns are not restricted to Peruvian-Chilean anchovy/sardine fisheries but co-occur throughout the world. Landings of the SE Asian mackerel purse-seine fishery experienced a dramatic decrease of 47.75% following the 1997/98 *El Niño*, due to changes in sea surface temperatures in the area between Chinese Taipei and Japan (Sun *et al.*, 2006). Based on comprehensive daily logbook records during 1982–99 and a fishing cost survey, the loss to the fishery was estimated to be USD 6.22 million for 1998 (Sun *et al.*, 2006).

Changes in migration routes and fish distribution can also affect fishermen; for instance increased travel time can lead to increased fuel and ice costs. Fluctuations in sea surface temperatures, such as driven by *El Niño* events, have significant effects on fishing effort in the albacore tuna, chinook salmon, sablefish and squid fisheries in Monterey Bay, California (Dalton, 2001). Fishing effort was defined by Dalton as the number of vessels or boats landing an individual species. Under a scenario of a 1.2 °C sea surface temperature increase corresponding to the ENSO events of 1983, the number of vessels or boats landing each species decreased. Decreases in effort ranged from 60% for the sablefish fishery to 400% for the squid fishery (Dalton, 2001). The anticipated increased travel costs due to increased sea surface temperature disproportionately decreased the number of boats targeting squid (Dalton, 2001). Decreased revenues for fishermen due to decline in total catch and stock abundance are commonly cited as a consequence of climate variability and change (Callaway *et al.*, 1998).

In Belize, Hurricane Mitch (1998) destroyed the main lobster and finfish fishing grounds of the northern part of the country in 1998. This translated into a loss in production of 65 000 lbs that year (Gillet, 2003). Direct losses to fishers in relation to the loss of fishing tackle and associated infrastructures as a consequence of the hurricane has been estimated at USD 1.2 million (Gillet, 2003).

Climate variability and increased sea-level rise, storminess and floods can lead to decreased fishing capacity and decreased access to markets. Storm and severe weather events can destroy or severely damage infrastructures and equipments such as port, landing sites and boats (Jallow *et al.*, 1999). For instance, during hurricane Gilbert in 1998, Jamaican fishermen lost 90% of their traps, resulting in a loss of revenue and high cost of repairs, as well as the inability to resume fishing activities promptly (Aiken *et al.*, 1992). In Antigua and Barbuda 16% of the fishing fleet was destroyed or lost, while 18% was damaged due to Hurricane Luis in 1995 (Mahon, 2002). The overall loss of the industry was estimated at 24% of the annual mean revenue.

In less developed countries, and particularly in the Least Developed Countries in West Africa, the mainstay of both artisanal and industrial fisheries is small pelagic fishes, such as sardines (*Sardinella* spp.) and mackerels (*Scomber* and *Trachurus* spp.). These species have relatively short life cycles and feed on plankton and consequently their dynamics and productivity are strongly influenced by climate-forced upwelling of nutrients from eastern boundary currents (Binet *et al.*, 2001; Binet, 1997). These fisheries are subject to exploitation by foreign fleets, mainly from the European Union, but also from Russia and Asia. Despite increasing catches by foreign fishing fleets, the economic growth and social benefits from marine resources have not been met for many western

African countries that host these fleets (Atta-Mills *et al.*, 2004; Alder and Sumaila, 2004). Further climate change-induced changes in fish catches may deepen these problems.

In developing Asian countries, small pelagic fisheries make a prominent contribution to the livelihoods of inshore fishers, as well as to protein consumption of poor households. However, decades of overexploitation have dramatically reduced small pelagic fish stocks in the region, and have increased the vulnerability of these stocks to adverse climate change (Briones *et al.*, 2005). Artisanal fishers in India, Thailand and the Philippines rely on the simplest gears and vessels and are highly dependent on small pelagic fisheries. A simulation analysis of the effects of a climate-induced reduction in small pelagic fish landings upon catch values suggests that modest gains in freshwater capture and culture and marine culture sectors will be massively overshadowed by the decline in producer income from the marine sector. This results in a substantial total economic loss to society, which varies in degree from country to country. The loss ranges in value from USD 53-210 million (India), USD 165-700 million (Philippines), USD 1-300 million (Thailand) depending on the level of decline in small pelagic fish catches, which ranges from 5% -20% (Briones *et al.*, 2005).

The warm *El Niño* event of 1997/98 resulted in nearly USD 15 million worth of damages to infrastructures in the Peruvian fishing sector (CAF, 2000). Rural fishing villages in the northern part of the country were damaged from heavy rains and were unable to get their products to markets due to washed out roads and bridges (Broad *et al.*, 1999). Macroeconomic consequences of climate variability and changes in the fisheries sector range from impacts to the labour market, industry reorganisation, to loss of export earnings to national economies due to declines of catches (Glantz and Thompson, 1981). Chile and Peru produce almost half of the world's fishmeal supply (Merino *et al.*, 2010; Mullon *et al.*, 2009). In Chile, the *El Niño* event of 1972/73 resulted in a decrease in catches of anchovies and cool-water species like sardines and hake which created an inflated demand for fish derivates (fish meal and fish oil). This led to an increase in world market prices (USD 325 per ton in 1975 compared with USD 90 per ton in 1965). It is worth noting that while some communities were adversely affected by the reduced stock of anchovies and sardines in the eastern pacific upwelling areas, fishermen in Denmark received near record prices for Baltic sprat and North Sea sand eel, a competing species for fishmeal production (MacKenzie and Visser, 2001). Modelling the future climatic and market forces on fishmeal production, Merino *et al.* (2010) note that the way society responds to climatic and fishing effects will define the sustainability of stocks, while market demand and the development of fishmeal substitutes will influence market dynamics within the system.

In addition to the effects of climate variability and change on fisheries systems there are likely to be considerable costs associated with other aspects of climate change. The likely ecological effects of ocean acidification are poorly understood, however there is convincing evidence for significant negative impacts on marine ecosystems, particularly for coral reefs and calcifying organisms in the southern ocean. The socio-economic effects are hard to determine but could amount to many billions of dollars. The vast majority of the studies that have been published on the impacts of ocean acidification so far have tended to focus on benthic or planktonic species that are of limited importance for fisheries and aquaculture. However, it is clear that commercial species of shellfish may be impacted in the future. At high pCO2 (low pH) the growth and shell formation of oysters and mussels seems to be impaired (Gazeau *et al*., 2007) and in the north-west Pacific commercial oyster hatcheries are already reporting reduced survival of juveniles and hence reduced viability of aquaculture operations attributable to low pH in coastal

waters. With an average annual increase of 7.9% over the last 30 years, global shellfish production reached 11.7 million tonnes in 2002, corresponding to a commercial value of USD 10.5 billion (Gazeau *et al.*, 2007). In a case study of US commercial fishery revenues, Cooley and Doney (2009) attempted to provide a first estimate of the economic effects of ocean acidification over the next 50 years using atmospheric CO2 trajectories and laboratory studies focusing especially on molluscs. In 2007, the USD 3.8 billion annual domestic ex-vessel commercial harvest contributed USD 34 billion to the US gross national product of which molluscs contributed 19% (USD 748 million). Assuming harvest decreases of 6%-25% accompany 0.1-0.2-unit pH decreases over 50 years (2010–60) results in losses of USD 0.6-2.6 billion through to 2060. Shellfish fisheries have grown in importance in many OECD countries in recent years (e.g. Canada, the UK and US) as finfish populations have dwindled; consequently ocean acidification represents a growing threat to fishing communities and economies in these countries.

The potential economic effects of climate change on coral reefs have been explored for the Great Barrier Reef, Australia. The contribution of reef-interested tourism was 68% of the regional Queensland economy, totalling AUD 1.4 billion (GBP 0.58 billion, May 2005 exchange rate) (Royal Society, 2005). Reduced Caribbean coral cover linked to climate-related disease outbreaks, more frequent and severe hurricanes and sea temperature increases are predicted to decrease annual fish production by up to 40% by 2015, a net revenue loss of between USD 95 million and USD 140 million for more than 100 000 fishers (Trotman *et al.*, 2009).

Arnason (2007) estimated the economic impact of climate change on fisheries and on the national economies of Iceland and Greenland. The author assumed that fisheries yields would increase by around 20% for the most important fish stocks (in particular cod and Atlanto-Scandian herring) in Iceland and up to 200% in Greenland over the next 50 years (based on projections from ACIA, 2004). The analysis then used econometric techniques based on economic growth theory to estimate the role of the future fisheries sector in the wider economy of each country. Somewhat surprisingly the dramatic increase in fisheries yields assumed for Iceland resulted in only miniscule increases in national GDP, despite the fishing industry currently accounting around 10% of GDP and 40% of export earnings. The accumulative impact of climatic warming on Icelandic GDP was only 4% by 2054, and given economic volatility and measurement errors, this level of economic growth is considered hardly detectable at the 95% significance level. Benefits for the national economy of Greenland were greater (a 40% increase in GDP by 2054) but this assumed an enormous increase in the fish stock (by 200%) and it should be remembered that the fishing industry in Greenland is the main source of non-government employment and local economic activity (over 90% of all exports).

How can policy makers respond?

Policy makers can respond along three broad lines: pursue mitigation strategies, build social and economic capacity to adapt, and pursue a portfolio management approach across natural resource sectors (Dulvy and Allison, 2009).

Pursue mitigation

Reducing carbon dioxide emissions to the atmosphere appears to be the only practical approach to mitigate against the degree of impact from anthropogenic climate change, with the aim of minimizing the probability of "dangerous" climate change and the risk of

large-scale and long-term changes to ecosystems (Royal Society, 2005; Scholze *et al.*, 2006). Ocean acidification is a powerful reason, in addition to climate change, for reducing global CO_2 emissions. There appears to be no practical way to remove this additional CO_2 from the oceans after it has been absorbed, nor any realistic way to reverse its widespread chemical and probable biological effects (see the recent Royal Society report on *"Geoengineering the climate: science, governance and uncertainty"*; 2009). It will take many thousands of years for natural processes to remove this excess CO_2 and return the oceans to a level close to their pre-industrial state. Thus, it appears that the only practical way to minimise long-term consequences for the oceans is to reduce CO_2 emissions to the atmosphere (Royal Society, 2005).

The fisheries sector itself can only play a small part in reducing CO_2 emissions to mitigate against future climate change; the world's marine fishing fleets are estimated to burn 1.2% of global fuel oil used per year, equivalent to that consumed annually by The Netherlands (Tyedmers *et al.*, 2005). However, there may be synergies between emissions reductions, energy savings and responsible fisheries. For example, policy support for the following measures could contribute to all three of these goals:

- Raising awareness of the impacts of climate change, to ensure that the special risks to the fishery sector are understood and used to plan national responses to climate change, including the setting of mitigation targets through mechanisms such as the Kyoto Protocol.
- Reducing fuel subsidies granted to fishing fleets, to encourage energy efficiency and assist towards reducing overcapitalisation in fisheries.
- Supporting the use of static-gear – pots, traps, longlines and gillnets, which uses less fuel than active gear such as trawls and seines – and therefore emits less CO_2.
- Supporting the use of alternative fishing gears (*e.g.* semi-pelagic trawls rather than demersal trawls) that are more fuel efficient.
- Restoring mangroves and protecting coral reefs, which will contribute to CO_2 absorption, coastal protection, fisheries and livelihoods.

Maintain and build socio-ecological resilience, or adaptive capacity

The effects of climate change are already apparent and foreshadow what is to come (McCarthy *et al.*, 2001; Parmesan and Yohe, 2003). Cutting CO_2 emissions tomorrow cannot immediately eliminate the effects of anthropogenic climate change, since it will take many decades to turn around changes that are already "locked in". Since climate change cannot be locally mitigated, minimisation of the impacts of climate change requires adaptation and the development of socio-ecological resilience (Adger *et al.*, 2005a). Societies, organisations and individuals have adjusted their behaviour in response to past climatic changes, and many are now contemplating adapting to altered future climatic conditions. Much of this adaptation is reactive, in the sense that it is triggered by past or recent events, but it is also anticipatory in the sense that it is based on some assessment of conditions in the future.

Adaptation to climate change can be defined as an adjustment in ecological, social or economic systems in response to observed or expected changes in climatic stimuli and their effects, in order to alleviate adverse impacts of change or take advantage of new opportunities (IPCC, 2001). Adaptation can involve both building adaptive capacity thereby increasing the ability of individuals, groups, or organisations to adapt to changes,

and implementing adaptation decisions, i.e. transforming that capacity into action. Adaptation can be manifested in myriad ways: through market exchanges or through extension of social networks, or through actions of individuals and organisations to meet their own individual or collective goals. It can be undertaken by an individual or by governments and public bodies to protect their citizens.

In December 2009 Rashid Sumaila and William Cheung (writing in a report for the World Bank) attempted to establish the costs of adaptation to climate change in the fisheries sector worldwide. The analysis began by detailing the likely impact of climate change on the productivity of marine fisheries (more than 1 000 species) and, through that, on landed catch values and household incomes. Adaptation costs were then estimated based on the costs of restoring these revenue indicators to levels that would have prevailed in the absence of climate change. The impact of climate change on marine fisheries was assumed to primarily occur through changes in primary productivity, shifts in species distribution and through acidification of the oceans. The authors considered three scenarios that reflect these impacts. Climate change was predicted to lead to losses in gross fisheries revenues world-wide of USD 10-31 billion by 2050. In Europe (including the UK) the estimated annual cost of adaptation was between USD 0.03 and 0.15 billion which is relatively minor, compared to USD 1.05-1.7 billion of anticipated annual adaptation costs in East Asia and Pacific.

Options for adaptation can be considered at local and regional (national and international) scales. At local scales, action can be undertaken to promote diversity in ecological and local livelihood systems and to build legitimate and inclusive governance structures and social capital. Diversity in ecological systems and functionality can be maintained or enhanced through promoting sustainable use (Hilborn *et al.*, 2003). The same is true of diversified rural livelihood systems that have evolved in response to variations and uncertainties in fishery production systems (Allison and Ellis, 2001). As such any local or regional activity that seeks to achieve the World Summit on Sustainable Development goals; "to achieve a significant reduction in the current rate of loss of biological diversity by 2010", and "to maintain or restore stocks to levels that can produce the maximum sustainable yield, and on an urgent basis where possible for depleted stocks not later than 2015", thus will also contribute to adaptation to potential effects of climate change (WSSD, 2002).

At regional (national and international) scales, appropriate adaptation actions include pursuance of a mitigation strategy (see above), avoidance of perverse or harmful incentives for ecosystem degradation that increase sensitivity to hazards, promotion of early warning networks and structures and enhancement of disaster recovery through appropriate donor responses (Adger *et al.*, 2005b). The impacts of climate change events must be recognised by fisheries management agencies and the fishing industry and factored into management plans (Allison *et al.*, 2005). Actions that are likely to enhance adaptive capacity include a move toward sustainability, removal of harmful subsidies, increasing management adaptability, and promotion of diverse, less capital intensive fisheries. Below we briefly highlight some actions that can enhance local and regional capacity to adapt.

Move toward sustainable fisheries

Many stocks are managed to hover around the "limit" (*i.e.* lowest permissible) reference levels, although improvements have been seen in recent years (Rosenberg *et al.*, 2006; Pitcher, 2001). The recovery and maintenance of fisheries resources closer to the

larger stock sizes implied by target reference points will provide greater robustness to uncertainty in fishing mortality and the direct and indirect effects of climatic variability (Cabinet Office, 2004). This will also benefit fishers through sustainable and less uncertain catches and potentially greater profitability (Pauly *et al.*, 2003).

Reduce harmful subsidies

Governments pay out some USD 6 billion a year to support the fisheries sector in OECD countries. This money, variously called subsidies, support and/or financial transfers, is used to help manage fish stocks, to modernise fishing fleets, and to help communities and regions that can no longer make a living out of fishing to develop other economic activities. The money is also intended to assist in resolving problems of overfishing and over-capacity that affect many parts of the OECD fishing industry. However questions have been raised as to the true benefit of some forms of subsidies, as they may encourage fishers to remain in an industry incapable of supporting them in the medium to long term (OECD, 2005).

Sustainability and profitability can be enhanced by the removal of harmful subsidies. For example in many European and other developed country fisheries this will involve the removal of subsidies for vessel construction (OECD, 2005). Raising the efficiency of fishing effort through improved boat designs, subsidising credit for purchases will only increase incomes if the resource remains relatively under-exploited compared to the long-run sustainable catch. As soon as the catch rate approaches or exceeds this sustainable long-run level, increased efficiency must result in a reduced number of individuals or families involved in fishing. The alternative is that the same number of people stay in fishing but under-utilise their enhanced capacity to catch fish, thus making no gains in income, and incurring a social waste of resources in the idle capacity represented by their improved assets (Bailey and Jentoft, 1990).

Enable mobility of large-scale fishing fleets

Given that fish stock production, distribution and species composition may all change under future climate change, it is important for economic efficiency and sustainability that national fishery legislation and investment programmes do not lock fleets, processing capacity and marketing chains into exploiting particular species caught within national boundaries. The current hostility towards the "roving bandits" (Berkes *et al.*, 2006) of the global fishing fleet and the questions raised around fairness of EU-West African nation bilateral fishing agreements (Kaczynski and Fluharty, 2002) – although see Witbooi (2008) for recent changes – make the current legislative climate hostile towards the notion of enabling global mobility of capital and labour in fisheries. Nevertheless, from the point of view of adapting to climate change, such mobility has always been important. Fishing fleets have to retain some flexibility in where they fish and what they catch. Thus, it is necessary to establish institutional mechanisms to enhance the capacity of fishing interests (fleets, processing capacity, and quota ownership) to move within and across national boundaries to respond to changes in resource distribution. This implies developing bilateral and multilateral agreements. This can only be recommended in the context of functional transboundary fishery governance regimes and effective systems to control illegal, unreported and unregulated fishing. Thus, the key link remains the promotion of sustainable fisheries (see above).

As part of this, issues of trade must be considered. FAO figures suggest that 38% (live weight equivalent) of all fish production was exported in 2004, and total world exports of fish and fish products reached a record value of USD 71.5 billion (FAO, 2004). In turn, world fish imports rose 25.4% from 2000 to 2004, reaching the new record of more than USD 75 billion in 2004. Developed countries accounted for about 81% of the total value of imports. The fishery net exports of developing countries (*i.e.* the total value of their exports less the total value of their imports) were USD 20.4 billion in 2004. These figures were significantly higher than those for other agricultural commodities such as rice, coffee and tea. In the future, a balance may be needed between gaining income from third country agreements and the international export of fish, and the protein and micronutrient needs of a tropical nation's population that are hardest hit by the impacts of climate change on fisheries (Alder and Sumaila, 2004).

Promote diverse, less capital-intensive fisheries

Diversification of activities is a key factor in building adaptive capacity to climate change (Adger *et al.*, 2005a; Allison and Ellis, 2001). It reduces the risk of livelihood failure by spreading risk across more than one income source. It also helps to overcome the uneven use of assets (principally labour) caused by seasonality, to reduce vulnerability, and to generate financial resources in the absence of credit markets, and it confers a host of other advantages in the presence of widespread market failures and uncertainties. In Mexico, diversified multi-species multi-gear traditional fishers, in contrast to the highly specialised and technologically rigid industrial fishing fleet, see the measurement and quantification of climate variability at the core of their adaptation strategies (Vasquez-Leon, 2002). Danish small-scale fisheries, artisanal fisheries in Galicia (north-east Spain) and some Icelandic fishing towns show similar flexibility, where fishers switch between different target species, gear types and fishing areas on a seasonal or annual basis (Hamilton *et al.*, 2003; Vestergaard, 1996; Freire and Garcia-Allut, 2000). In Denmark, income uncertainties are buffered by supplier credits, while families are willing to reduce their levels of spending or to earn supplementary incomes outside fishing. Furthermore, fishers are able to mobilise cheap or unpaid assistance within the fishing enterprise in times of need. Diversification of nutritional sources may reduce vulnerability in some areas strongly affected by climate change.

The promotion of increased specialisation through investment in more capital-intensive fishing technologies tends to reduce capacity to adapt and respond to change (Hamilton *et al.*, 2003). In Greenland heavy investment in a cod processing plant at the village of Paamiut contributed to socio-economic failure when climate change and overexploitation led to the demise of Greenland cod (Hamilton *et al.*, 2003). Investment can push part-time fishers into full-time operations simply to repay loans and to earn an adequate return on the increased investment. Increased dependency on fishing can mean that individuals find it harder to turn to non-fishing alternatives during periods of resource scarcity. This, in turn, can compromise resource sustainability (Allison and Ellis, 2001).

From an institutional perspective, system-wide adaptation can be supported through insurance, subsidies or other government aid. However, while small-scale diversified fishers may be better able to adapt to the uncertainties of fisheries, they are more vulnerable if governments withdraw support from that sector in favour of more industrial sectors. This is offset where fishers have diversified beyond pure fishing incomes to mixed livelihoods. In Indonesia, for example, South Java Coast individuals switch between rice-farming, tree-crop farming and fishing in response to seasonal and inter-

annual variations in fish availability (Musa *et al.*, 2001). Elsewhere (*e.g.* in Europe and Canada) inshore fishermen switch between fishing and tourism (whale watching, recreational fishing or dive charter). Migration allows fishers to move to areas with greater resources, where access is unlimited. An example is the flexible access rights around shallow African lakes, whereby landowners allow access by large numbers of migrant fishers to exploit fisheries resources that fluctuate with climatically driven lake water levels (Allison and Mvula, 2002; Jul-Larson *et al.*, 2003). Outsiders can access village-based fishing territories in times of their need, or when there are local surpluses, often in exchange for an access fee. Reciprocal access agreements, rather than exclusive territoriality, seem to be common features of indigenous "community-based" management systems. Flexible financial mechanisms at local level recognise the inherent variability of fishing. Permeable barriers to entry allow those in need of a "safety net" access to the fishery, while there is recognition of the importance of ease of exit from the fishery in times of resource scarcity.

In many developed countries with industrial fisheries, this flexibility does not exist and can be less easily negotiated within the strict management regimes that operate. To adjust to the multiple potential impacts of climate change, management measures need to be flexible, adapting to changes identified, and transparent in the use of information and in governance (Brander, 2007). Adaptation may involve the abandonment of previous livelihood options. Low-lying atoll and coastal nations may be forced into adaptation strategies that involve long-term migration of human populations due to sea level rise and other factors (Barnett and Adger, 2003). Whether fishing remains a viable option in new locations will be a case-specific question.

In fisheries with excess fishing effort the use of financial incentives to promote reduction of fleet capacity through vessel decommissioning coupled with a promotion of alternative land-based jobs is one approach to moving toward more sustainable resilient marine ecosystems and coastal communities (OECD, 2006).

Manage an adaptation "portfolio" across natural resource sectors

It is worth considering whether fisheries and aquatic environmental management systems can function effectively in isolation of other natural resource industries. Many natural resource sectors overlap both geographically and socially, with many of the poorest people relying on two or more natural resource sectors to provide for the bulk of their livelihood, e.g. water resources, forestry, farming, aquaculture, and capture fisheries. This pattern may be particularly acute in river catchments where capture fisheries exist downstream of other natural resource sectors and ecosystem services, such as water abstraction, forestry and agriculture, themselves acutely affected by climate change (Badjeck *et al.*, 2010). Other upstream activities, such as damming for hydroelectric power generation, will obviously affect downstream ecosystem services (e.g. Dugan *et al.*, 2010). An example is for Lake Chilwa, where the combination of a series of droughts and the expansion of rice cultivation to the fringing wetlands have put severe pressures on water resources and fisheries (Allison *et al.*, 2007).

Climate change is expected to result in increased summer continental drying and associated risks of drought (IPCC, 2001). Adaptation in other sectors may result in increased water offtake to support increased irrigation demands of climatically stressed crops, as well as increased damming of rivers. Increased upstream water use as a result of climate change adaptation activities may therefore reduce outflows from rivers, affecting salinity levels, nutrient levels, reproductive success and other physical and biological

factors, which will compromise fisheries and associated livelihoods. For example, in Bangladesh by 2050 the negative impacts of climate change on water availability are predicted to lead to declines in rice (8%) and wheat (32%) yields. Maintenance of food self-sufficiency would require about 40% to 50% of the dry season water availability. Meeting such a high agricultural water demand can be expected to cause significant negative impacts on the domestic and commercial water supply, fisheries, and ecosystems (Faisal and Parveen, 2004).

A cross-sectorial view of adaptive activities to climate change needs to be taken not only in the fisheries sector. For example, in water management there is a prevailing perception that it is wasteful to allow freshwater to reach the sea. This is a fallacy: the concept of an ecosystem take should be paramount to ensure sufficient water in the lower river to support riverine and coastal fisheries and other ecosystem services critical to the local communities. When the production of one kilogram of beef requires 16 thousand litres of water, the benefits of wild fish capture and aquaculture for protein, as well as the provision of micronutrients, becomes clear. In turn, aquaculture can be integrated with other livestock farming as a strategy for small farmers in many developing countries to increase farm returns from per unit area of land. This portfolio approach helps a farmer insure himself against the risk of falling into crises of subsistence by spreading the risk of production over several activities.

The key message is that interactions between natural resource sectors are often poorly characterised and the interactions are rarely considered by sectorially-focussed planners. Any improvements to cross-sectoral planning and adaptation, such as the development of the ecosystem approach to fisheries management, or attainment of WSSD goals, concurrently will improve the socioecological resilience of fisheries systems.

Mainstream fisheries in wider development processes

Climate change is not the only stress facing fishing communities. Many fishing communities are poorly served by infrastructure, markets and social services and are thus economically, socially and politically marginalised (FAO, 2005). Building adaptive capacity to address these multiple stressors will require cross-sectoral approaches implemented through newly decentralised governance approaches. The thrust of current fisheries development policy in non-OECD countries is to ensure that, in countries where fisheries are important to the economy, the sector is adequately represented in national-level planning processes related to poverty reduction and maintenance or enhancement of food security (Béné and Heck, 2005; FAO, 2005). In the case of the highly indebted poor countries, incorporation of the fisheries sector in the national poverty reduction strategy process (PRSP) is critical for allocation of funds for building adaptive capacity in the sector (Thorpe, 2005).

The least developed countries (LDCs) are also eligible for UN funding to engage in long-term adaptation planning through the national adaptation programmes of action (NAPAs; *www.undp.org/cc/napa.htm*). Again, in countries where fisheries are important, sector-specific adaptation needs should be planned and budgeted for in this process.

Concluding remarks

Human-induced climate change has occurred and the effects are predicted to increase over this century. There is high certainty of increasing CO_2, temperature, sea level, ocean

acidity and extreme events. There is high certainty for climate-induced biological change; however the detail of change is less certain at larger ecological scales. Overall, it appears that climate change has strongly negative consequences for a variety of aquatic ecosystems, especially those in the tropics and developing world. The social and economic impacts of climate change on fisheries are less well-understood. Notwithstanding this limitation, the impacts of climate variability on fish availability, fish prices and the hazard impacts on coastal communities are substantial and can have profound social and economic consequences at local, national and international scales. The degree to which national economies are vulnerable to the impacts of climate change on fisheries depends upon their degree of exposure to climate change, dependence on fisheries, and the capacity to adapt and response to the opportunities, challenges and dangers. The countries with national economies most vulnerable to the impacts of climate change on fisheries sectors are primarily in Africa and Asia and include many of the world's least developed nations. This is a consequence of high social and economic dependence on fisheries for livelihoods and food. Most OECD countries are likely to be least vulnerable to climate change impacts on their fisheries sectors (some may even benefit, *e.g.* Iceland and Norway), due to the increased adaptive capacity of these nations. However, some OECD countries may have a role to play as they have fishing access agreements and strong fish trade links with the most fisheries-dependent vulnerable least developed nations.

Policy makers can respond by pursuing a mitigation strategy to limit CO_2 emissions, maintaining and building adaptive capacity or "socio-ecological resilience", and by managing natural resources as a portfolio to ensure adaptation in one sector will not have adverse effects on other "downstream" sectors.

Notes

1. The oceanic zone where enough light is present for photosynthesis to occur.
2. Aragonite and calcite are the two crystalline mineral forms of calcium carbonate, caco3.

Annex 1.A1

Table 1.A1.1. Vulnerability of national economies to the impacts of climate change on fisheries[1]

Country	Fisheries dependence	Climate change exposure		Adaptive capacity	Vulnerability	
OECD countries		A1F1	B2		A1F1	B2
Australia	2	2	2	4	1	1
Austria	1	3	3	4	1	1
Belgium	1	2	2	4	1	1
Canada	4	4	4	4	2	2
Czech Rep	1	3	2	4	1	1
Denmark	3	2	2	4	1	1
Finland	2	4	4	4	2	2
France	2	3	2	4	1	1
Germany	1	2	2	4	1	1
Greece	3	3	3	4	2	2
Hungary	1	4	4	3	1	1
Iceland	4	1	2	4	1	2
Ireland	2	1	1	4	1	1
Italy	2	3	2	4	1	1
Japan	4	4	3	4	2	2
Korea	NA	4	4	NA	NA	NA
Mexico	4	3	3	3	3	3
Netherlands	2	2	1	4	1	1
New Zealand	3	1	1	4	1	1
Norway	4	3	3	4	2	2
Poland	2	3	3	4	2	2
Portugal	4	4	3	4	2	2
Spain	4	3	3	4	2	2
Sweden	2	3	4	4	1	1
Switzerland	1	3	3	4	1	1
Turkey	2	4	4	2	3	4
UnitedKingdom	2	1	1	4	1	1
United States	3	4	4	4	1	1

Table 1.A1.1. Vulnerability of national economies to the impacts of climate change on fisheries (*cont.*)

Country	Fisheries dependence	Climate change exposure		Adaptive capacity	Vulnerability	
Non-OECD countries		A1F1	B2		A1F1	B2
Afghanistan	NA	4	3	NA	NA	NA
Albania	1	3	3	2	2	2
Algeria	2	4	4	2	3	4
Angola	3	3	3	1	4	4
Antigua & Barbuda	NA	1	1	NA	NA	NA
Argentina	2	2	2	3	1	1
Armenia	1	4	4	2	2	2
Aruba	NA	1	1	NA	NA	NA
Azerbaijan	1	4	4	2	2	2
Bahamas	NA	1	1	NA	NA	NA
Bahrain	NA	2	3	NA	NA	NA
Bangladesh	4	2	2	1	4	4
Barbados	NA	1	1	NA	NA	NA
Belarus	1	4	4	3	3	3
Belize	3	3	3	3	2	2
Benin	NA	2	2	NA	NA	NA
Bermuda	NA	2	1	NA	NA	NA
Bhutan	NA	2	2	NA	NA	NA
Bolivia	1	4	4	2	3	3
Bosnia & Herzegovina	1	4	4	3	2	2
Botswana	1	4	4	2	2	3
Brazil	3	4	4	3	3	3
Brunei Darussalam	NA	2	1	NA	NA	NA
Bulgaria	1	4	4	3	2	2
Burkina Faso	1	3	2	1	4	3
Burundi	2	3	2	1	4	4
Cambodia	4	2	2	2	4	4
Cameroon	3	2	2	1	3	3
Cape Verde	NA	1	1	NA	NA	NA
Central African Rep.	NA	3	3	NA	NA	NA
Chad	NA	3	3	NA	NA	NA
Chile	4	1	1	4	1	1
China	4	3	3	4	3	3
China, Hong Kong	NA	2	2	NA	NA	NA
China, Macao	NA	2	2	NA	NA	NA
Colombia	3	4	4	2	4	4
Comoros	NA	1	1	NA	NA	NA
Congo	1	2	2	1	3	2
Congo, Dem. Rep.	4	3	3	1	4	4
Cook Islands	NA	1	1	NA	NA	NA
Costa Rica	2	2	2	4	1	1
Côte d'Ivoire	3	2	2	1	4	4
Croatia	3	4	4	3	3	3

Country	Fisheries dependence	Climate change exposure	Adaptive capacity	Vulnerability	Country	Fisheries dependence
Non-OECD countries		A1F1	B2			
Cuba	NA	2	2	NA	NA	NA
Cyprus	2	1	1	4	1	1
Djibouti	NA	4	3	NA	NA	NA
Dominica	NA	1	1	NA	NA	NA
Dominican Rep.	2	1	2	3	1	1
Ecuador	3	3	3	2	3	3
Egypt	3	3	3	2	3	3
El Salvador	2	3	3	2	3	3
Equatorial Guinea	NA	2	2	NA	NA	NA
Eritrea	NA	3	3	NA	NA	NA
Estonia	3	4	4	4	3	3
Ethiopia	1	2	2	1	2	2
Fiji	4	1	1	3	1	1
French Guiana	NA	2	2	NA	NA	NA
French Polynesia	NA	1	1	NA	NA	NA
Gabon	3	2	2	2	3	2
Gambia	2	2	3	1	4	4
Georgia	1	4	4	3	2	2
Ghana	4	2	2	2	4	4
Grenada	NA	1	1	NA	NA	NA
Guadeloupe	NA	1	1	NA	NA	NA
Guatemala	2	4	3	2	3	3
Guinea	3	2	2	1	4	4
Guinea-Bissau	2	2	2	1	4	4
Guyana	3	3	3	3	3	3
Haiti	2	2	2	1	3	2
Honduras	2	2	3	2	2	3
India	4	2	2	2	3	3
Indonesia	4	1	1	2	3	3
Iran	3	3	3	2	3	3
Iraq	NA	4	4	NA	NA	NA
Israel	1	2	2	4	1	1
Jamaica	2	1	1	3	1	1
Jordan	1	3	3	3	1	1
Kazakhstan	1	4	4	2	3	3
Kenya	3	2	2	1	3	3
Kiribati	NA	1	1	NA	NA	NA
Korea	NA	3	3	NA	NA	NA
Kuwait	1	2	2	3	1	1
Kyrgyzstan	NA	4	4	NA	NA	NA
Lao	2	2	2	1	3	3
Latvia	2	4	4	3	3	3
Lebanon	1	3	3	3	2	2
Lesotho	NA	3	2	NA	NA	NA
Liberia	NA	2	2	NA	NA	NA
Libya	2	3	3	2	3	3

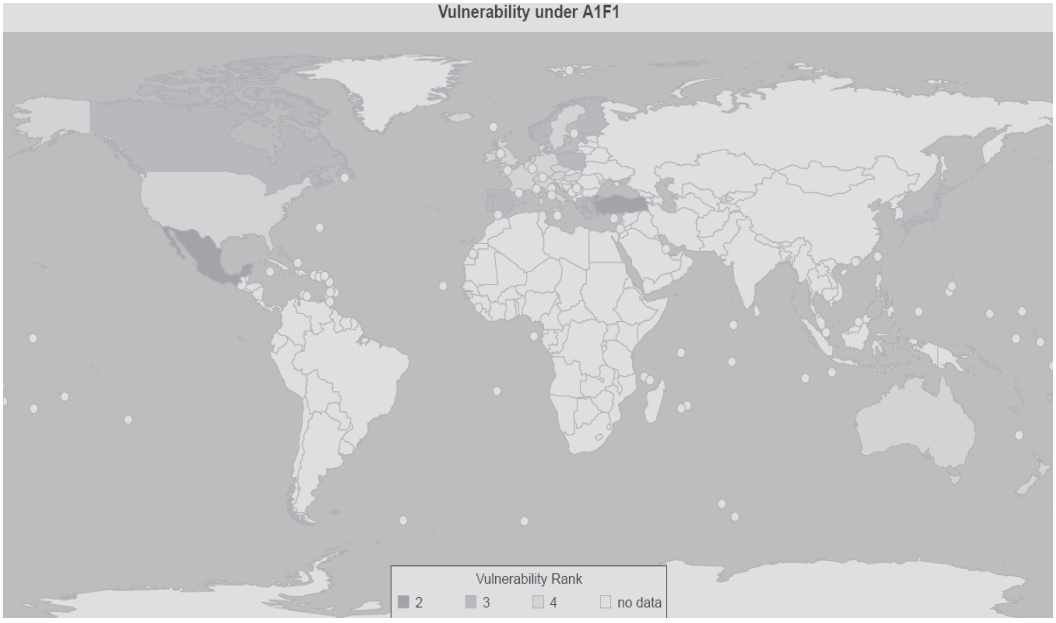
Country	Fisheries dependence	Climate change exposure		Adaptive capacity	Vulnerability	
Non-OECD countries		A1F1	B2		A1F1	B2
Lithuania	2	4	4	3	3	2
Macedonia	1	4	4	3	2	3
Madagascar	4	1	1	1	3	3
Malawi	3	3	3	1	4	4
Malaysia	4	2	2	3	2	2
Maldives	NA	1	1	NA	NA	NA
Mali	3	4	3	1	4	4
Malta	1	1	1	4	1	1
Marshall Islands	NA	1	1	NA	NA	NA
Martinique	NA	1	1	NA	NA	NA
Mauritania	3	4	4	1	4	4
Mauritius	3	1	1	3	1	1
Micronesia, Fed. States	NA	1	1	NA	NA	NA
Morocco	4	4	3	2	4	4
Mozambique	3	3	3	1	4	4
Myanmar	NA	2	2	NA	NA	NA
Namibia	3	3	3	2	3	3
Nauru	NA	1	1	NA	NA	NA
Nepal	2	2	2	1	3	3
Netherlands Antilles	NA	1	1	NA	NA	NA
New Caledonia	NA	1	1	NA	NA	NA
Nicaragua	3	2	3	2	3	3
Niger	2	3	3	1	4	4
Nigeria	4	2	2	1	4	4
Oman	NA	2	2	NA	NA	NA
Pakistan	4	3	3	1	4	4
Palau	NA	1	1	NA	NA	NA
Panama	3	2	2	3	2	2
Papua New Guinea	4	1	1	2	2	2
Paraguay	1	4	4	2	2	2
Peru	4	4	4	3	4	4
Philippines	4	1	1	3	2	2
Puerto Rico	NA	1	1	NA	NA	NA
Qatar	NA	3	3	NA	NA	NA
Réunion	NA	1	1	NA	NA	NA
Romania	1	4	4	3	2	2
Russian Federation	4	4	4	3	4	4
Rwanda	NA	3	2	NA	NA	NA
Saint Kitts and Nevis	NA	1	1	NA	NA	NA
Saint Lucia	NA	1	1	NA	NA	NA
St. Vincent/Grenadines	NA	1	1	NA	NA	NA
Samoa	NA	1	1	NA	NA	NA
Sao Tome & Principe	NA	1	1	NA	NA	NA
Saudi Arabia	2	3	4	2	2	3
Senegal	4	3	3	1	4	4
Serbia & Montenegro	NA	4	4	NA	NA	NA
Seychelles	NA	1	1	NA	NA	NA

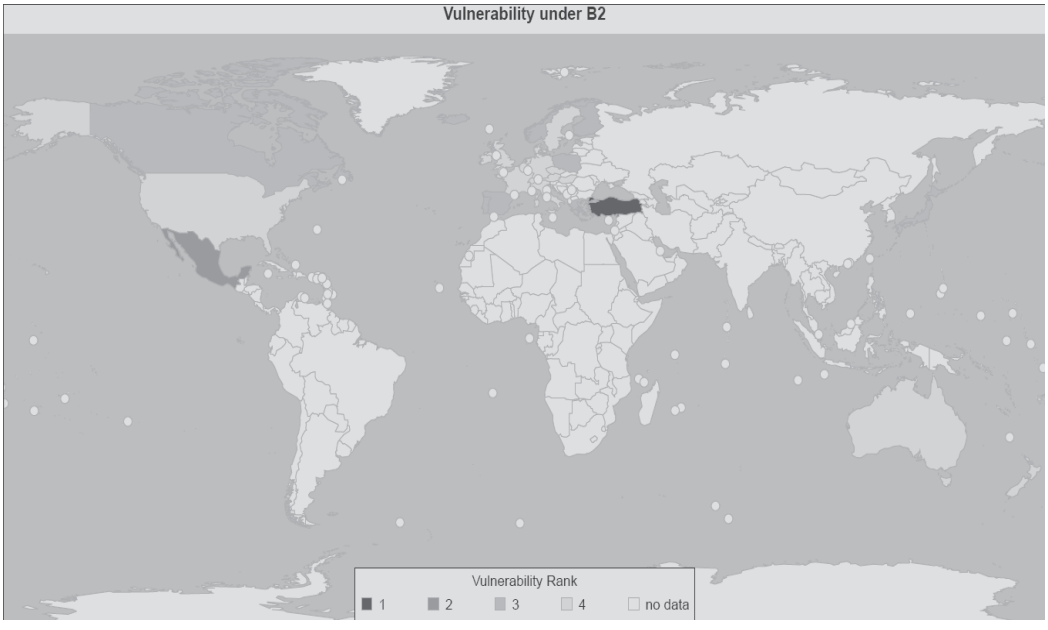
Country	Fisheries dependence	Climate change exposure		Adaptive capacity	Vulnerability	
Non-OECD countries		A1F1	B2		A1F1	B2
Sierra Leone	4	2	2	1	4	4
Singapore	NA	1	1	NA	NA	NA
Slovenia	1	4	3	4	1	1
Solomon Islands	NA	1	1	NA	NA	NA
Somalia	NA	2	2	NA	NA	NA
South Africa	2	2	3	2	2	2
Sri Lanka	4	1	1	2	2	2
Sudan	1	3	3	1	3	3
Suriname	3	2	3	3	2	3
Syria	1	4	4	2	2	2
Tajikistan	NA	4	4	NA	NA	NA
Tanzania	4	2	2	1	4	4
Thailand	4	2	2	3	3	2
Togo	3	2	2	1	4	3
Tonga	NA	1	1	NA	NA	NA
Trinidad & Tobago	2	1	1	3	1	1
Tunisia	4	2	2	3	2	2
Turkmenistan	1	3	3	2	2	1
Tuvalu	NA	1	1	NA	NA	NA
Uganda	4	3	3	1	4	4
Ukraine	3	4	4	3	4	4
United Arab Emirates	NA	3	3	NA	NA	NA
Uruguay	2	2	2	4	1	1
Uzbekistan	1	4	3	2	1	1
Vanuatu	NA	1	1	NA	NA	NA
Venezuela	3	4	4	3	4	4
Vietnam	4	2	2	2	4	4
Yemen	3	3	3	1	4	4
Zambia	3	3	3	1	4	4
Zimbabwe	1	4	4	1	4	4

NA indicates that no data were available.

1. Ranked scores of fisheries dependence, exposure to climate change (A1F1 & B2 scenarios), adaptive capacity and vulnerability for 27 OECD and 166 non-OECD countries. A rank score of 1 indicates countries in the upper quartile for fisheries dependence or vulnerability (see Annex 1.A2 for further details of the methods).

Figure 1.A1.1. Vulnerability of OECD national economies to the impacts of climate change on fisheries under A1F1 and B2 emission scenarios*





OECD national vulnerability presented as ranked quartiles within the overall global analysis (see Table 1.A1.1)

Annex 1.A2

Further details on the calculation of an index of vulnerability of national economies to the impacts of climate change on fisheries

Vulnerability is usually defined as a combination of the extrinsic exposure of groups or individuals to a hazard, such as climate change, their intrinsic sensitivity to the hazard, and their capacity to modify exposure to, absorb, and recover from losses stemming from the hazard, and to exploit new opportunities that arise in the process of adaptation (Smit and Wandel, 2006; Turner *et al.*, 2003). At sub-national and regional scales, vulnerability is regarded as a context-specific local property that varies by socio-economic grouping and geographically within and among countries (Brooks *et al.*, 2005). However, vulnerability can be influenced by national policies within the context of larger (regional and global) and smaller scale (individual, community and district) processes. There are no objective, independently derived measures of vulnerability, exposure, sensitivity, or adaptive capacity. The usual approach is to select proxy measures that capture the properties of interest (Turner *et al.*, 2003). Vulnerability was calculated simply by averaging the three indicators of exposure, fisheries dependence and adaptive capacity as $V = f(E, D, AC)$. Further details on the calculation of this vulnerability index can be found in Allison *et al.* (2005).

An index of exposure to climate change

The aim was to create an exposure index representing the degree to which fisheries will be subject to climate change. Climatic change influences fisheries production through a range of both direct and indirect pathways (Allison *et al.*, 2005). The direct effects include changes in the abundance and distribution of exploited species and increases in the frequency and severity of extreme events, such as floods and storms, which affect fishing operations and infrastructure. The indirect effects include: (i) impacts on aquatic habitat quantity and quality, ecosystem productivity, and the distribution and abundance of aquatic competitors and predators; (ii) impacts on other food production sectors that might affect people's livelihoods and food security; and (iii) other climate change impacts on aspects of people's lives unrelated to their fishing activities, such as diseases or damage to their homes (see above, "How and where does global warming potentially impact on fisheries?"). We focused on projected land surface temperature change, because it is the most direct, best understood, and most readily available measure of future warming. We used projected annual mean temperature change by 2050 as a proxy variable of climate change exposure. Mean temperature changes at 1.5 m above the surface was calculated for 2050 by rescaling the 2080 values from the TYN CY 3.0 dataset, which provides country-specific projections based on gridded values from HadCM3 climate model outputs (Table 1.A2.1).

The model results used here are from the UK Hadley Centre model (HadCM3), with two IPCC emissions scenarios (B2 and A1F1) (Gordon *et al.*, 2000). The two IPCC climate change scenarios were selected because they represent two contrasting potential futures. The A1FI world is characterised by a high dependence on fossil fuels, reflected in

higher temperatures than in the B2 world, in which economic development is more moderate.

An index of fisheries dependence

We calculated an index of fisheries dependence to represent the national role and importance of fisheries for the economy. Dependence upon fisheries was measured using national fishery landings, and the contributions of fisheries to employment, production, export income and dietary protein (Table A1.2.1). This assumed that countries with greater landings and higher contributions of fisheries to employment, export income, and dietary protein were more likely to be impacted (positively or negatively) by warming-related changes in fishery production. We calculated two measures of the contribution of fisheries to national employment: total numbers of fishers and the number of fishers expressed as a proportion of the economically active population. Fisheries production was measured as capture fisheries landings for coastal and inland waters, summed across edible fish, crustaceans and molluscs (FAOSTAT, 2004). Annual fishery-related export value (USD) was the sum of exports and re-exports of products fit for human consumption for each country, averaged over the four-year period 1998-2001 (FAOSTAT, 2004). Total fish and animal protein available for consumption was estimated as annual total supply (production + imports - exports) from FAO food balance sheets (FAOSTAT, 2004).

An index of adaptive capacity

We calculated an adaptive capacity index from four variables: healthy life expectancy, education, governance and gross domestic product (GDP) using the Climate Analysis Indicator Tool (CAIT) of the World Resources Institute (CAIT, 2005) (Table 1.A2.1). Healthy life expectancy was the number of years a newborn child can expect to live in full health based on current mortality rates and the distribution of health states in the population (WHO, 2002). The link between health and climate change involves opportunity cost, such that countries with significant health costs are likely to find it socially and politically difficult to allocate resources to mitigate and to adapt to climate change. Education levels were measured as a weighted combination of adult literacy and school enrolment rates (UNDP, 2003). The World Bank governance index combines six components of governance: political stability (*e.g.* perceptions of likelihood of armed conflict); government effectiveness (*e.g.* bureaucratic quality); regulatory quality (*e.g.* regulatory burden, market-friendliness); rule of law (*e.g.* black markets, enforceability of contracts); voice and accountability (*e.g.* free and fair elections, political rights); and corruption (*e.g.* its prevalence among local officials) (Kaufmann *et al.*, 2002). GDP was the sum of gross value added by all resident producers in the economy, plus any product taxes, less any subsidies not already included in product values. We used the total GDP, converted from local currency to 2000 US dollar value using purchasing power parity, as a measure of the size of the economy.

Where appropriate, variables were normalised and standardised to a range between 0 and 1. For exposure and fisheries dependence, the country with the lowest value scored 0, and the country with the highest value scored 1. For adaptive capacity, the converse applied.

Table 1.A2.1. Summary of variables used to calculate exposure, fisheries dependence and adaptive capacity, and their interpretation

Years shown indicate periods over which data were available

Component	Interpretation	Variable	Reference
Exposure	Gross measure of projected levels of climate change	Mean projected surface temperature increase (°C at 1.5m) by 2050	(Mitchell *et al.,* 2004)
Fisheries-dependency		Number of fishers (most recent year 1990-96)	(FAO, 1999)
	Index of employment and economic dependence on the fisheries sector	Fisheries export value as proportion (%) of total export value (averaged over 1998-2001)	(FAOSTAT, 2004, World Bank, 2003)
		Proportion (%) of economically active population (1990) involved in the fishery sector	
		Total fisheries landings (tonnes, averaged over 1998-2001)	
	Index of nutritional dependence	Fish protein as proportion of all animal protein (% g person^{-1} day^{-1}, averaged over 1998-2001)	(FAOSTAT, 2004)
Adaptive Capacity	Health	Healthy life expectancy (years, 2000)	(CAIT, 2005)
	Education	Literacy rates (% of people ≥ 15 years, 2000-01)	(CAIT, 2005)
		School enrolment ratios (% in primary, secondary and tertiary education, 2000-01)	
	Governance (2000-1)	Political stability	(CAIT, 2005, Kaufmann *et al*., 2002)
		Government effectiveness	
		Regulatory quality	
		Rule of law	
		Voice and accountability	
		Corruption	
	Size of economy	Total GDP (2000)	(CAIT, 2005)

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PART II
CLIMATE CHANGE IMPACTS ON FISHERIES AND ADAPTATION FISHERIES

Chapter 2

Economic and policy issues related to the impact of climate change on fisheries

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This chapter addresses climate change effects in capture fisheries and options for policy response. Climate change creates both physical and biological pathways of impacts on marine fish that affect fishery economic performance, which in turn influences management effectiveness and shapes the landscape of policy response. This chapter discusses the linkages between these issues.

First of all, the physical changes symptomatic of climate change and their biological and ecosystem effects in the ocean environment are described. Then, it addresses the economic effects brought about by the changes in biological processes and ecosystems, beginning with describing the importance of the economic context of capture fisheries. A range of areas of economic effects is discussed, including the value of the catch, costs of production, profitability, employment, fishing community economies, the redistribution of benefits and costs among stakeholders, economic stability and economic vulnerability.

The governance effects of climate change are influenced by, and in turn influence, the economic effects. This chapter describes what fishery governance is and what it does as well as factors influencing governance effectiveness, including the economic context, scientific uncertainty and transactions costs. Options for strengthening fishery governance under conditions of climate change through the promotion of adaptability, flexibility and resilience are also discussed.

Fishery policy is the path through which government can direct actions to influence fishery outcomes. The goal of fishery policy is to increase the resilience and adaptive capacity of the fishery, fishing industry, fishing communities and fishery governance. In responding to climate change, policy options are either to mitigate impacts through prior actions or to minimise impacts through adaptation. A central concept is to avoid surprise and unexpected events. This chapter discusses a range of options policy makers have to adapt to climate change, including research, stakeholder engagement, risk assessment, strategic planning, cross-sector co-ordination, market integration and regulatory control. In addition, it discusses how policy makers can implement these options through improving the information base, building literacy and capacity, reducing risk, expanding policy frameworks, increasing co-ordination, strengthening linkages and adopting flexible management.

Physical changes and biological effects in the marine environment

Climate change creates both physical and biological pathways of impacts on fish in the marine environment. These include biophysical impacts on the distribution or productivity of marine populations through the pathways of ocean acidification, habitat damage, extreme weather events, changes in circulation and availability of nutrients (Daw *et al.*, 2009). Climate effects generate change, alter rates of change, and erode the ability to predict change. All affect a fishery's economic performance, management effectiveness and policy response.

Physical changes

Climate-induced changes in the physical environment include temperature, stratification, precipitation, currents, winds, sea level, and pH level. Increasing levels of carbon dioxide and other "greenhouse" gases in the atmosphere are linked to changes in surface temperature, melting of ice caps and sea level rise. Temperature differences between land and sea and across latitudes are predicted to have important disruptive effects on weather and climate. These differences also drive changes in precipitation, wind and currents, affecting important oceanic weather systems such as the *El Niño* Southern Oscillation (ENSO) (FAO, 2009).

Temperature: the Intergovernmental Panel on Climate Change (IPCC) predicts a global average temperature increase of 0.2 °C per decade for the next two decades, causing sea surface temperature increase, polar ice melt and sea level rise (IPPC, 2007). Ocean temperature increases will not be geographically homogeneous (Barange and Perry, 2009).

Stratification: ocean water stratification is predicted to increase with increasing water temperatures and changes in levels of precipitation. The combined effect of temperature and salinity changes are expected to reduce the density of the surface ocean, increase vertical stratification and change surface mixing (Barange and Perry, 2009). The increased vertical stratification and water column stability is likely to reduce nutrient availability in the euphotic zone, leading to a loss in primary and secondary production, except for at the high latitudes where primary production may increase (Roessig *et al.*, 2004; Barange and Perry, 2009).

Coastal upwelling: coastal upwelling is the source of nutrients to many fish populations. Although there is some evidence of recent increases in upwelling intensity, global circulation models do not yet show a clear pattern of upwelling in response to warmer ocean temperatures. The seasonality of upwelling may be affected by climate change (Barange and Perry, 2009).

Sea levels: sea level has been rising globally at an increasing rate, putting several low-lying coastal areas at risk and damaging coastal habitat (Barange and Perry, 2009).

Ocean acidification: ocean acidification is expected to continue increasing, with particular impacts for crustaceans, corals and other calcium dependent organisms.

Major oceanic events: major events such as ENSO are predicted to increase in frequency and intensity with climate change, affecting circulation and food availability

for fish (FAO, 2009). Changing currents may affect larval dispersal and retention in ways unfavourable to stock productivity (Roessig *et al.*, 2004).

Biological effects

Climate-induced physical changes in the marine environment create a range of biological effects, including changes in primary productivity, distribution, life history strategies, behaviour, ecosystem composition, interactive effects, invasive species, substitution effects, habitat availability, larval dispersal and viability.

Changes in species distribution: temperature shifts cause mobile species to follow their thermal preferences to new areas, thereby redistributing themselves (Roessig *et al.*, 2009). A typical pattern is to see displacement from the centre of a species' home range as ocean temperatures warm. In rare cases, an example being Humboldt squid, a species may maintain the centre of its range while also expanding it (Zeidberg and Robison, 2007). Many commercially important species are predicted to redistribute in different ranges as a result of changing conditions; for example, Rose *et al.* (2000) describe the southward shift of northern cod in the early 1990s in response to changing food availability and other environmental conditions.

It is known that even relatively small temperature changes can lead to larger biological effects such as the redistribution of mobile species and the change of species migration patterns (Roessig *et al.*, 2009; Soto, 2002; Murawski, 1993). Southward *et al.* (1995, cited in Roessig *et al.*, 2009) predict a latitudinal range shift of 322-644 km in the plankton community off Britain's south-west coast will occur with a 2 °C increase in temperature, resulting in changes in structure of both benthic and pelagic communities.

Primary productivity: fish production depends on net primary production at the base of the aquatic food chain (Brander, 2007). Increases in water temperature, ocean stratification and upwelling alter primary productivity which in turn causes changes in community structure (IPPC, 2007; ISAB, 2007; Roessig *et al.*, 2004).

Stock productivity: the productivity of fish stocks can be altered through a number of climate-related effects. Higher ocean temperatures and changes in ocean currents may reduce recruitment success through alterations in spawning, migration, food availability, and susceptibility to disease. The timing of life history stages may change with ocean conditions. Changing current may affect larval dispersal and viability. Changes in pH through increased CO_2 and acidification of ocean water can reduce productivity for sessile calciferous species such as mollusks, crustaceans and corals. Sea level rise can lead to loss of feeding, breeding and nursery habitat (FAO, 2009).

Substitution effects: not all climate changes will be negative for fish productivity. The same factors can lead to favourable conditions for some species (*cf.* Arctic Council, 2005). A modelling framework developed by scientists at the Alaska Fishery Science Center predicts increases in year classes of northern rock sole in the Eastern Bering Sea in response to changes in cross-shelf transport (Hallowed *et al.*, 2009).

Ecosystem effects

The ecological systems that support fisheries are known to be sensitive to climate variability (Barange and Perry, 2009). Warmer temperatures are likely to result in diminished ecosystem productivity in most tropical and subtropical oceans and increased productivity at high latitudes. The distribution of marine species will also change; warm-

water species will be redistributed towards the poles, with consequent changes in the size and productivity of their habitats. The range of warmer-water species will be expanded, while that of coldwater species will contract. Pelagic species will redistribute themselves in the water column in response to warmer sea surface temperatures. Climate change is already affecting the seasonality of some biological processes – such as the timing of life history events – and altering marine food webs (Barange and Perry, 2009; FAO, 2009).

The IPCC has identified various risks to aquatic ecosystems from climate change, including loss of coastal wetlands, coral bleaching, changes in the distribution and timing of fresh water flows, and acidification (IPCC, 2007). Warmer temperatures are associated with an increased risk of species invasions and spreading of vector-borne diseases (FAO, 2009).

Because they involve many interactive and synergistic effects, predicting ecosystem responses to climate change is necessarily more complicated than predicting physical or biological effects alone. Ecosystems can respond to physical or biological forcing in both linear and non-linear ways, and uncertainty about whether response will be linear or non-linear introduces a limitation to forecasting change. Brander (2007) outlines three differences between past and future changes in climate that will alter the adaptive resilience of ecosystems: the rate of change in the future is likely to be more rapid; pressures on marine systems have interactive effects that reduce system resilience; ocean acidification has unknown effects. The consequences of these processes are complex and will impact community composition, production and seasonality processes in plankton and fish populations.

Jennings and Brander (2010) note that the effects of climate change on the structure and function of marine communities have received little research attention and are subject to considerable uncertainty. They suggest that predicting the size-structure and productivity of community responses to climate change across a range of trophic levels may be done based on knowledge of the processes that determine the size-structure of communities, such as metabolic scaling, predator-prey interactions and energy transfer in size-based food webs, provided that predictions of changes in primary production are available.

The longer the time scale of consideration, the greater are the uncertainties about ecosystem effects of climate change (Baranger and Perry, 2009). Hallowed *et al.* (2009) note that although models can be used to anticipate large-scale changes, they are not yet adequate to predict specific regional events in ecosystems. They developed a modelling framework that incorporates environmental variables and relies on known linkages between environmental forcing and fish production. The model shows a wide range of possible outcomes, with sources of uncertainty including model selection, lack of knowledge about environmental processes, measurement error, and estimation errors regarding spawner-recruit relationships.

Economic effects of climate change

The increased environmental variability resulting from the physical drivers of climate change and their biological and ecosystem effects leads to greater uncertainty throughout the fishery system. This uncertainty has economic effects on harvesters, processors and communities and on the economic performance of the seafood industry. Effects are both short-term and long-term.

Economic effects are complex, with effects in any given region intertwined with changes elsewhere. The specific economic effects are relative to particular fishery contexts, but many fishery contexts share common points of vulnerability. More research is needed elucidating the interactions among climate, biological processes and economic activities dependent on these processes (Miller and Fluharty, 1992), but previous fishery declines offer anecdotal insight into the likely range and magnitude of economics effects fisheries will experience under climate change.

Economic context of capture fisheries

Global marine production of food fish from capture fisheries was 81.9 million tonnes in 2006, accounting for 80.3% of total marine production. Production from world capture fisheries has remained relatively stable over the past decade with the exception of fluctuations accounted for by catches of anchoveta, which are the world's largest catch in weight and heavily influenced by ENSO events. Fish and fish products are heavily traded and the quantity traded is increasing. In contrast, employment in world capture fisheries is declining, having decreased 12% in the five year period 2001-06 (FAO, 2009).

The proportion of over-exploited, depleted and recovering stocks has remained relatively stable in recent history. The most recent reported data (2007) show that 52% of the world's stocks are fully exploited, 20% moderately exploited and 28% are overexploited (19%), depleted (8%) or recovering (1%). Regions with the highest percentage of fully exploited stocks are the North-east Atlantic, West Indian Ocean, and the North-west Pacific. Most assessed stocks (80%) are fully or over-exploited, so require effective precautionary management (FAO, 2009).

Value of catch

Capture fisheries depend on net primary production at the basis of the aquatic food chain. Larger fish, which are higher on the food chain, tend to carry more value in the market. Because of their high trophic position, larger fish experience relatively more variability in catch, and therefore value, in the degree to which changes in net primary production are translated directly to changes in fish productivity (Brander, 2007).

The recent northward expansion of Pacific sardine as a function of warmer ocean temperatures has enabled the development of a valuable new fishery off the coasts of Oregon and Washington. Large Pacific sardine are harvested and processed for export markets. There is a potential for this positive change in value of the catch to become negative if ocean temperatures cool and sardine distribution changes. However, some key factors will prevent the loss of this fishery from having an extreme economic impact. Excess processing capacity in the region of the new fishery meant that new capacity investment was not required. Vessels have permits in multiple fisheries that afford them substitute harvest possibilities. For both harvester and processor sectors investments were rational, based on expectations formed by previous experience with short-lived sardine fisheries (Herrick *et al.*, 2006).

Potential threats to the value of traditional sources of catch may also result from changing species distributions. The northward range expansion of Humboldt squid in response to warmer ocean temperatures is a case in point. Humboldt squid is large aggressive pelagic squid that opportunistically feeds on a wide range of pelagic and demersal fish, crustaceans and squids, and for which there is as yet no fishery in the eastern North Pacific. Although it is a species that might generate some value to a new

fishery, it is presently viewed as an invasive species and appears to be diminishing the value of valuable target stocks on which it preys, such as Pacific whiting (Zeidberg and Robison, 2007).

Costs of production

Fisheries have a number of production costs that vary with the type of the fishery, the gear employed, and the approach to management. Fishing costs are roughly categorised as fixed and variable. Fixed costs are those that do not vary directly with the amount of fishing. These include vessel mortgage, insurance, standard maintenance, and gear depreciation. Variable costs vary with the amount of fishing, and include fuel, ice, bait, fishing supplies, food and water.

The effects of climate change on the costs of production will vary according to the nature of the change and the specific characteristics of the fishery. In general, since fixed costs do not vary with the amount of fishing they will remain unaffected by climate change. An exception to this general rule is that an increase in the frequency of extreme weather events could lead to decreases in fishing safety and increase the cost of insurance. Vessels may need to be refitted to adapt to new target species and gear. They may need more significant reconstruction to maintain safety and stability in altered ocean and storm conditions (Hannesson, 2010).

Variable costs will be affected by climate change. For example, a change in the distribution of fish stocks may mean that travel distances to fishing grounds increase, with greater time spent and fuel consumed. It is also possible that changing distributions could have the effect of bringing the fishing grounds closer to port.

The variable costs that may be most sensitive to the biological effects of climate change are those associated with energy consumption. Fishing is heavily dependent on fossil fuels for harvest, processing, storage and transport. The fuel efficiency of fishing and the concept of "green fleets" have not been a major consideration of fishery management or national fishery capacity policies, but they are linked to management outcomes. Overcapacity and excess fishing effort mean lower catches per unit of effort and suboptimal fuel efficiency. Fisheries managed under regulations that support a race for fish provide incentives to invest in increased fishing power and contribute to higher levels of fuel consumption.

Through the consumption of fuels as well as the use of refrigerants fisheries contribute to greenhouse gas emissions, and could be subject to carbon taxes enacted as climate change mitigation measures. Carbon emission mitigation measures would raise costs of production for fishing vessels dependent on fossil fuels (Tyedmers *et al.*, 2005; Hannesson, 2010).

Profitability

Profitability is determined by the difference between revenues and costs, and so varies with their particular combinations.

Climate change effects on revenues and costs, and therefore profitability, are influenced by the economic context of the fishery and fishing region. One factor is the degree within a fishery or region of substitution possibilities in response to changing stock productivity or availability. Acheson (1992) addressed the question of substitution possibilities in the face of a fishery decline by looking at the historical example of catch

declines in the Maine lobster fishery in the period between WWI and WWII. These catch declines took place within a context of economic stagnation and decline, with few growth industries to offer alternative employment. Looking at the response strategies by lobstermen to their declining catch, Acheson find little evidence of switching to substitute fisheries, little opportunity to enter non-fishing employment, outmigration from coastal communities, and intensified subsistence.

The Maine example indicates the value to long-term fishery profitability of a having a prior recognition of the uncertainties associated with fishery productivity and building them into rational investment decisions. It also illustrates the economic vulnerability of having a high degree of fishery dependence on a single stock, particularly in an area with few employment alternatives.

Climate change effects on profitability are also influenced by the approach to management. For example, access limitation or capacity reduction programs that reduce the number of vessels provide the potential for an easier transition from one form of fishery management to another (*cf.* Herrick *et al.*, 2006).

Employment

Commercial fisheries contribute billions of US dollars to the world economy and create millions of jobs in harvesting, processing, marketing and the manufacture of supplies. In the US alone, commercial fisheries accounted for USD 103 billion in sales in 2006 and generated over 1.5 million jobs. Recreational fisheries added another USD 82 billion in sales and over 500 000 jobs (NMFS, 2007). For many countries, commercial fisheries provide a large percentage of traded goods, with associated employment effects. In industrialised countries the importance of capture fisheries to overall employment tends to be relatively low, but may be a significant contributor to employment at the sub-national level.

As economic development proceeds employment becomes increasingly specialised, making it likely that fishing industry labour displaced as a result of climate-associated fishery declines is much less transportable than previously to different economic sectors (Hannesson, 2007).

For example, Roessig *et al.* (2007) cite cases of unemployment associated with changing ocean conditions such as an ENSO event. The 1972-73 ENSO event in Peru resulted in severe declines in anchoveta catch, causing 1500 fishing vessels and 200 processing plants to cease operations and over 100 000 people to be unemployed. This was followed by another extreme loss of employment during the 1998 ENSO. ENSO events in 1982 and 1983 and in several years have also generated employment loss in the Pacific salmon fishery on the U.S. West Coast (Miller and Fluharty, 1992) Roessig *et al.* make the case that an increase in the frequency of ENSO events could cause employment losses to become long-lasting or even permanent in some cases.

Fishing community economies

Fishing community economies are importantly influenced by the reach of the market for seafood products and their flexibility in responding to changes in supply and prices.

In an interesting comparative case study, McGoodwin (2007) examined how three different high-latitude fishing communities would be affected by climate change. He compared commercial-fishing communities in south-central Iceland and south-west

Alaska and a subsistence fishing community in south-west Alaska. Among these, he finds the commercial fishing economies in Iceland and Alaska to be the most vulnerable to climatic variability and long-term change because their fisheries are intensively fished to near sustainable limits, regulated by rigid management regimes, and subject to fluctuating prices and the vagaries of international seafood markets.

In contrast, he finds the Alaskan subsistence fishing community to be highly adaptable and to have a low degree of vulnerability to social and economic dislocations caused by the ecosystem effects of climate variability because their fishery dependence is spread over a portfolio of local resources and they can respond to changing climatic and ecological conditions. Their resilience is facilitated by their economic pluralism. This pluralism comes at a cost to overall standard of living, which by conventional measures would be considered to be low. In addition, long-term of permanent loss of salmon, the mainstay of the community's food base, would leave the community vulnerable in terms of food security.

Fishing communities are vulnerable to potential harm to shoreside infrastructure from climate change. Increased frequency and intensity of storms and flooding may damage jetties, docks, marinas and processing plants. Decreases in fishery productivity may lead to diminished flows of seafood catch that can leave ports below the minimum threshold of economic activity needed to maintain working waterfronts.

Redistribution of benefits and costs among stakeholders

Changes in the location or productivity of fish stocks targeted by capture fisheries will likely also change the distribution of benefits and costs from the fishery. There will be winners and losers associated with each major change. Some of the gains and losses will be short-term, others could become long-term or permanent. Whereas there may be no change in overall benefits and costs associated with a particular fishery, changes in the distribution of those benefits and costs can create important economic effects at a sub-fishery level. Conflicts among stakeholders created by these redistributions may also create significant costs for management and enforcement.

Miller and Fluharty (1992) provide an interesting example of the redistribution of benefits and costs among fishery stakeholders associated with a climate change effect. ENSO events along the U.S. West Coast in 1982 and 1983 led to reduced fishing opportunities for salmon trollers and charter boat operators in California, Oregon and Washington, while Alaska fisheries fared well. The impacts were highly uneven across species and areas. Trollers in Oregon and Washington faced both low volumes and low prices, coming on the heels of three years of low earnings. In contrast, landings in Alaska increased enough to compensate for the low prices set in international markets. Consumers were in a positive situation of ample supply and low prices. Processors were diversified and could absorb the decline in harvest. Lower harvester incomes and declines in recreational fishing reduced income to coastal communities already struggling with a recession and high unemployment.

In another example, the northward expansion of Humboldt squid means that its range now overlaps that of Pacific whiting, the most important commercial capture species off the West Coast of the U.S. The range expansion coincides with a decline in Pacific whiting and with changes in seasonal patterns of abundance (Zeidberg and Robison, 2007). This possible impact of Humboldt squid range expansion generates a cost to the Pacific whiting fishery without a corresponding benefit to another West Coast fishery, as

a targeted Humboldt squid fishery is not present in this region. The directed fisheries for Humboldt squid in Mexico, Peru and Chile may or may not benefit, depending on whether the expansion of range leads to changes in productivity in its traditional range.

Economic stability

In considering the example of the collapse of Pacific sardine, Euber and MacCall (1992) conclude that we can expect climate change to cause large international relocations of fishing industries, as industrial structure is rapidly transferred from collapsing fisheries to emerging or new fisheries. In this way climate change may introduce instability into both old and new fisheries through the rapid transfer of harvesting and processing capacity. However, as Herrick *et al*. (2007) demonstrate, shifts within this same fishery can have different effects at different points in time, because of the changing conditions in the fishery. In contrast to the shifts in the sardine fishery in the late 1940s, later climate-induced shifts in the distribution of Pacific sardine led to increased economic stability as sardine was absorbed into an existing diverse harvesting and processing portfolio. Low levels of uncertainty about the likely impermanence of a sardine fishery prevented a potentially destabilising level of industrial expansion in response to the appearance of sardine stocks off the coasts of Oregon and Washington. and precluded development of a strong degree of fishery dependence on this stock.

Economic vulnerability

As the above examples have illustrated, the economic effects of climate change on capture fisheries depend in large part on the fishery context, the degree of fishery dependence and availability of substitutes. A region's vulnerability to economic effects of climate change will depend in part on the degree to which a region's fisheries are exposed to physical and economic effects, the degree of sensitivity to those effects, the level of fishery dependence, and the response capacity within the economy and management system. Artisanal fishers with small boats, limited fishing areas and few alternatives will bear relatively greater impact than fishers with larger more mobile boats and greater access to financial capital and substitute fisheries, provided those fisheries are open to new entrants (Brander, 2007; FAO, 2009; Grafton, 2010).

Governance effects of climate change

What governance is

Governance is the system of implementing contractual relationships between individuals within an institutional environment (Williamson, 1994) and the process of making binding decisions (Hanna, 1999). Governance is the exercise of economic, political and administrative authority. Fishery governance is a broad concepts that incorporates a number of structural elements outlined by the FAO (*www.fao.org/fishery/topic/2014/en*):

- guiding principles and goals
- organisation and co-ordination of information, stakeholders and decision makers
- institutional infrastructure

- management instruments
- operational processes
- participant roles
- policies, plans and actions
- monitoring and enforcement
- performance

Fishery governance proceeds at multiple scales, the particular combination of which depends on the specific legal context. Governance authority may reside at local, national, regional and international scales. It covers a wide array of spatial scales, from coastal zones to Exclusive Economic Zones (EEZs), and addresses a range of scope from single species to ecosystems and from single gear types to entire fisheries. It includes multiple time scales, including short-term decisions and implementation actions as well as long-term planning (Hanna, 1998, 1999).

What governance does

Marine fisheries are publicly owned resources that are used by diverse groups acting within nested institutional structures. The "organisational imperative" of fishery governance is to shape human behaviour so that the transactions of management accommodate limited information, safeguard social objectives, and are conducted at minimum costs (*cf.* Williamson, 1985). These fundamental requirements for effective governance apply in all ocean fishery contexts and at all management scales—international, national, or local.

What we ask of fishery governance is that it co-ordinates institutional rules and individual actions by performing the following functions. It must incorporate multiple objectives representing conservation and use. It must bring the short-term time horizons of private individuals into line with the intergenerational time horizons of society. It must send signals of resource scarcity, and enable effective adaptive responses in the face of uncertainty. It must promote legitimacy by reflecting accepted norms of equity and by controlling harmful opportunism. It must contain the level and distribution of transactions costs, (Hanna, 1996). These functions are expressions of Williamson's organisational imperative.

Governance of capture fisheries takes a variety of structures; all involve trade-offs between stability and flexibility, authority and representation, social and individual. There is no best governance structure for all contexts. Arguments are sometimes advanced for the superiority of particular types of governance structures, for example co-management or strong central authority (Hanna, 2003), but empirical evidence suggests that a number of governance structures can perform well depending on the economic, cultural and ecological context of the fishery. The important governance attribute is that the structure promotes the basic governance functions (Hanna, 1998, 1999, 2002, 2006).

There are many examples worldwide of these fundamental requirements of governance failing to be met in a wide range of governmental scales and contexts.

Factors affecting governance effectiveness

The basic function of a governance structure is to provide stability and consistency for decision making while retaining flexibility and adapting to changing conditions. This attribute is particularly important for accommodating the variability associated with climate change. The effectiveness with which governance performs these functions depends on three key attributes: fishery context, uncertainty and transactions costs.

Economic context

The context of fisheries provides the backdrop on which climate-induced changes play out. The economic context is one of almost full utilisation. Production of capture fisheries, after peaking in the 1980s, has in recent years been relatively stable and is considered to be at its maximum (FAO, 2009). Many stocks have been, or are at risk of being, overexploited. Overfished stocks, in addition to making suboptimal economic contributions, are also subject to increased variability and reduced resilience (Hilborn *et al*., 2003; Daw *et al*., 2009).

Overcapacity in capture fishing fleets presents an additional piece of the fishery context. Despite international agreements to reduce capacity and end harmful subsidies that promote the development of excess fishing capacity, overcapacity is a lingering problem for governance that complicates attempts to take more biologically conservative and precautionary approaches. In 2007 the FAO Committee on Fisheries referred to the lack of progress in this area and the need to match fishing capacity with sustainable harvesting levels (FAO, 2009).

Full utilisation, economic under-performance and overcapacity are complications presented to governance in effectively addressing the need to flexibly adapt to climate-induced change.

Scientific uncertainty

The variability associated with climate change adds new uncertainties for governance. It generates confusion about which adaptive actions should be taken, and so complicates the development of incentives to promote those actions. For example stock assessment models typically assume stable environmental conditions with random inter-annual variability and become unrealistic in conditions of larger-scale change. Stability-based approaches tend to be unsustainable in variable environments, especially when expectations about harvest are formed at the high end of the range of natural variation. Uncertainty tends to shorten time horizons over which people plan, generating incentives for stakeholders and managers alike to think more about the short term (Ludwig *et al*., 1993). Variability also contributes to public uncertainty and scepticism about climate change, which hinders attempts to take proactive governance actions (ISAB, 2007; Hanna, 2008).

Transactions costs

Transactions costs are the costs of arranging, monitoring, or enforcing agreements; the costs associated with all the exchanges that take place within fishery governance (Eggertsson, 1990; North, 1990). The structure of governance influences the magnitude of transactions costs because it determines how users are co-ordinated, how information is generated, how decisions are made, and how monitoring and enforcement take place.

Conversely, transactions costs influence the effectiveness of governance. For example, as biological resources become more scarce, the management structure must account for more trade-offs between user groups, between direct and indirect uses and between present and future uses. As they become more variable, it becomes more difficult for the governance structure to do this. Under these conditions, stakeholder conflicts may increase and the rules that govern resource distribution and use become correspondingly more complex and costly. A management structure that is low cost at one time in a fishery may become high cost at another time, if it does not adapt (Hanna, 1999).

Strengthening fishery governance

A major challenge for fishery governance in accommodating climate change is to be structured in a way that it can function effectively in an environment of uncertainty. National and international fishery governance systems have been established on the basis of a set of conditions that may no longer exist with climate change. A governance system may be able to absorb change that is gradual, consistent, and predictable up to a point, after which it may become overwhelmed and subsequently fail (Healey, 1990; McIlgorm *et al*., 2010). There are a number of attributes through which fishery governance could be strengthened to promote effectiveness under conditions of climate change. These are adaptability, flexibility and resilience. Each, in addition to carrying promise, carries its own challenge.

Adaptability

Governance will need adaptive capacity to address the variability inherent in climate change. Adaptation may be either anticipatory or reactive, aimed at reducing the vulnerability to change. Building adaptive capacity may require changing the existing regulatory structure, removing constraints to change, and strengthening the information base. A complicating factor in adaptation is that fishery management plans contain a mix of often incompatible biological, economic, social and political objectives (Grafton *et al*., 2007). A further complication is that existing regulations and governance processes may be too rigid and complex to promote adaptation (Adger *et al*., 2005; Frankhauser *et al*., 1999; McGoodwin, 2007). However, balancing these complications are international agreements and national policies calling for an ecosystem approach to management that are laying the groundwork for broader, more adaptable governance.

Flexibility

Governance will need flexibility to respond to changing and unforeseen conditions. At the same time flexibility in governance can directly conflict with the need for a stable decision environment and consistent expectations (Hanna, 2008). The flexibility to deal with complexity and change is one of the key attributes observed to be a factor in fishery management success (Cunningham, 2005). Adaptive management, through which information gathered through explicit experimentation is used to inform the next management actions, is a way to promote flexibility. The greater the level of uncertainty and the less managers can predict consequences of management actions, the more valuable is adaptive management (Grafton, 2010). However experimentation may run counter to existing rules and frameworks and require modification to these structures (Hanna, 2008). In addition, learning through monitoring and evaluation requires a

reconciliation of the relatively short time scales of resource management with the longer time scales of ecosystem change (Lichatowich, 1997).

Resilience

Whereas adaptive management allows *ex post* flexibility, resilience helps in the *ex ante* adaptation to shocks and surprises, particularly in the case of significant levels of uncertainty (Grafton, 2010). In general, resilience is the amount of disturbance that an ecosystem, economic system or governance system can absorb before shifting to a regime with a different structure, function and feedback mechanisms (Walker *et al*., 2004). Governance to promote ecological resilience must proceed with explicit acknowledgement of the state of uncertainty. It must be conducted in a way that accommodates normal ranges of conditions as well as episodic change, each being a departure from stability-focused harvest management frameworks. To promote economic resilience of fishers and fishing communities, governance can promote risk reduction through enabling diversification of harvest opportunities, innovation, adoption of new technologies. Building processes of stakeholder participation will also promote resilience. A governance system that is designed to promote resilience of the ecosystem or human systems under conditions of climate change faces a number of challenges. There are classic externality problems in the *ex ante* adaptation to climate change that make it difficult to build political support. Those who absorb the cost of anticipatory actions are not necessarily those who will benefit. There are competing interests for ecosystem goods and services that make it difficult to build consensus around trade-offs and create winners and losers when trade-offs are made. There is the path dependence created by the history of management. Governance actions to promote resilience are further hampered by fragmented decision jurisdictions (Hanna, 2008).

Policy responses to climate change

Fishery policy comprises the actions of government at various levels to influence fishery outcomes. It includes guidance and directives on economic, social, biological, ecological and governmental matters. Who is a policy maker varies according to the particular political and legal context of a fishery. Over a variety of different political and legal contexts the implicit goal of fishery policy is to increase the resilience and adaptive capacity of the fishery, fishing industry, fishing communities and fishery governance.

Mitigation and adaptation

Policy options fall into two categories: mitigation (*ex ante* actions) and adaptation (*ex post* actions). Both are attempts to reduce the impacts of climate change (FAO, 2006). The general policy question becomes one of trade-offs among mitigation and adaptation actions, as they are done by different people operating at different spatial and temporal scales and compete for limited implementation resources (Tol, 2005). Other authors (Tompkins and Adger, 2005) have seen the appropriate trade-off as not between mitigation and adaptation but between investment in the development and diffusion of new technology, and investment in encouraging and enabling society to change its behaviour and/or adopt the new technology. According to this view policy makers begin with a complete picture of the response options available to them. They next consider who is responsible for making climate response decisions and when actions should be

taken to maximise the potential for social learning and institutional change. These are all shaped by the particular institutional setting (Tompkins and Adger, 2005).

Avoiding surprise

Central to the concept of policy responses to climate change is the ability to avoid surprises and irreversible effects. A surprise is an unanticipated outcome, an unexpected event that represents a rapid, non-linear response. Climate changes can produce these types of surprises because of the complexity of interactions among physical drivers and biological effects and our incomplete understanding of them (Schneider, 2003). Schneider also distinguishes "imaginable abrupt events" as those that are rapid but not truly unexpected. The imaginable abrupt events are the focus of anticipatory policy actions; the true surprises require reactive policy action. Grafton (2010) notes that climate change requires policy that provides a degree of leverage to known environmental surprises and to unexpected "emergent risks".

Some of the effects of climate change on governance described in the previous section will require changes in fishery policy. Keeping in mind the policy options of mitigation and adaptation, as well as the goal of avoiding surprise, how should capture fishery policy proceed? This question contains the more specific questions of what policy makers should do, how they should do it and when.

What policy makers should do

What policies can address climate change in capture fisheries to increase flexibility, adaptability and resilience? Policy makers have a number of options in research, education, risk assessment, strategic planning, cross-sector co-ordination, market integration and regulatory control. All engage the use of tools in processes that promote the enhancement of knowledge, transparency, incentives and adaptation.

Research

Research is the primary tool with which to build an information base to support effective adaptation to climate change. The knowledge base of most capture fisheries is focused on understanding the biology of fish stocks and is lacking in a number of basic pieces of information about the human and ecological dimensions of fisheries. Under changing climate conditions the information gaps widens. Familiarity with fishery data, existing management systems and their drivers is an important base from which to alter governance. Additional information about fishers, processors and their communities assists in the prediction of impacts and planning governance response (McIlgorm *et al*., 2010). Research can provide needed information to assess the overall range, combination, likelihood and potential impacts of climate related effects in the biological, economic, social and ecological contexts of fisheries. It can provide a better understanding of the biological and economic risks associated with variations in stock productivity and distribution. It can analyse the economic and ecological linkages within fisheries that affect the degree of impacts and adaptation (FAO, 2006). It can also result in improved information systems to integrate knowledge from different coastal sector and plan for strategic response (Daw *et al*., 2009).

Stakeholder engagement

Education of fishery stakeholders is an important policy tool to raise awareness of the impacts of climate change and to ensure that the special risks to the fishery sector are understood (FAO, 2006). Stakeholder support is critical to the implementation of policy programs and stakeholder knowledge is fundamental to policy design. Stakeholder education and engagement can extend beyond the narrow definition of traditional fishery stakeholders to include the broader seafood industry, seafood preparers and seafood consumers.

Risk assessment

Risk assessment is a tool to identify the current and future risks, potential impacts and response mechanisms for a fishery. It offers a mechanism to engage stakeholders and communities with government agencies and non-governmental organisations to derive a common understanding of risks posed to the fishery by climate change as well as the potential changes in economic contributions from the fishery under different climate scenarios and the costs of adaptation (FAO, 2006).

Strategic planning

Long-term strategic planning allows the anticipation of extreme events and initiates the shaping of adaptive response, for example adaptations to sea level rise and damage to fishery shore-side infrastructure (Daw *et al*., 2009). Planning will need to consider the possibility of surprises, or unforeseen events. Past management practices under conditions of surprise will provide some information about effectiveness of response as well as identify information gaps and capacity requirements.

Cross-sector co-ordination

There is a need to improve understanding of the interactive effects of climate change with fisheries, as well as in combination with other stressors (FAO, 2009). This will require integrating research, information and management actions across governmental sectors that address fishery management, waterborne pollution, oceanographic research and coastal zone management. In some cases improving coordination will require national level legislative action; in other cases is can be accomplished through better consultation between government agencies and non-governmental organisations (FAO, 2009). Multi-sector contribution is fundamental to a comprehensive approach to climate changes in fisheries and can assist in building institutions that are responsive to these broad-scale effects. Such co-ordination can usefully include international networks to share information experiences in fisheries and between fisheries and other sectors.

Market integration

The potential for reduced fishery productivity and yields places a greater emphasis on higher value products. Shocks to trade patterns and markets leads to benefits from diversification in products and markets (Daw *et al*., 2009) The variability of yield generates a need to develop markets and trading mechanisms for the purpose of buffering variability in supply (FAO, 2009). The resilience of fishing communities depends on robust markets for seafood products to support the economic base. All of these market

effects stemming from climate change can be addressed through a stronger integration of fishery policy with seafood markets.

Regulatory control

Regulations governing the behaviour of fishery participants are key policy instruments. Regulations that strengthen the economic and biological condition of the fisheries will also provide the basis from which the fishery will be resilient to climate change. The types or regulatory tools that are needed in most capture fisheries are those that reduce the level of fishing pressure and promote flexible adaptation to change. Reducing fishing pressure can be accomplished through actions to reduce fishing capacity, eliminate harmful subsidies and reduce fishing effort. It is also accomplished through a precautionary ecosystem approach to fisheries management and targeted financial instruments to create incentives to switch to low-impact gear (FAO, 2009). Flexibility is enhanced by incentive-based access instruments that enhance the capacity of fishing interests to move within and across jurisdictional boundaries to respond to changes in resource distribution. Incentives to adopt green technologies will also strengthen the position of the fishing industry in anticipation of carbon fees (FAO, 2006). Overall actions taken to improve the economic status of the fishery and adopt best practices for fishery management will best equip the fishery to respond flexibly to change.

How policy makers should implement options

To maximise their effectiveness in addressing the impacts of climate change, the tools described above should be applied in a way that contributes to the flexibility, adaptability and resilience of a capture fishery and its governance.

Research: improving the information base

For fishery managers to adequately anticipate change they need to have adequate information for effective decision making and approaches that engage all sectors. Policy makers can encourage approaches to information development that take into account the uncertainty of unforeseen events, such as the increasing frequency of extreme weather events and other "surprises". Resources can be directed toward learning from examples of past management in response to variability; what worked well and what did not work well? What can we learn about the essential attributes of robust and responsive approaches to adaptation (FAO, 2009)?

Stakeholder engagement: building literacy and capacity

Building effective stakeholder engagement depends on a base level of literacy about climate change and the capacity to engage. Communication with stakeholders about climate change should incorporate the recognition that fisheries have a wide array of stakeholders who comprise multiple audiences representing varying levels of literacy, all of whom need information in usable and accessible formats (FAO, 2009). There are opportunities to educate about climate change through innovative approaches such as "fishermen-chef connection" programs that expand awareness of fishery conditions to the broader reaches of the seafood sector. Opportunities to build capacity for effective

engagement in fishery governance exist with fishing community members as well as with industry representatives (FAO, 2009).

Risk assessment: risk reduction

Risk reduction initiatives apply the results of risk assessments to address the vulnerabilities they identify. Fishery vulnerabilities may range from loss of infrastructure on working waterfronts to loss of seafood markets or decreased fishing safety. Policy responses should be specific to the identified risk points, and could include investments in shoring up waterfronts, exploration of product and market diversification or programs to increase the stability of vessels and safety training of fishers. Regulations can also be adapted to respond to identified risk, for example by moving away from time-dependent effort controls that may force people to fish in unsafe storm conditions.

Strategic planning: expanding policy frameworks

Policy makers can support a number of efforts to expand policy frameworks in ways that will enhance the effectiveness of strategic planning for a changing future. Managers can be trained in techniques for decision making under uncertainty (FAO 2009). Guidelines can be developed to broaden existing fishery management plans (FMPs) to explicitly incorporate the variability inherent in climate change and to integrate with coastal zone management plans. Some regions are already evaluating methods for incorporating climate data into stock assessments and management plans (*cf.* A'mar *et al*., 2009; Schirripa *et al*., 2009).

FMPs can be required to contain objectives that are specific and measurable, so that progress toward meeting those goals can be monitored and evaluated. There is a general trend toward performance-based management in capture fisheries, based on the idea that monitoring and feedback on the effectiveness of management programs can support learning and evaluation for program improvement and avoid the past history of management failures (Degnbol, 2005; Nielsen and Holm, 2007).

Fishery managers at sub-national levels can be encouraged to explicitly integrate management actions with the goals of international agreements such as the FAO Code of Conduct for Responsible Fisheries (CCRF) and the suite of International Plans of Action (IPOAs), guidelines and instruments that incorporated into legal frameworks and national management plans (FAO 2009).

Cross-sector co-ordination: increasing co-ordination

Policy makers can take action to require specific co-ordination between fishery management and other coastal and ocean authorities to integrate research, information and management actions across governmental sectors. This co-ordination can take the form of new legislation, jointly funded research, collaborative strategic planning, informal communication and information sharing, and formal consultations over management actions with potential interactive effects. Policy makers can provide financial resources as an incentive to develop this co-ordination at regional, national and international levels. Policy can also emphasise actions to strengthen existing regional co-ordination structures and processes to be able to accommodate the likely spatial displacement species and even people in response to climate change effects (FAO, 2009).

Market integration: strengthening linkages

In general, the economic focus of fishery management does not extend to seafood markets. Yet management, to the degree that it affects the mix, quantity and timing of seafood commodities delivered into ports, is linked to seafood markets in outcomes if not in intent. Policy makers can make explicit changes to fishery management plans to include objectives related to maintaining viable seafood markets and fishing community economies. Fishery policy, in anticipating changes to fishery landings resulting from climate effects, can support programs that acknowledge these changes in the commodity mix and provide incentives to develop alternative product forms and markets. Research can be supported into market access, composition and function to provide a scientific basis for new investments.

Regulatory control: adopting flexible management.

Policy can provide incentives for the adoption of management approaches that are flexible to variable harvest quantities and locations. This means directing management away from fixed time, fixed location, fixed gear harvest controls to instruments that are more adaptable to changing volumes and locations of catch and that provide incentives to switch to low impact gear types and to less heavily exploited stocks. It requires transparency in allocation and transfer of harvest rights and implies the development of cross-jurisdictional harvest agreements. This can only be recommended in the context of well-functioning fishery governance that includes and effective monitoring and enforcement systems to control illegal, unreported and unregulated fishing (FAO, 2006). Targeted application of financial instruments to provide incentives for efficiency and safety improving technological innovations, increased fuel efficiencies, product enhancement and market development may contribute to the flexibility of management.

Policy can also provide disincentives for fishing practices characterised by low energy efficiency, high levels of by-catch, harmful habitat impacts and low product value. An obvious policy need is to provide disincentives, or at least remove the incentives, for the expansion of fishing capacity and the overuse of carbon fuels (Daw *et al*., 2009).

The timing of policy action

When should decision makers act to develop and implement policies: should they act in anticipation of impacts or wait until they observe impacts? The question of when a given policy action should be taken – whether it should be in anticipation of an event or reactive to it – is a matter of benefits and costs. Each action has both benefits and costs associated with it, some of which are known and others completely unknown or understood with some level of probability. The trade-offs represented by alternative timing of an action have to do with the effect of the timing on costs and benefits. These costs and benefits are specific to each fishery's context and conditions.

Both the magnitude and distribution of costs and benefits are important to the calculation of optimal timing. The magnitude of costs has obvious relevance to the competition for resources within limited government and industry budgets. The distribution of both costs and benefits is of great importance in fishery policy, as it determines the winners and losers from a given action.

Costs and benefits also have a time component. Costs can be realised in the short term or over the long term, as can benefits. Actions can create disparities in the timing of

benefits and costs and thereby also create disparities in their distributional effects. For example, taking actions to reduce a long-lived species' total allowable catch (TAC) to a precautionary level will generate short-term costs with the expectation that there will be long-term benefits of improved stock biomass and productivity. In the case of a long-lived species, recovery will be slow and will mean that those presently fishing will incur the short-term costs of lower catch but will not reap the benefits from rebuilding. These distributional disparities can generate political pressures on fishery decision makers that also become costs to be included in the calculation about taking action.

Daw *et al.* (2009) present a table of specific fishery management actions taken in response to climate effects, and identify each as to whether it should be taken in anticipation of the realised effect, in reaction to it, or either. They identify an action as being anticipatory or reactive based on the degree of effectiveness of when an action can be implemented. However, from the management perspective there is always a broader consideration of costs of taking action than direct implementation costs. Costs also include the transactions costs of information gathering, co-ordination, conflict resolution, monitoring and enforcement. As a practical matter, the uncertainties associated with many climate change effects reduce the stakeholder support for action and thereby increase the costs to decision makers of taking action in anticipation of an effect. In addition, uncertainties about the actual values of benefits and costs can discourage managers from taking action until they are closer at hand and more easily estimated, even if delay results in an increase in their magnitude.

The uncertainties associated with costs and benefits of actions taken to adapt to climate change, as well as the political and management costs associated with their distributional effects do not eliminate the necessity to act. Rather, they describe a need for tools and frameworks that enhance the process of decision making under uncertainty, which is the essence of climate change response.

Grafton (2010) also notes that taking adaptive action involves costs and involves trade-offs between the present and future and consideration of the risks and returns of adaptive investments. To address the "decision-making under uncertainty" characteristic of adaptive actions, he argues for using a "risk and simulation" approach using Monte Carol simulations to generate probabilities for the expected losses associated with climate change impacts as well as the expected benefits of adaptation responses or investments in adaptive capacity. He notes that in almost all cases decision makers will not know the underlying distribution of potential costs associated with climate change impacts, but they may be able to place upper and lower bounds on these costs that will be sufficient to look at sensitivity under different scenarios.

The general paucity of economic data in marine fisheries combined with competing demand for fishery and ocean resources has led to increases in the number of software decision tools available to resource managers that accommodate uncertainty about the likelihood of an event and the magnitude of its impact. For example, economic choices about trade-offs among different mixes of ecosystem services in marine reserve design and implementation or for the placement of marine aquaculture combine ecological, economic, and social dimensions. The empirical assessment of these trade-offs is an emerging area of analysis to support decision making (*cf.* Fisher *et al*., 2009; Whitmarsh and Palmieri, in press).

Conclusions: insights on climate change and capture fisheries

The discussion in this paper has identified some key points regarding the economic effects, governance effects and policy responses to climate change in capture fisheries. This section summarises these points by category.

Economic effects

- The economic effects of climate change on fisheries can be both negative and positive.
- Climate change effects do not exist in isolation. They are layered on and mix with other changes in the economic-regulatory system within which the capture fishery operates.
- Economic effects are complex. At any given time and for any given region they are intertwined with the effects of fishery changes elsewhere, as well as with effects of changing market conditions and regulatory programs.
- The economic effects of climate change on capture fisheries depend in large part on the fishery context, the degree of fishery dependence and availability of substitutes.
- Substitution among fisheries or between industries may or may not be possible, because many fisheries are fully subscribed.
- Changes in the location or productivity of fish stocks targeted by capture fisheries will likely also change the distribution of benefits and costs from the fishery.
- Fishing costs that may be most sensitive to the biological effects of climate change are those associated with energy consumption.
- Long-term fishery profitability requires having a prior recognition of the uncertainties of fish stock productivity and building them into rational investment decisions.
- More research is needed on the interactions among climate, biological processes and economic activities dependent on these processes.

Governance effects

- Over a variety of different political and legal contexts the implicit goal of fishery policy is to increase the resilience and adaptive capacity of the fishery, fishing industry, fishing communities and fishery governance.
- Fishery management operates with multiple and competing objectives, so responding to climate change effects requires accounting for distributional and community effects as well as efficiency effects.
- A major challenge for fishery governance in accommodating climate change is for it to be structured in a way that it can function effectively in an environment of uncertainty.
- Fishery governance could be strengthened to promote effectiveness under conditions of climate change through increasing adaptability, flexibility and resilience.

- Taking action to strengthen adaptive capacities and promote resilience will also have the beneficial effect of actions that promote sustainable use. Good governance should strengthen fisheries and fishing communities.
- Managing portfolios of fisheries offers more opportunities to promote resilience than managing specialised fishery units.
- Long-term planning that accounts for uncertainty can help rationalise expectations and avoid management error.

Policy responses

- Central to the concept of policy responses to climate change is the ability to avoid surprises and irreversible effects.
- Accommodating the multiple completing objectives of fishery management may slow the rate of policy response to climate change.
- The choice of anticipatory versus reactive policy response to climate effects is determined by the magnitude, distribution and timing of benefits and costs.
- The most appropriate policy response to climate change is a mixture of tools and processes.
- Policy makers have a number of options to engage tools in processes that promote the enhancement of knowledge, transparency, incentives and adaptation.
- Policy can provide incentives for the adoption of management approaches that are flexible to variable harvest quantities and locations.
- Uncertainties associated with costs and benefits of actions taken to adapt to climate change, as well as the distributional costs of these actions, indicate a need for tools and frameworks that enhance the process of decision making under uncertainty.

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Chapter 3

From an ecosystem approach to assess climate change impacts on fisheries

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Climate changes, such as global warming, decadal climatic regime shifts and inter-annual variability of the El Niño-Southern Oscillation (ENSO) phenomenon, can affect ocean conditions and thus affect the functioning of marine ecosystems as well as the distribution and abundance of fisheries resources. For example, there has been a trend of increasing sea surface temperatures in Korean waters, which has accelerated in the last decades. This recent warming trend is associated with a decline in cold-water species (e.g. walleye pollock) and an increase in warm-water species (e.g. common squid and bluefin tuna). It is also associated with changes in the distribution of fish stocks such as chub mackerel in Korean waters.

This chapter explores how to assess the impact of climate changes on fisheries from the perspective of an ecosystem approach to fisheries (EAF). It discusses how an EAF can contribute to understanding the impact of climate changes on fisheries and the development of adaptation strategies. It reviews the reported major impact of climate changes on fish and fisheries from an EAF perspective; introduces the integrated fisheries risk analysis method for ecosystems (IFRAME) model as an EAF assessment approach; and identifies the management objectives and attributes of an EAF. It also discusses the development of indicators, reference points and risk indices for assessing fisheries affected by climate changes. In addition, it demonstrates an approach to evaluating fisheries management from an EAF perspective. Finally, it reviews current fisheries management systems and discusses implications for management under changing climate conditions.

Introduction

Climate changes influence various aspects of fisheries and aquaculture, such as primary production levels, growth, recruitment, mortality, distribution, migration patterns, species composition of fish stocks, seasonality and productivity of marine and freshwater systems, and input costs. Fluctuations in climate conditions can affect the distribution of fish as well as their growth and survival. The impact of climate change on marine biodiversity is likely to intensify in the future, with the intensity varying geographically according to changes in ocean conditions and the sensitivity of the affected species (Roessig *et al*., 2004; Harley *et al*., 2006; Munday *et al*., 2008).

Several studies have demonstrated the impact of climate changes on fish and fisheries. For example, from 1985 to 2006 the species richness of the North Sea fish fauna increased in response to large-scale bio-geographical patterns and climate change (Hiddink and Hofstede, 2008). The production of northern rock sole in the eastern Bering Sea has increased due to climate changes (Hollowed *et al.*, 2009). Nye *et al*. (2009) found that fish stocks located in the southern extent of their survey area exhibited much greater poleward shifts in the centre of biomass, and that some fish stocks occupied habitats at increasingly greater depths in relation to climate change in the north-east of the United States continental shelf. Cheung *et al.* (2009) investigated the global patterns of the impact of climate change by projecting the distribution of 1 066 fish and shellfish for 2050. These projections showed that climate change may lead to numerous local extinctions in the sub-polar regions, the tropics and in semi-enclosed seas. Simultaneously, species invasion is projected to be most intense in the Arctic and the Southern Ocean. In the Pacific bluefin fishery, the fishing area has tended to shift northward year by year. Yamada *et al.* (2009) examined the effect of global warming on the distribution of Pacific bluefin tuna, and studied water temperatures in the fishing ground of the purse seine fishery. They concluded that water temperature in recent years seemed to be higher than normal, but that these changes were not necessarily related to global warming because other fluctuations over periods lasting from ten years to several decades were dominating (Yamada *et al.*, 2009). Rijnsdorp *et al*. (2009) stated that the review of a number of well-studied fish species in the north-east Atlantic did not allow them to test their working hypotheses, but supported the hypothesis that species exhibited distributional shifts in response to temperature increase. More recently, Seo (2010) reported that the fast growth of Hokkaido chum salmon at the age of one year, which was related to global warming, would positively affect the survival rate and in turn would affect the population density-dependent growth and maturing at age two to four due to the limited carrying capacity of the Bering Sea.

According to Hollowed *et al.* (2009), three modelling approaches are typically used to evaluate the effects of climate change on fish and shellfish resources. These are statistical downscaling, dynamic downscaling on regional scales, and dynamic global models. They suggest a unified framework approach to forecasting the implications of climate changes for marine fish production which involves: (i) identifying relevant mechanisms; (ii) conducting a feasibility assessment of the implications of downscaling climate scenarios; (iii) evaluating climate model scenarios and selecting Intergovernmental Panel on Climate Change (IPCC) models; (iv) extracting environmental variables from climate scenarios and incorporating them into projection models; and (v) evaluating fish and shellfish production under a changing ecosystem. Recently, Zhang *et al.* (2010a)

developed an integrated fisheries risk analysis method for ecosystems model (IFRAME), which is composed of sub-models of assessment, forecast and management.

The single species management paradigm is known to suffer from a number of shortcomings, since it has led to overfishing in many areas. According to the Food and Agriculture Organization's (FAO) exploitation state summary of 441 assessed stocks, 77% were fully exploited or overfished, depleted or recovering (Kelleher, 2005). For example, the current spawning stock biomass of southern bluefin tuna is only 4.6% of the unfished level. Single species management only focuses on sustainability, ignoring habitat quality, biodiversity and socio-economic factors. Ecosystem-based fisheries management has been a common theme in fishery policy and management discussions worldwide (NMFS, 1999; FAO, 2003; Garcia *et al*., 2003; National Research Council, 2006; Plagányi, 2007). The North Pacific Marine Science Organization (PICES) has addressed this issue and established a working group in 2005 that focuses on ecosystem-based management science and its application in North Pacific countries. The International Council for the Exploration of the Sea (ICES) has developed a science plan for 2009-2013, which states that "The scientific needs for an ecosystem approach to management (EAM) are an overarching motive for the ICES Science Plan. EAM has application to fisheries, other industry sectors (…) and ecosystems as a whole." Many countries, including Australia, Canada and the USA, are considering how to implement marine fisheries management which take ecosystem concepts into consideration (US Commission on Ocean Policy, 2004; AFMA, 2005; CSIRO, 2005). Fisheries management should play a crucial role in adapting fisheries to a changing climate. The management system should be adaptive, flexible and based on a precautionary and ecosystem-wide approach to fisheries management. However, challenges exist; chief among these are the uncertainties and complexities in understanding and forecasting the interactions between climate changes and fisheries.

When considering the ecosystem, we must include not only target species, but also their effect on dependent or competing non-target species, as well as on the habitats shared by common species (Cury and Christensen, 2005); reductions in target species may allow competitors to increase in abundance (Fogarty and Murawski, 1998). Numerous studies on ecosystem indicators have been carried out such as Fulton *et al*. (2004) and Jennings (2005). While a large variety of indicators have been developed, few of them have been validated, very few have associated reference points and still fewer could be delivered to managers for use in decision making (Rochet and Trenkel, 2003). Moreover, few approaches have synthesised indicators to obtain an integrated assessment such as Australia's Commonwealth Scientific and Industrial Research Organisation's (CSIRO) ecological risk assessment for the effects of fishing (ERAEF) (CSIRO, 2005), the Marine Stewardship Council's (MSC) fishery assessment methodology (FAM) (MSC, 2009), and Korea's ecosystem-based fishery assessment approach (EBFA) (Zhang *et al*., 2009). In fact, the speed at which policies are being adopted has necessitated equally rapid development of scientific and management tools to support their practical implementation (Smith *et al*., 2007).

The purpose of this paper is to discuss how the IFRAME approach can contribute towards better understanding of the impact of climate changes on fisheries. First it reviews the major reported impact of climate changes on fish and fisheries from an EAF perspective and introduces the IFRAME model as a tool for assessing and forecasting risks to fisheries and ecosystems. It then identifies management objectives and attributes for an EAF and discusses the development of indicators, reference points and risk indices for assessing those fisheries affected by climate changes. It demonstrates how to evaluate

fisheries management from an EAF perspective by investigating the impact of climate changes using distribution projections of pelagic fish for the next 50 and 100 years. Finally, it reviews current fisheries management systems and discusses the implications for management under changing climate conditions.

The IFRAME model as an EAF approach: elements and structure

The EBFA for Korean fisheries was developed based on four considerations (Zhang *et al.*, 2009). First, the approach should be evolutionary rather than revolutionary and has to be applicable using available information. It should be precautionary and environmentally sound, and, most importantly, be simple and pragmatic. The EBFA approach is a two-tier assessment system. Tier 1 is based on a quantitative analysis and requires a high level of information, while Tier 2 is a semi-quantitative or a qualitative analysis, which requires a lower level of information. The EBFA approach includes: management objectives and attributes, indicators and reference points, nested risk indices, and management status indices. Its four management objectives are to maintain system sustainability, to maintain biodiversity consistent with natural processes, and to protect and/or restore fish and prey habitats.

The IFRAME approach is an extension of the EBFA. Evalutating the EBFA approach, Kruse *et al*. noted: "From a practical standpoint, the ecosystem-based fisheries assessment approach (Zhang *et al*., 2009) is very appealing for its ability … but, this approach should be further refined, sensitivity analyses conducted, the forecasting version of this approach further developed, and future applications tested in other ecosystems." (Kruse *et al.*, 2009) Recently, Zhang *et al*. (2010b) revised the indicators and reference points for the ecosystem-based fisheries assessment approach and extended the approach to include socio-economic factors as another objective. As shown in Figure 3.1, the attributes for this component include economic production, revenue, market and employment. Zhang *et al*. (2010a) incorporated forecasting and management into the approach and named it the IFRAME.

Figure 3.1. Identification of objectives (circles) and attributes (bulleted list) for the ecosystem-based fisheries assessment approach

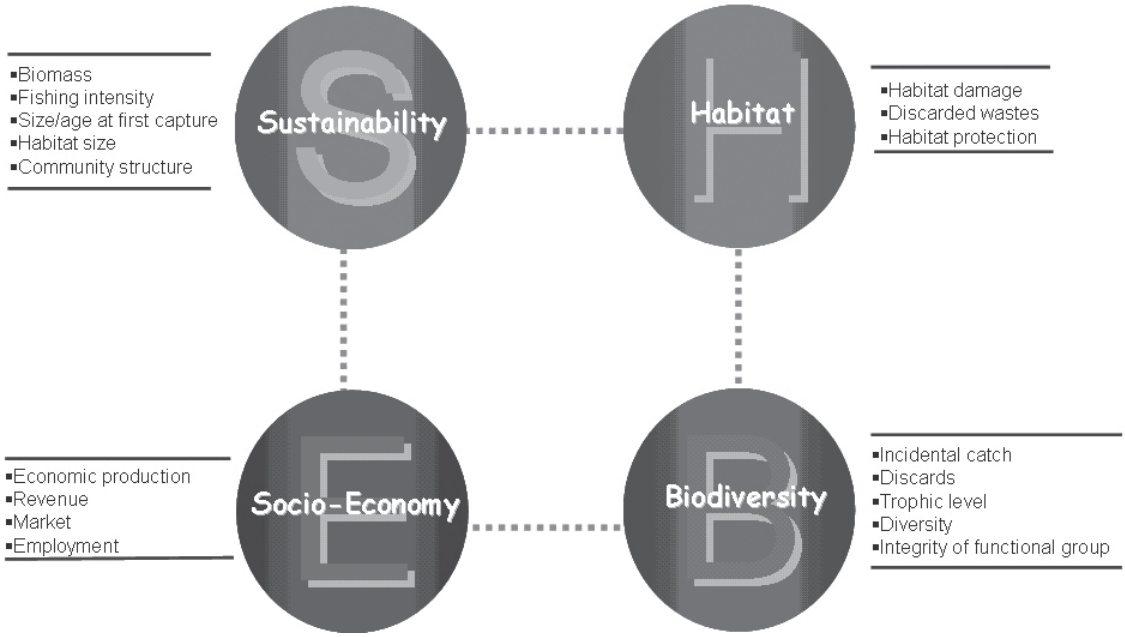
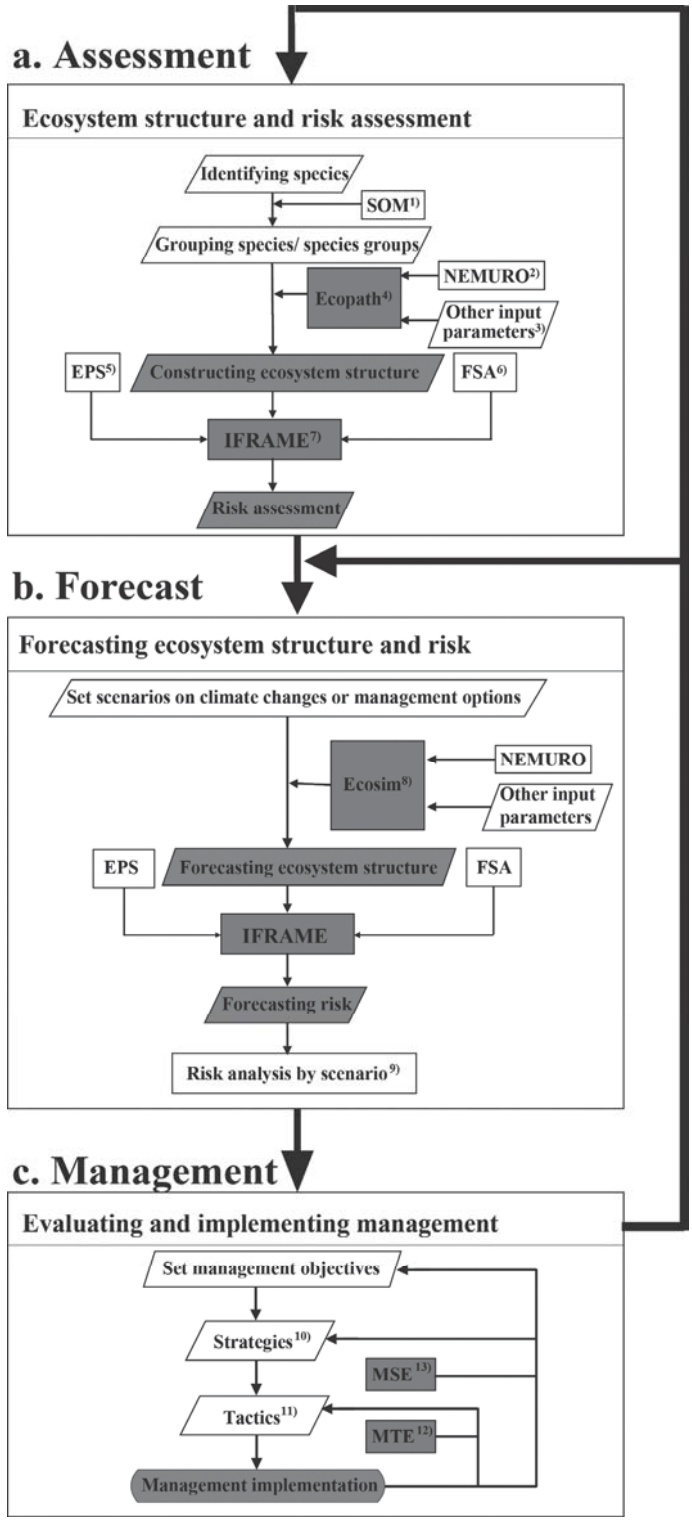


Figure 3.2 shows the structure of the IFRAME model. The framework is made up of three sub-models: assessment, forecast and management. Figure 3.2a shows the assessment sub-model, which is used to construct the ecosystem structure and to assess risks. First, species in an ecosystem are identified and then grouped by the self-organising mapping (SOM) analysis based on nine ecological characteristics (Chon *et al*., 1996). The ecosystem structure is constructed using the Ecopath model, which has been widely used to describe the trophic relationships in aquatic ecosystems on quantitative bases (Pauly *et al*., 2000). The NEMURO model (Kishi *et al.*, 2007) is used to estimate input parameters of lower trophic level groups, such as biomass and production of phyto- and zoo-plankton groups. Other input parameters, such as biomass, catch, production/biomass ratio (P/B), consumption/biomass ratio (Q/B), and diet compositions, are also used for the Ecopath run. Finally, the outputs of the Ecopath run, together with results from ecological process studies and fishery socio-economic analyses, are used for the IFRAME risk assessment.

Figure 3.2b shows the forecasting sub-model, which forecasts changes to the ecosystem structure and risks based on various scenarios. First, scenarios on management options and/or climate changes are selected. NEMURO is then reapplied based on these altered conditions to get the revised input parameters for the Ecopath. The Ecosim (Christensen and Walters, 2004) analysis is conducted to simulate expected biomass under the altered conditions. The IFRAME analysis is then carried out to forecast risks for the scenarios using all the changed parameters.

Figure 3.2c shows the management sub-model, which evaluates management tactics and strategies and implements management practice. First the management objectives are set, then these objectives are translated into strategies, *i.e.* what will be done, and then strategies into tactics, *i.e.* how it will be done. After implementation, the management tactics and strategies are evaluated through the framework's feedback system and modified management options are adopted.

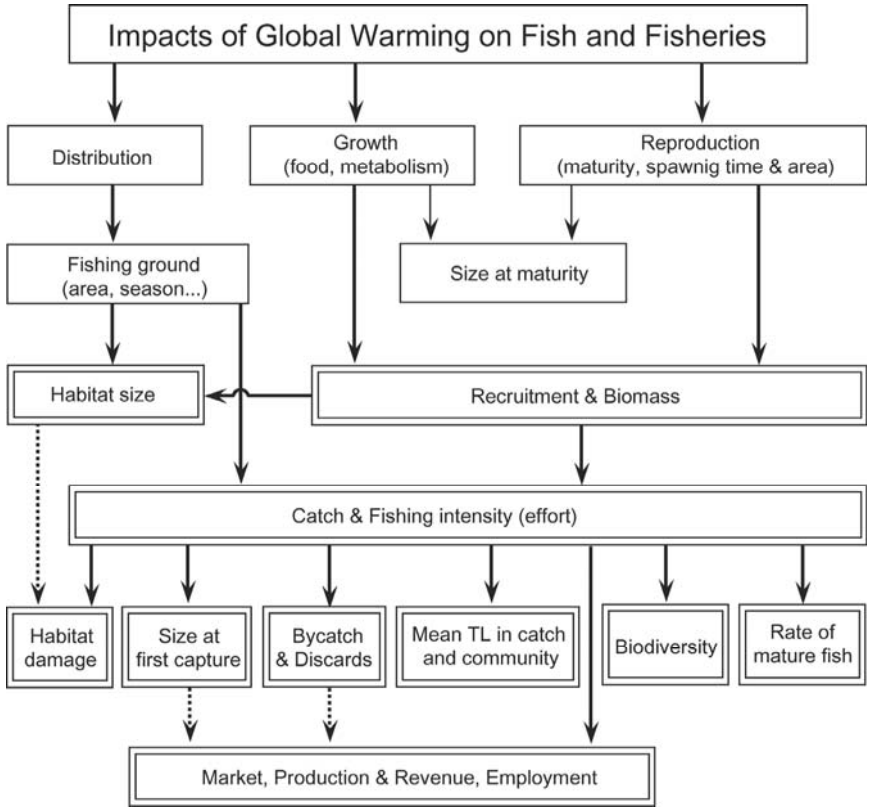
Figure 3.2. Flowchart illustrating the integrated ecosystem-based risk assessment, forecast and management approach



Development of indicators, reference points and risk indices for assessing fisheries affected by climate change

Figure 3.3 shows the expected impact on various attributes and indicators of changing fishing intensity of a fishery under the changing climate. Global warming will influence sustainability, biodiversity, habitat quality and socio-economic factors in a marine ecosystem, such as biomass, catch, by-catch rate, discard rate, pollution levels in the spawning and nursery grounds. Biomass changes can inversely influence fishing intensity. The mean trophic levels of the fishery catch and community could be influenced by the altered biomass and fishing intensity. Biomass will affect the size at first capture, the percentage of mature fish, etc. Indicators for the socio-economic component will affected by the fishing effort and catch amount. The values of these indicators could be forecasted by the mechanisms explained in Figure 3.3.

Figure 3.3. Flowchart showing the impact of global warming on marine ecosystems (Double rectangles represent IFRAME indicators).



In this study, we have developed indicators and reference points for the IFRAME approach to assess fisheries affected by climate changes, based on the concepts in Figure 3.3. A total of 21 indicators were developed for Tier 1. There are seven indicators for sustainability, five for biodiversity, three for habitat quality and six for socio-economy (see Tables 3.A1.1a-d in Annex 3.A1). Based on the indicator status using the target and limit reference points in Table 3.A1.1, risk scores for each indicator are calculated using a pre-defined formula as described in Zhang *et al.* (2009). In the Tier 2 analysis, a total of 30 indicators were developed; twelve for sustainability, five for biodiversity, seven for habitat quality, and six for socio-economy (see Table 3.A1.2 in Annex 3.A1).

The IFRAME approach has nested risk indices. For each species, the objective risk index (ORI) is calculated for sustainability, biodiversity, habitat quality and socio-economy. Subsequent estimates can then be made for the species risk index (SRI), fishery risk index (FRI), and ecosystem risk index (ERI). The equations used to calculate the ORIs, SRIs and ERIs are described in Zhang *et al*. (2009). The FRI is the weighted average risk index for exploited species in each fishery, and is calculated using the following equation (1):

$$FRI = \frac{\sum B_i P_i SRI_i}{\sum B_i P_i} \qquad (1)$$

where B_i is the best available biomass or biomass index for species i, such as catch per unit of effort, and P_i is the price of the unit fish weight of species i.

Demonstration of the IFRAME approach on the Korean large purse seine fishery

The large purse seine fishery is one of Korea's major fisheries. With an annual catch of about 250 000 tonnes, it accounts for more than 20% of total catch of the Korean coastal and offshore fishery. The main fishing ground is around Jeju and Tsushima Islands. Major species taken by the fishery include chub mackerel (*Scomber japonicus*), jack mackerel (*Trachurus japonicus*), common squid (*Todarodes pacificus*), hairtail (*Trichiurus lepturus*), bluefin tuna (*Thunnus thynnus*), Spanish mackerel (*Scomberomorus niphonicus*), and yellowtail (*Seriola quinqueradiata*). Chub mackerel accounts for more than 90% of the total catch (Cha *et al*., 2004; Choi *et al*., 2004). Since 1999, this fishery has been managed on the basis of annual total allowable catches (TACs) for chub mackerel, jack mackerel and Pacific sardine. These annual TACs are determined by the TAC Management Committee, which is composed of officials from central and regional governments, scientists, fishing representatives and non-governmental organisations (NGOs).

Because the large purse seine fishery has been extensively studied and yielded relatively good scientific data, the proposed IFRAME approach was applied to it, as an example of a typical commercial fishery. The main commercial species were to be assessed using the Tier 1 analysis, and the other species were assessed by the Tier 2 analysis. Chub mackerel was selected for a Tier 1 analysis, because of its importance in the catch. Since quantitative data were not available for species taken as by-catch, bluefin tuna (*Thunnus thynnus*) was assigned to Tier 2.

Habitat distributions of chub mackerel

Chub mackerel is a coastal pelagic species, widely distributed throughout the North Pacific Ocean, and particularly abundant in the waters off Korea, China, Japan and California, USA (Collette and Nauen, 1983; Yamada *et al*., 1986). The spawning grounds of this species are the offshore waters between Jeju Island, Korea and Tsushima Island, Japan from April to May. Chub mackerel is a commercially important species in Korea and most are harvested by the large purse seine fishery (Choi *et al*., 2004).

The catch per unit of effort (CPUE) time-series data of the Korean large purse seine fishery were used as basic data to determine changes in fishing grounds of chub mackerel in Korean waters. The centre of the fishing grounds was estimated from CPUE data from 1980 to 2008, using Cheung *et al*. (2009)'s method, as in the following equation (2):

$$C = \frac{\sum_{i=1}^{N} A_i \cdot Lat_i}{\sum_{i=1}^{N} A_i} \qquad (2)$$

where C is the centre of the fishing grounds. A_i and Lat_i are the relative biomass and latitude in sea block (30'x30') i, respectively. N is the total number of sea blocks. The centre and area of fishing grounds were also calculated from Korean purse seine fishery CPUE data using the equal-frequency ellipse (Sokal and Rohlf, 1994) as in equation (3), which calculated the 95% confidence fishing area for chub mackerel in the fishery:

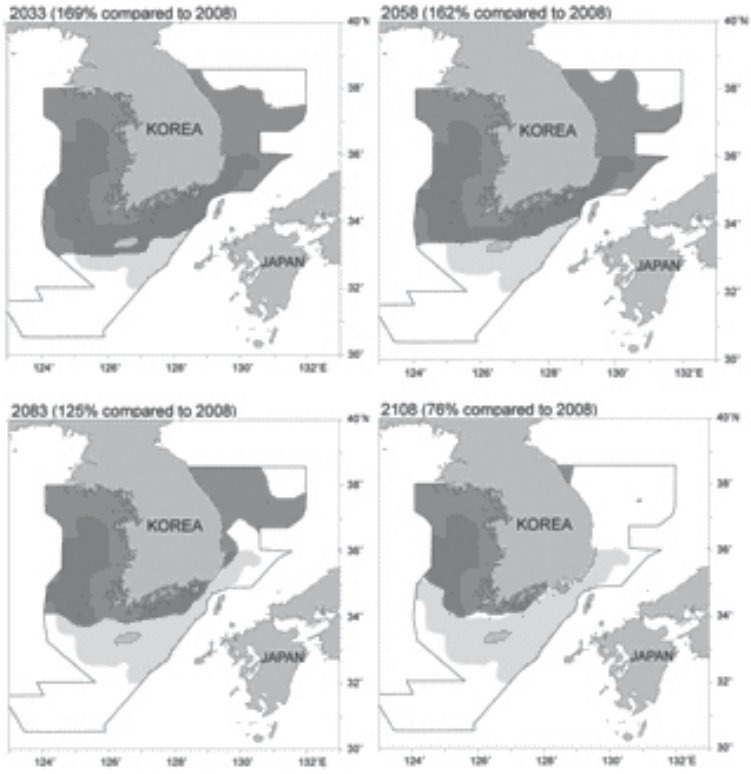
$$C_{0.5} = \frac{\lambda_1 \lambda_2 (n-1)2}{n(n-2)} F_{0.5[2,n-2]} \qquad (3)$$

where λ1 is the long and λ2 the short axis of an ellipse, n is the number of data and F.05[2,n-2] is variance ratio within the 95% confidence area .

We assumed that chub mackerel would change their habitat distribution to inhabit the area with the optimum water temperature as the environment warmed. Based on this assumption, we predicted the locations and extent of chub mackerel fishing grounds in 2033, 2058, 2083 and 2108 using a warming rate of 0.06 °C/year to the sea surface temperature (SST). This scenario was based on the IPCC SRES A2 CO2 emission scenario giving a mean temperature warming rate over the Korean Peninsula and East Asia of 0.61 °C/decade during 2001-2100, which is lower than the actual warming rate occurring in Korean waters since 2000 (Zhang *et al*., submitted).

Figure 3.4 shows the predicted habitat areas of chub mackerel in 2033, 2058, 2083 and 2108. The mean temperature range of the fishing grounds was 14.4-22.5°C. Chub mackerel is a migratory species that moves according to water temperature conditions. The species is predicted to extend its habitat to the northern Japan/East Sea and Yellow Sea as the surface water temperature increases. The fish, which were mainly distributed around Jeju Island in 2008, will move out of Jeju Island after 2058, and they will move out of the Korean exclusive fishery zone (EFZ) in the Japan/East Sea in 2108. However, the species will still occur in the north-eastern Korean EFZ in the Yellow Sea in 2108 (Figure 3.4).

Figure 3.4. Predicted habitat distribution (red shaded area) of chub mackerel in 2033, 2058, 2083 and 2108 (Blue shaded areas are the habitat of chub mackerel in 2008. Thick solid lines are Korean EFZ boundaries).



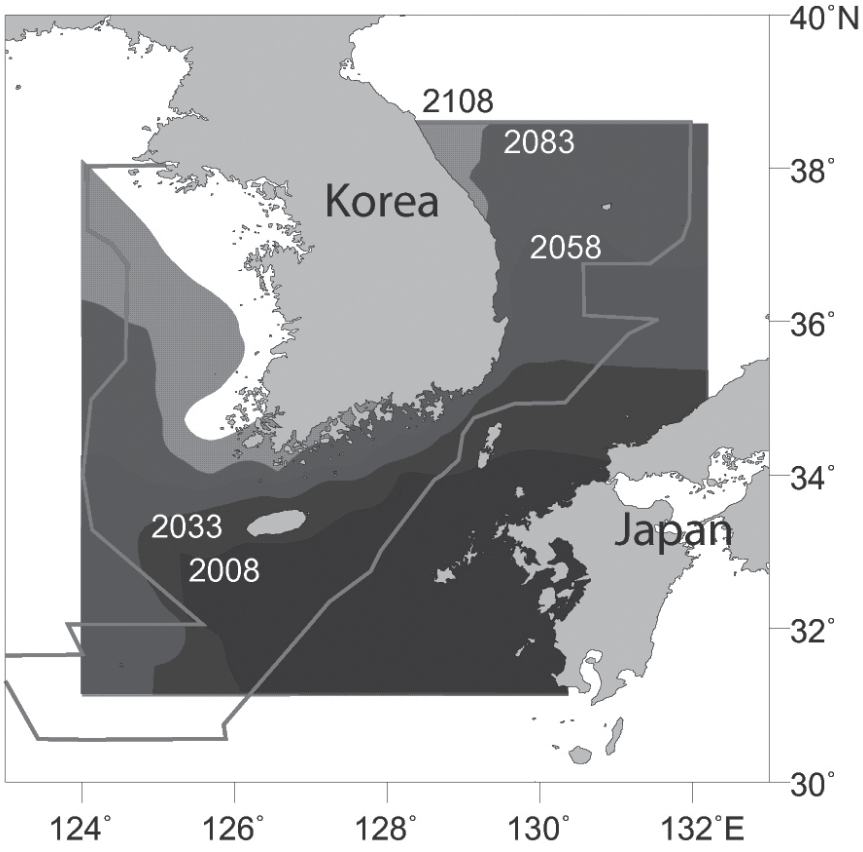
Habitat distributions of bluefin tuna

The catch of bluefin tuna in the Korean large purse seine fishery has been steadily increasing since the late 1980s. The catch started to be compiled officially from 1982, peaked at around 2 000 t in 2003 and then remained at the level of 1 000 t in recent years in Korean waters (Zhang *et al*., submitted). The increase of SST in the southern Korean waters due to global warming has allowed this subtropical species to extend its distribution to the north, which may have resulted in the increased catch. The fishing ground of bluefin tuna was formed at the SST range of 18.9-21.2 ^{o}C around Korean waters, and the increase of SST in the centre of fishing ground shows a positive correlation with the increase in bluefin tuna catch (Zhang *et al*., submitted). Official catch statistics of bluefin tuna by area show that the fishing grounds of bluefin tuna were 26.1% of those of chub mackerel in 2003 and have extended to 89.7% in 2008 (Zhang *et al*., submitted).

Bluefin tuna in the western North Pacific inhabit areas with an SST range of 24-29 ^{o}C (Bayliff, 1994) and larvae of the fish were found where SST was around 26 ^{o}C with a range of 22-31 ^{o}C (Yamada *et al.*, 2009). However, the extended distribution of fishing grounds could be attributed to the increase in SST, considering their highly migratory behaviour and since initial fishing grounds were formed at below normal temperature ranges in Korean waters. The 20.1 ^{o}C contour of SST is considered to be the northern limit of the central bluefin tuna fishing ground in Korean waters. Based on this, the

distribution of the bluefin tuna fishing grounds was forecasted using the warming rate of 0.6 °C/decade. The habitat areas of bluefin tuna were forecasted to extend to the middle of the Japan/East Sea and the Yellow Sea in 2058, and further into the northern waters of the Korean EFZ in 2108 (Figure 3.5).

Figure 3.5. Predicted habitat distribution of bluefin tuna in 2033, 2058, 2083, and 2108 by SST contour of 20.1 ℃



Forecasting risk scores and risk indices

The ecological risk for chub mackerel was examined for the year 2058 under the changing climate using the IFRAME model. Of the 21 indicators developed for this study (Table 3.A1.1 in Annex 3.A1.1), 16 were selected due to limited data availability for some indicators. We adopted the method in Zhang *et al.* (submitted) to assess and forecast risk scores. As an example, for the indicator "biomass", risk scores for the fishing mortality (F) scenarios higher than the 0.75 F_{ABC} level increased, since the increased fishing mortality caused the reduction of simulated biomass of chub mackerel (Figure 3.6). Other indicators for the four objectives were also assessed and risk scores calculated.

Figure 3.6. Estimated risk scores for the indicator *biomass* of chub mackerel in the Korean large purse seine fishery under nine F scenarios for 2058.

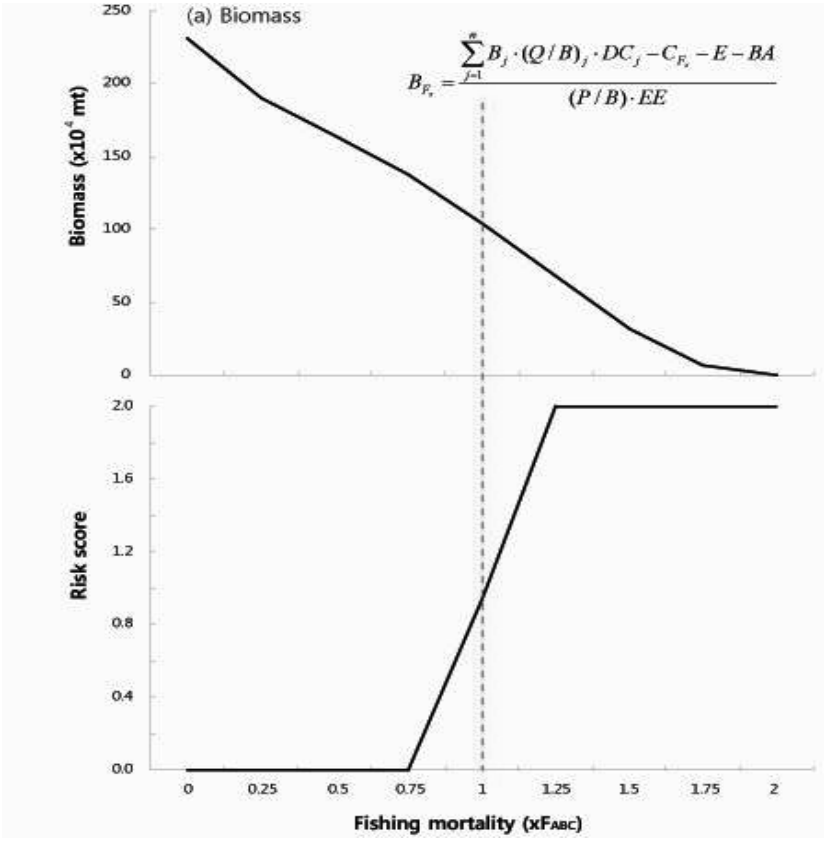
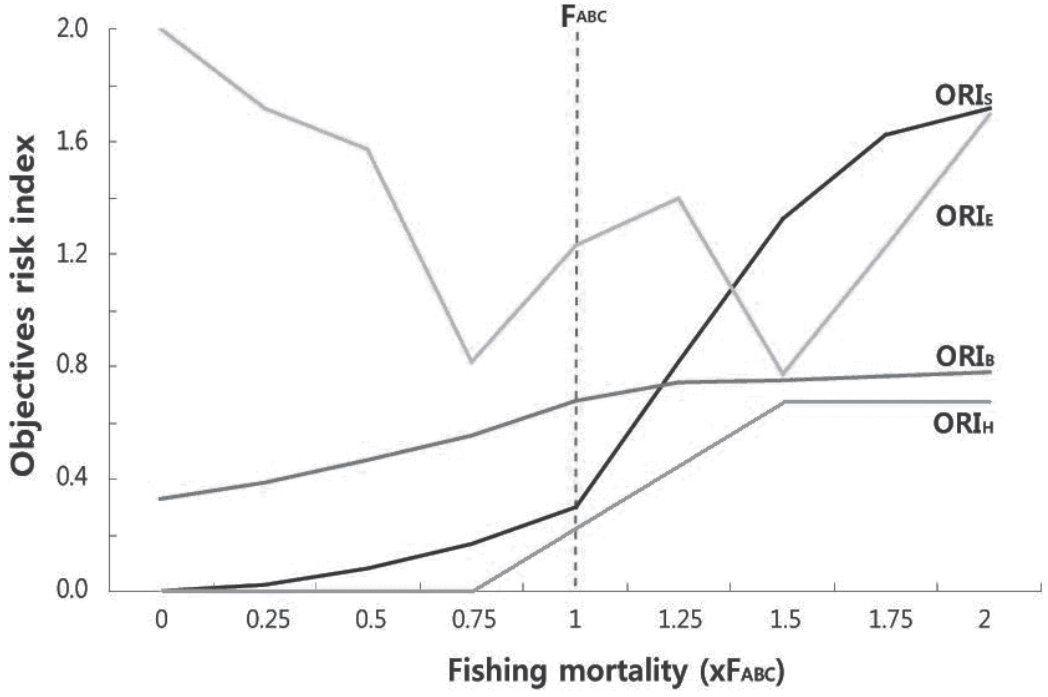


Figure 3.7 shows the forecasted ORIs of chub mackerel under nine F scenarios for 2058. The dashed line is the F_{ABC} line of 2008. All the ORIs were calculated as the weighted average of risk scores of indicators (Table 3.A1.3 in Annex 3.A1) and had a similar trend of risk indices, except the socio-economic ORI which showed the opposite trend to other three indices. ORIs for sustainability began to increase as the fishing mortality increased. ORIs for biodiversity and habitat quality moderately increased as the fishing mortality increased, while the ORIs for socio-economy showed a W-shaped risk trend with low risks at 0.75 F_{ABC} and 1.25 F_{ABC} as the fishing mortality increased. This phenomenon makes sense since lower catches cause decreased income which would translate to a higher socio-economic risk.

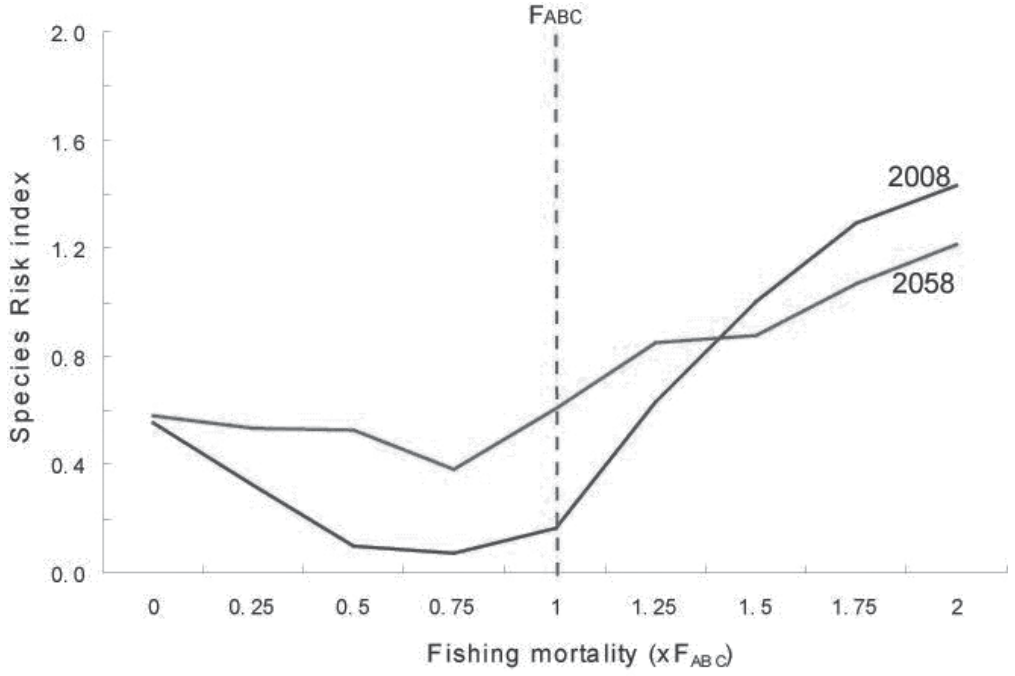
Figure 3.7. Objective risk indices of chub mackerel under nine F scenarios for 2058. The dashed line is F_{ABC} of 2008.



The forecasted SRIs of chub mackerel for 2058 showed a generally increasing trend with the increase in fishing mortality, while those for 2008 showed skewed U-shaped risks (Figure 3.8). In both cases, the lowest SRIs were for the fishing mortality of 0.75 F_{ABC} (Table 3.A1.3 in Annex 3.A1 and Figure 3.8). After the fishing mortality reached 0.75 F_{ABC}, SRIs started increasing with the increase in fishing mortality. This phenomenon is due mainly to socio-economic effects. According to this forecast, the most suitable fishing mortality when considering all the ecosystem components is 0.75 F_{ABC}, which is below the current population-based optimum level of F_{ABC}. This analysis indicates that the population-based F_{ABC} level of harvest will result in an "ecological overfishing" under a changing climate, requiring an alternative harvest policy.

Bluefin tuna biomass and catch were expected to increase due to the expanded habitat caused by warming temperatures in Korean waters. The quantitative data and information for bluefin tuna were insufficient for the Tier 1 IFRAME analysis. Therefore, the Tier 2 analysis was employed to evaluate a total of 27 indicators of which 12 indicators were for sustainability, 5 were for biodiversity, 4 for habitat, and 6 for socio-economic factors for the year 2058.

Figure 3.8. Species risk index of chub mackerel under nine F scenarios for 2008 and 2058. The dashed line is FABC of 2008.



The 12 sustainability indicators evaluated were: CPUE, adoption of the precautionary approach and sensitivity of stock assessments, restriction of access, fishery monitoring and sampling, fishing method, size at entry, documentation of population structure, maximum age or age at maturity, extent of overlap of adult habitat with juvenile habitat, existence of a management plan for the fishery, management of illegal, unreported or unregulated (IUU) fishing, and the existence of a recovery plan and period for depleted stocks. As an example of risk-scoring, the CPUE and the proportion of catch are expected to increase in the Korean large purse seine fishery as the biomass and catch of bluefin tuna increase due to the increase in SST. In this case fishery management indicators, such as levels of fishery monitoring and sampling, would become more important. Other indicators for biodiversity, habitat quality and socio-economic components were also evaluated. Table 3.A1.4 of Annex 3.A1 shows risk scores of bluefin tuna for 2058. Objective risk indices and species risk indices of bluefin tuna for 2058 are shown in Table 3.A1.5 of Annex 3.A1.

IFRAME is still in the development stages. Preliminary results indicate that this approach has potential as a tool for forecasting objective, species and fisheries risk indices. However, it is still a long way from practical application due to a lack of knowledge about the assessment of risks for a number of indicators. In particular, we need ecological process studies on the indicators and reference points under a changing climate.

Evaluating management strategies and tactics

IFRAME allows for the effective assessment of fisheries management measures when used as a tool for ecosystem-based fisheries management. The characteristics of IFRAME are summarised below.

First, whereas the effects of fishery management measures were previously commonly assessed only through changes in resource levels and economic factors, IFRAME allows for a wider assessment of the effect of measures on the ecosystem, looking at indicators such as biodiversity, habitat and socio-economic factors, not just changes in fishery resources and sustainability.

Second, previous assessment of fisheries management measures analyse economic effects in isolation from social effects, whereas the user of IFRAME can develop quantitative indicators not only for changes in the fisheries income (or benefits) after the application of a measure but also for changes in maximum economic yield (MEY), return on investment, wage, rate of food self-sufficiency, etc. This tool also encompasses socio-economic factors, which ultimately has policy implications for the economically viable management of fisheries.

Third, previous assessments do not take into account long-term changes in the climate and marine environment. IFRAME, however, analyses and predicts long-term changes in the fishing grounds of target fish species and ecosystems, which helps to select and assess effective measures of fisheries management that are able to adapt and respond to climate changes.

Finally, it is necessary to develop useful and significant indicators by conducting scientific research and collecting data on attributes used by IFRAME and to consider uncertainties of the indicators in the assessment of fishery management measures. These efforts will help establish practical policies to prevent ecological and economic overfishing.

The result of the analysis of the large purse seine fisheries in which both ecosystem and socio-economic factors were taken into account shows that the level of fishing mortality needs to decrease by 25% in order for fisheries to adapt in the long term to future changes in climate. This result has significant implications for those assessing fisheries management measures and developing alternative measures to adapt to climate changes.

Currently the total allowable catch (TAC) per year is applied to those species caught mainly by large purse seine fisheries, such as common mackerel and jack mackerel, and the number of fishing boat licenses is limited to 29. Based on the results of the IFRAME analysis, alternative measures of fisheries management need to be used to reduce the fishing effort (fishing capacity) in order to decrease the level of fishing mortality by 25%. These measures could include a reduction in the TAC in order to decrease the number of fishing days when vessels are operated, a revision of licensing limits to reduce the number of fishing boats, and limiting the number of fishing days per trip. Of course, it will be necessary to consider the condition of the fishing business and consult representatives of the fishing industry in order to select the most effective and practical alternatives.

Regarding the IFRAME objectives, more specific management strategies and tactics can be proposed as shown in Table 3.1. In order to ensure the sustainability of species, fishing intensity should be decreased to 0.75FABC. The number of permits and trips should be limited and new fishing gear and methods should be considered for shifted species and fisheries. In order to maintain and manage habitat and biodiversity, habitat damage and incidental catch should be prevented and the diversity and trophic level must be preserved. For these reasons, we suggest establishing new Marine Protected Areas (MPAs), and modifying the existing closed season and areas and stock enhancement program according to the conditions of the ecosystem. A temporary fishing cessation

could also be implemented. On the socio-economic aspect of the fishery, consideration needs to be given to the enhancement of a community-based management system, government support for shifted fisheries and species, and predictions made about employment and supply and demand of shifted species to ensure an economically viable development of the fisheries. In addition, international co-operation for EAF needs to be strengthened.

Table 3.1. IFRAME management objectives, strategies, and tactics for fisheries in a changing climate

Management Objectives	Strategies	Tactics
Sustainability	- Increasing biomass - Reducing fishing capacity - Maintaining community structure	- TAC reduction (by $0.75F_{ABC}$) - Reducing number of licenses or permits - Limiting number of trips and/or fishing days - Developing new fishing gear and methods
Habitat	- Preventing habitat damage - Restricting discarded wastes	- Establishing Marine Protected Areas (MPAs) - Modifying closed season and areas
Biodiversity	- Preventing incidental catch and discards - Preserving diversity and trophic levels	- Restricting the use of harmful fishing gear - Adopting temporary fishing cessation - Modifying stock enhancement programs
Socio-economy	- Increasing revenues - Maintaining viable production - Supporting employment	- Enhancing community-based management - Government support due to shifted fisheries - Predicting supply and demand of shifted species - Predicting employment changes due to shifted fisheries - Strengthening international co-operation for EAF management

Implications for fisheries management under a changing climate

A variety of fisheries management measures have been used in Korea for different species and fisheries. Furthermore, the Korean government has made practical efforts to manage and recover fishery resources through the Fish Stock Rebuilding Plan, community-based fishery management systems and the active participation of fishers.

However, a key feature of the Korean coastal and offshore fisheries – multi-species and multi-fisheries – have limited the establishment and implementation of these management measures. Those measures that were implemented have had different effects on other fishery resources, and have become less efficient in managing the resources and aiding their recovery from over fishing.

Therefore, the Korean government has endeavoured to understand the relationships between multi-species and multi-fisheries and set up fish stock rebuilding plans for individual species of fish. By doing so, the government hoped to recover recklessly fished resources, while securing a considerable catch of fish and developing economically viable fisheries. The government encouraged fishers to participate actively in this process, and used their traditional information and community-based knowledge to select and operate

effective measures for resource recovery. With these efforts, fishery resources are expected to recover and be managed efficiently.

However, the fish stock rebuilding plans do not take into consideration climate changes, but have selected fishery management measures based solely on changes in fishery resource levels and income. As seen in the IFRAME application, the analysis of ecological and socio-economic effects on the level of fishing mortality has significant implications for selecting measures of fisheries management in response to climate change. We need to understand how climate change will cause changes to fishing grounds and the marine ecology. This can be used to decide the most efficient level of fishing mortality in terms of the fishery's ecosystem and socio-economy and then set up relevant management measures.

New fisheries management measures, such as market-based measures, can be used to adapt to climate changes. Some current measures, such as temporary fishing cessation and marine protected areas, are also effective at protecting habitats and managing fishing grounds. Existing fish stock enhancement programmes (artificial fish reefs, marine ranching, etc.) are highly effective in responding to climate changes and should be operated appropriately, taking into account biodiversity and habitat protection. In addition, management measures that can most effectively respond to climate changes, establish close relationships with fishers to reach safe levels of fishing mortality, and set up policies in fisheries management that will minimise adverse effects on fishing business conditions must be selected.

Table 3.2 compares measures for an EAF-based management system with those of a conventional management system. In an EAF-based management system, its expanded goals can go beyond the protection and management of fisheries to incorporate ecosystems' responses to climate changes. Objectives can also target wider aspects of the ecosystems, such as the sustainability of species, habitat quality, biodiversity, and socio-economic benefits, instead of narrowly focusing on the sustainability of species itself as in a conventional fisheries management system. Management measures are based on both scientific data as well as non-scientific knowledge and can be applied flexibly as the situation changes. The range of management areas for an EAF-based management system should be broadened to areas within and beyond a nation's exclusive economic zone (EEZ). Establishing regional fisheries management bodies may be a useful and effective way to manage fisheries and regional ecosystems in response to climate changes.

The Fishery Resources Management Act (FRMA) was framed in April 2009 in an attempt to set up the systematic and comprehensive management of fishery resources and the effective operation of fish stock rebuilding plans. The objective was to establish a comprehensive fishery resources management plan based on scientific research and resource assessment, to put in place systematic measures to protect these resources, to strengthen the basis of management by arranging a system of self-management agreements for the recovery and development of resources, and ultimately to contribute to the sustainable development of fisheries while increasing the profits of the fishing industry. This was in addition to the Marine Ecosystem Conservation and Management Act (MECMA) which was implemented in October 2006 for the protection of marine ecosystems, preservation of marine biodiversity, and appropriate use of marine resources.

The main elements of the FRMA are as follows. First, it made the conduct of yearly surveys and assessments of fishery resources compulsory. Second, it requires that a master resource management plan for each fishery should be established every five years. Third, it set up the institutional foundations for the self-management of fishery resources

in order to resolve disputes over fishing through agreements with industry representatives or fishers' organisations. Finally, the act embraces international regulations including the encouragement of international co-operation, digitisation of information and use of eco-friendly fishing gear.

Although the FRMA does not explicitly mandate an ecosystem approach to fisheries, it stipulates that management of habitats and ecological environments should be included in the fishery resource management master plan along with policy goals and primary directions of the management, scientific research and assessment systems. Thus, it could be argued that the concept of EAF is implicitly reflected in the fisheries management policies. While the master plan is to be formulated every fifth year, it has to be reviewed every year and amended if needed. A detailed enforcement plan should also be drawn up yearly. These provisions will help fisheries take flexible and prompt action in the uncertain situation of a changing climate.

The conditions of fishery resources and marine ecosystems need to be surveyed annually in order to detect changes in conditions caused by climate change and other factors. Both the central government and local authorities play a role in research and assessments. The assessments for each species of fish are to take into account the characteristics of the species concerned and the factors that influence the climate and the ecosystem.

However, there are limitations on how far these ecosystem-based fisheries management measures can respond to climate changes. These are:

First, we need additional data on fishery resources and marine ecosystems. Effective measures of fisheries management, including fish stock rebuilding plans, need to be established based on data. Realistically, there has been little practical scientific research and the lack of data has resulted in a high degree of uncertainty over the effects of external factors like climate change. This has limited the establishment of ecosystem-based fisheries management measures in response to climate changes. We need increased research into resources, marine ecosystems and the environment, and the continued collection of relevant data. This will permit the effects of climate changes on the ecosystems to be identified more accurately and comprehensively. This is particularly important for the practical application of IFRAME which needs sufficient scientific data for the related indicators and reference points. When based on sufficient data, the use of IFRAME will help minimise uncertainties about the effects of climate changes and help formulate effective measures of fisheries management.

Second, it is difficult to enforce the fish stock rebuilding plans for individual species because of the nature of Korea's "multi-species and multi-fishery" coastal and offshore fisheries. As mentioned above, when the plan for each species is formulated there is no proactive consideration of climate changes in the selection of fisheries management measures. Yet in formulating these plans, it is necessary to consider not only related species of fish but also the effects of climate changes on the ecosystem. The holistic management of ecosystems in the coastal and offshore ecosystems in response to climate changes needs an ecosystem-based scheme for resource recovery and measures to manage multi-fisheries effectively.

Third, there needs to be international co-operation among neighbouring nations in fisheries management. Most of the species caught in the coastal and offshore waters of Korea are also caught by China and Japan in their EEZs of the South, East, and West Seas. Climate changes are a worldwide issue, so even when one country establishes and implements ecosystem-based measures, it is almost impossible for that country alone to

manage resources effectively and take complete countermeasures against them. Enhanced international co-operation and the formation of joint fisheries management systems are much needed. Such attempts will enable the formulation of effective policy on climate changes and the successful implementation of management measures.

Table 3.2. Comparison of current management system and measures to EAF-based management system and measures responding to climate changes

Management	Current management system and measures	EAF-based management system and measures
Goal	Recovery and management of species	Protection and management of fisheries and their ecosystems in response to climate change
Objectives	Sustainability of species	Sustainability of species, habitat quality, biodiversity, socio-economic benefits, responding to climate change
Information	Scientific research and fishery data	Scientific research and fishery data, and non-scientific knowledge and information from fishers
Bodies	Central and local governments	Central and local governments and all stakeholders including fishers, through the establishment of Fishery Management Councils
Flexibility	Restricted	Flexible
Range of areas	Areas within one nation's EEZ	Areas within and beyond one nation's EEZ, co-operating with neighbouring nations, possibly by establishing the Regional Fisheries Management Body
Management period	Short-term	Short-, mid- and long-term

Further research

IFRAME is a helpful tool for an ecosystem approach to fisheries and we expect it to be useful in establishing management policies in response to climate changes. IFRAME can generate indicators that can be applied in analysing significant changes, while integrating the assessment of sustainability of fishery resources, habitats, biodiversity, and socio-economic concerns. By doing so, IFRAME can offer a useful scientific basis for ecosystem-based fisheries management. This tool is expected to provide data as a basis for deciding effective levels of fishing mortality for the entire ecosystem and establishing measures of fisheries management that can respond to climate changes.

However, IFRAME has limitations on its full-scale implementation. There have been few scientific studies into the indicators and reference points that it uses. Some of the ecological indicators have not been studied at all, making it difficult to set up appropriate reference points. Data on species of fishes for the socio-economic indicators are also lacking or inappropriate for use as reference points. Valuable indicators and reference points could be provided if continuous studies on changes in ecological factors (ecosystem process) are carried out, and socio-economic data per fishery and per species are accumulated. With these in place, IFRAME can be fully implemented.

Effective fisheries management policies must include proactive measures against likely uncertainties and flexibility in legal systems. They also need to establish management bodies for ecosystem-based fisheries management, encourage the active participation of fishers and use local knowledge at fishing sites. It is also necessary to support promotional and educational activities in order to improve public awareness and establish policies for enhancing international co-operation.

Annex 3.A1
Indicators and reference points used in the IFRAME approach

Table 3.A1.1a. Indicators and reference points for the sustainability objectives used in the Tier 1 IFRAME approach

Indicator	Indicator status		
	Better than target	**Between target and limit**	**Beyond limit**
Biomass (B)	$B_{MSY} \leq B$	$1/2(B_{MSY}) \leq B < B_{MSY}$	$B < 1/2(B_{MSY})$
or CPUE	$CPUE_{MSY} \leq CPUE$	$1/2(CPUE_{MSY}) \leq CPUE < CPUE_{MSY}$	$CPUE < 1/2(CPUE_{MSY})$
Fishing mortality (F)	$F \leq F_{MSY}$	$F_{MSY} < F \leq 2F_{MSY}$	$2F_{MSY} < F$
or Catch (C)	$C \leq MSY$	$MSY < C \leq 2MSY$	$2MSY < C$
Age (or length) at first capture (t or L)	$t_{target} \leq t$ or ($L_{target} \leq L$)	$0.9t_{target} \leq t < t_{target}$ or ($0.9L_{target} \leq L < L_{target}$)	$t < 0.9t_{target}$ or ($L < 0.9L_{target}$)
Habitat size (H)	$0.9H_{target} \leq H$	$0.8H_{target} \leq H < 0.9H_{target}$	$H < 0.8H_{target}$
Mean trophic level in catch (TL)	$3.43 \leq TL$	$3.26 \leq TL < 3.43$	$TL < 3.26$
Rate of mature fish (MR)	$MR_{40\%} \leq MR$	$MR_{20\%} \leq MR < MR_{40\%}$	$MR < MR_{20\%}$
Slope of size spectra	$0.10 \leq P$	$0.01 \leq P < 0.10$	$P < 0.01$
Ratio of (released stock abundance)/(wild stock abundance) in catch (Rr/w)	$Rr/w \leq 0.5$	$0.5 < Rr/w \leq 1.0$	$1.0 < Rr/w$

Table 3.A1.1b. Indicators and reference points for the biodiversity objectives used in the Tier 1 IFRAME approach

Indicator	Indicator status		
	Better than target	**Between target and limit**	**Beyond limit**
By-catch rate (BC/C)	$(BC/C) \leq (BC/C)_{target}$	$(BC/C)_{target} < (BC/C) \leq (BC/C)_{limit}$	$(BC/C) > (BC/C)_{limit}$
Discards rate (D/C)	$(D/C) \leq (D/C)_{target}$	$(D/C)_{target} < (D/C) \leq (D/C)_{limit}$	$(D/C) > (D/C)_{limit}$
Mean trophic level of the community (TLc)	$(TLc) \geq 3.25$	$3.25 > (TLc) \geq 2.75$	$(TLc) < 2.75$
Diversity index (DI)	$(DI) \geq DI_{target}$	$DI_{target} > (DI) \geq DI_{limit}$	$(DI) < DIlimit$
Pelagic sp./ Benthic sp. (P/B)	$\lvert (P/B)-(P/B)_{target} \rvert \leq 0.05(P/B)_{target}$	$0.05(P/B)_{target} < \lvert (P/B)-(P/B)_{target} \rvert \leq 0.1(P/B)_{target}$	$\lvert (P/B)-(P/B)_{target} \rvert > 0.1(P/B)_{target}$

Table 3.A1.1c. Indicators and reference points for the habitat objectives used in the Tier 1 IFRAME approach

Indicator	**Indicator status**		
	Better than target	**Between target and limit**	**Beyond limit**
Critical habitat damage rate (DH/H)	$(DH/H) \leq (DH/H)_{target}$	$(DH/H)_{target} < (DH/H) \leq (DH/H)_{limit}$	$(DH/H) > (DH/H)_{limit}$
Pollution rate of spawning and nursery ground (PG/G)	$(PG/G) \leq (PG/G)_{target}$	$(PG/G)_{target} < (PG/G) \leq (PG/G)_{limit}$	$(PG/G) > (PG/G)_{limit}$
Lost fishing gear (frequency, FR)	$FR \leq FR_{target}$	$FR_{target} < FR \leq FR_{limit}$	$FR > FR_{limit}$

Table 3.A1.1d. Indicators and reference points for the socio-economic objectives used in the Tier 1 IFRAME approach

Indicator	Indicator status		
	Better than target	Between target and limit	Beyond limit
Maximum economic yield (MEY)	|L-MEY| ≤ 0.1MEY	0.1MEY <|L-MEY| ≤ 0.2MEY	|L-MEY| >0.2MEY
Income per person employment (IPPE)	IPPE ≥ UIPPE[1]	LIPPE[2] ≤ IPP <UIPPE	IPP <LIPPE
Ratio of profit to sales (RPS)	RPS ≥ URPS[3]	0% ≤ RPS <URPS	IPP <0%
Ratio of cost to sales (RCS)	RCS ≤ URCS[4]	URCS <RCS ≤ 1	RCS >1
Ratio of landing to total supply (RLTS)	RLTS ≥ URLTS[5]	0.5URLTS ≤ RLTS <URLTS	RLTS <0.5URLTS
Employment rate (ER)	ER ≥ UER[6]	0.5UER ≤ ER <UER	ER <0.5UER

[1]UIPPE: Monthly average income of urban working person
[2]LIPPE: Monthly minimum cost of living
[3]URPS: Average % of total fisheries
[4]URCS: Average value of total fisheries
[5]URLTS: Average value of total seafood
[6]UER: average annual ER % of total industries

Table 3.A1.2. Objectives, indicators, and status of indicator relative to target and limit reference used in the Tier 2 IFRAME approach.

Objective	Attribute	Indicator	Indicator status		
			Better than target	Between target and limit	Beyond limit
Sustainability	Biomass	CPUE 1	CPUE data are available and not declining	CPUE data are available, but declining	CPUE data are not available
	Fishing intensity	Restricted access	Fixed access, little latent effort exists ($\leq$30% of licenses inactive)	New entrants can be licensed $>$30% latent effort in fishery	Open access
		Fishery monitoring and sampling	Observer program in place, sampling for all fishery data	Monitoring and sampling for a limited number of fisheries	Negligible monitoring or sampling
		Fishing method	All fishing methods and patterns are evaluated and changes monitored	Fishing methods and patterns are evaluated for main methods and some geographical areas	Main fishing methods and patterns are not evaluated
		Precautionary approach and sensitivity of stock assessment	Adequate stock assessment is provided and precautionary approach is adopted	Inadequate stock assessment is provided, but precautionary approach is adopted	Inadequate stock assessment, and precautionary approach is not adopted
	Size at first capture	Size at entry	$\geq$Size at maturity	$<$Size at maturity, but less than 20% of catch immature	Greater than 20% of the catch immature or size at maturity unknown
	Life history characteristics	Maximum age or age at maturity	Low risk ($<$10, $<$5, respectively)	Medium risk (10-25, 5-10, respectively)	High risk ($>$25, $>$10, respectively)
		Adult habitat overlap with juvenile	Low	Medium	High or no data available
	Management	Management plan for fishery	Management plan is operational and reviewed annually	Management plan is operational, but irregularly reviewed	Management plan is not operational
		Management of IUU [2] fishery	All fisheries are legal and regulated	Some illegal fisheries exist	Little regulation exists

Objective	Attribute	Indicator	Better than target	Between target and limit	Beyond limit
	Recovery	Recovery plan and period for depleted stocks	Recovery plan and period are operational and annually reviewed	Recovery plan and period are operational, but irregularly reviewed	Recovery plan and period are not operational
	Genetic structure	Population structure	Number of spawning populations known and constant	Number of spawning populations known and declining	Number of spawning populations unknown or sharply declining
Biodiversity	Total by-catch	By-catch	By-catches are being monitored and controlled for all fisheries	By-catches are being monitored and controlled for some fisheries	Little monitoring or control of by-catches
	Total discards	Discard	Discards are being monitored and controlled for all fisheries	Discards are being monitored and controlled for some fisheries	Little monitoring or control of discards
	Diversity	No. of species	Decreases in the number of species have not occurred	Decreases in the number of species have occurred in some communities	Decreases in the number of species have occurred in several communities
Biodiversity	Integrity of functional group	Changes in ratio of functional groups in catch	Minor change in relative abundance of species in community	Ecosystem function altered measurably and some important species missing locally	Ecosystem function drastically altered with significant loss of important species
	Gear restrictions and avoidance tactics	Gear restrictions and avoidance tactics for non-target species	Gear restrictions and avoidance tactics operational	Development of gear restrictions and avoidance tactics in progress	Few gear restrictions or avoidance tactics
Habitat	Habitat damage	Impact of fishing gear on benthic habitat	Negligible impact (mid-water, surface fishing gears)	Identifiable impact (bottom fishing gear)	Serious impact (dredges)
		Pollution of habitat	Monitored, and unpolluted	Polluted, but monitoring or recovery plan in place	Polluted, but no monitoring or recovery plan in place
		Lost fishing gear	Sufficient knowledge of type, quantity and location of gear types lost and management plan in place	Type, quantity and location of gear lost during fishing operations are recorded and management plan in place	Little information and no management plan
	Discarded wastes	Discarded wastes	No waste discarded	Some waste retained	Little or unknown quantity of waste retained
	Habitat protection	Gear restrictions or habitat closure	Gear restrictions or closures that avoid damage to critical habitat	Habitat avoidance gear in development or habitat closures planned	No gear restrictions or critical habitat protection

Objective	Attribute	Indicator	Better than target	Between target and limit	Beyond limit
	Habitat recovery	Recovery of physically damaged habitat	Artificial reefs have recovered damaged habitat	Artificial reefs have partially recovered damaged habitat	No recovery
		Recovery of biologically damaged habitat	Seaweed beds have recovered damaged habitat	Seaweed beds have partially recovered damaged habitat	No recovery
Socio-economy	Productivity	Productivity and income trend	Total production and income data are available, and total production and income are increasing	Total production and income data are monitored, and either total production or income is declining	No monitoring for total production and income or both are declining
	Wage	Wage trend	Wages are increasing	Wages are maintained or a little declining	Wages are significantly declining
	Profitability of business condition	Sales trend	Sales data are available and sales are maintained or increasing	Sales data are available and sales are a little declining or little changing	Sales data are not available or sales are significantly declining
		Cost trend	Cost data are available and costs are declining	Cost data are available and costs are a little increasing or little changing	Cost data are not available or costs are significantly increasing
	Market	Imports	Imports data are available and imports are declining	Imports data are available and imports are a little increasing or little changing	Imports data are not available or imports are significantly increasing
	Employment	Employment trend	Total number of fishers data are available and fishers are increasing	Total number of fishers data are available and fishers are declining or little changing	Total number of fishers are significantly declining

[1] CPUE: Catch per unit effort. [2] IUU: Illegal, unregulated and unreported fishing.

Table 3.A1.3. Objective risk indices and species risk index of chub mackerel with F value for 2058

Year of assessment	Risk indices		Fishing mortality (×F_{ABC})								
			0	**0.25**	**0.5**	**0.75**	**1**	**1.25**	**1.5**	**1.75**	**2**
2058	Objectives risk index	Sustainability	0.000	0.022	0.082	0.168	0.298	0.815	1.320	1.624	1.714
		Biodiversity	0.324	0.385	0.462	0.550	0.675	0.741	0.747	0.762	0.777
		Habitat	0.000	0.000	0.000	0.000	0.226	0.445	0.667	0.667	0.667
		Socio-economy	2.000	1.719	1.571	0.816	1.232	1.398	0.769	1.224	1.697
	Species risk index		0.581	0.531	0.529	0.384	0.608	0.850	0.876	1.069	1.214

Table 3.A1.4. Risk scores of bluefin tuna for 2058

Objectives	Indicator	2058
Sustainability	CPUE	0
	Precautionary approach and sensitivity of stock assessment	2
	Restricted access	2
	Fishery monitoring and sampling	1
	Fishing method	2
	Size at entry	2
	Documentation of population structure	2
	Maximum age or age at maturity	2
	Adult habitat overlap with juvenile	0
	Management plan for fishery	0
	Management of IUU fishery	0
	Recovery plan and period for depleted stocks	2
Biodiversity	Gear restrictions and avoidance tactics for non-target species	2
	By-catch	2
	Discards	2
	Number of species	0

	Changes in ratio of functional groups in catch	1
Habitat	Influence of fishing gear on benthic habitat	0
	Pollution of habitat	0
	Lost fishing gear	2
	Discarded wastes	2
Socio-economy	Trend in landing and revenue	0
	Income trend	1
	Profit trend	1
	Costs trend	1
	Import amount	0
	Employment trend	1

Table 3.A1.5. Objective risk indices and species risk index of bluefin tuna by the Korean large purse seine fishery for 2058

Risk indices		**2058**
Objectives risk index	Sustainability	1.250
	Biodiversity	1.400
	Habitat	1.000
	Socio-economy	0.667
Species risk index		1.079

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Chapter 4

Dealing with uncertainty – implications for fisheries adaptation

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This chapter discusses uncertainties related to the impacts of climate change on marine social-ecological systems, with a focus on the management and governance challenges in helping fisheries to adapt.

Four types of uncertainty are identified, relating to observations, models, processes, and the development and implementation of policies. Observation uncertainty occurs due to natural variability and difficulties in making accurate observations. Model uncertainty is due to wrong or incomplete processes being included in the model and to a lack of knowledge of model parameter values. Process uncertainty results from a lack of knowledge of how the system is structured and how it functions and, in the case of social-ecological systems, includes uncertainty over human behavioural responses. Policy uncertainty recognises that policies are not applied perfectly, may be inappropriate for the given situation, and includes difficulties in communicating amongst stakeholders and policy makers.

Expected impacts of climate change on marine ecosystems include changes in species' distributions, changes in their abundance and resulting community compositions, and changes in ecosystem productivity. While global-scale projections of these impacts can be made, their details, in particular at regional and local scales, are highly uncertain, yet people interact with marine systems at these regional and local scales. Human fishery systems already have a number of strategies for adapting to variability and uncertainty in marine ecosystems, including intensification of effort, diversification of species, capacity building, restructuring, and community closure.

Climate change is an additional stress on social-ecological systems, one which may push these systems beyond their "normal" range of variability. This chapter provides fisheries policy makers with recommendations for addressing uncertainty in the marine social-ecological systems.

Introduction

Ocean ecosystems and the people who interact with them for their livelihoods form coupled marine social-ecological systems (Berkes and Folke, 1998). These are complex adaptive systems with feed-back relationships between the biophysical subsystem (also called the "natural" ecosystem) and the human social subsystem (including cultural, management, economic, socio-political, and ethical aspects). They embody an integrated humans-in-nature concept in which the delineation between the two subsystems is artificial (Berkes, in press). Such systems have always responded to changes in both subsystems (*e.g.* Perry *et al.*, 2010a), for example due to environmental variability and the more recent impacts of globalisation (*e.g.* Taylor *et al.*, 2007), but now these systems are faced with the additional uncertainties related to climate change (*e.g.* Daw *et al.*, 2009). This paper discusses uncertainties associated with the impacts of climate change on marine social-ecological systems, with a focus on the issues of adaptation by fisheries.

Types of uncertainty

Uncertainty related to environmental variability and climate change predictions can be separated into four main types:

- *Observation uncertainty* implies that the current state of the system is not completely known. This is due to natural variability on a variety of time and space scales, and to difficulties in making accurate observations.
- *Model uncertainty* recognises that the present models, and modelling capacities, are not perfect. Models may contain incomplete, or wrong, systems and components, or they may miss important components entirely. In addition, there is almost always a lack of knowledge of parameter values and their statistical uncertainties.
- *Process uncertainty* represents a lack of knowledge and understanding of how the system is structured and how it functions and, in particular for marine social-ecological systems, includes a lack of understanding of the interacting effects of multiple drivers of change and human behavioural responses.
- *Policy uncertainty*, in which polices are not applied perfectly or may not be appropriate for the current situation. This can include uncertainty over how the current situation and policies are communicated amongst stakeholders and decision makers (R. Peterman, Simon Fraser University, Burnaby, BC, pers. comm.).

There is a large and growing literature on the potential impacts of climate change to coupled marine social-ecological systems (e.g. Cochrane *et al.*, 2009; Perry and Ommer, 2010). In general, these impacts can be summarised under three topics:

- Changes in species' distributions. As ocean conditions change, and in particular as sea temperatures warm, species are expected to shift their distributions so as to maintain their optimal "adapted" thermal range. Such changes have been observed (Perry *et al.*, 2005) which have good physiological explanations (Pörtner and Knust, 2007). One model of potential range shifts on a global basis predicts average

relocations of 600 km for pelagic species and 200 km for demersal species, with 83% of these moving poleward (Cheung *et al*., 2009).

- Changes in species' abundances. The abundances of species in any particular location or ecosystem are expected to change due to shifts in their distributions, to environmental conditions exceeding physiological limits, and to changes in recruitment (Barange and Perry, 2009). Due to the multiple and interacting factors which control the recruitment to marine populations, such changes can be difficult to predict, including even the direction (increasing or decreasing recruitment, and therefore whether abundances will go up or down with climate change).
- Changes in the productivity of marine systems. This is one of the most difficult of the potential climate changes to predict, because it depends on a number of poorly understood processes such as controls on vertical stratification, nutrient supply, etc. (Barange and Perry, 2009). In general, the expectation is for marine ecosystem productivity to decrease at low latitudes and to increase at higher latitudes (Sarmiento *et al*., 2004; Polovina *et al*., 2008). The responses of wind-driven upwelling systems, which provide a large fraction of the global commercial fish yield, to climate change is particularly uncertain (Barange and Perry, 2009).

There are several factors which complicate the predictions of climate change impacts on marine systems, inducing large uncertainties. These include the downscaling of predictions made at the global scale to their detailed impacts at regional and local scales, and it is these latter spatial scales at which people interact with marine ecosystems. The uncertainties relating to downscaling include the specific effects of winds and how they interact with coastal topography, which have important influences on vertical stratification, nutrient inputs, and circulation patterns; the effects of non-linearities in the system in which, for example, the positive influences of winds on ocean productivity are maximised at some intermediate wind speed (Cury and Roy, 1989); and the potential for threshold effects, in which an apparently small change can push the system from one state to another (e.g. deYoung *et al*., 2008). As noted above, marine communities will be pulled apart and reformed into new communities as a result of different horizontal range shifts, rather than simply being displaced geographically as intact assemblages (e.g. Mueter and Litzow, 2008). Changes in seasonality are also expected, for example the timing of spawning or the peak in biomass of a key species in the ecosystem, which can create mismatches with the timing of dependent species (e.g. Mackas *et al*., 1998). Significant uncertainties in predicting the responses of marine ecosystems to climate changes are created by human actions such as fishing and habitat loss (Perry *et al*., 2010b). These activities can shorten the life spans of species and can cause the loss of sub-populations and genetic diversity, all of which decreases the adaptive capacities of these ecosystems to climate change (Perry *et al*., 2010b; Schindler *et al*., 2010). The strong implication is that marine ecosystems which are heavily exploited will not respond to climate variability and change as they did in the past (Perry *et al*., 2010b). The results of these factors, cumulatively, are increased model and process uncertainties.

Since these are coupled social-ecological systems, it is important to recognise that human drivers of change can also have significant direct and indirect impacts. Direct human impacts include fishing, habitat degradation, contaminants, introductions of exotic species and mineral extractions. Indirect human impacts can be generated by demographic changes (for example, an increase in retired people who drive an increase in recreational fishing), economic changes (for example where fishing may be considered as a livelihood of last resort), market and trade changes (e.g. marine certification programs, Thrane *et al*.,

2009), policy changes, and societal and international agreements (Perry *et al.*, 2010a). The interactions of these factors with "natural" ecosystem drivers of change such as climate create significant uncertainties of how climate change will be manifest at local spatial scales, and how fishing systems will respond.

How do human fishing systems respond to marine ecosystem variability?

Human social systems have developed several mechanisms to deal with variability and uncertainty within their "normal" range of experience, and to adapt to variability beyond their "normal" experience (Smit and Wandel, 2006; Perry *et al.*, 2010a). Coping strategies at shorter time scales and in response to "normal" variability include intensifying effort (*e.g.* to find the few fish that remain); diversifying effort to other gears and species; migrating to follow the distributional changes of the fish; and "hibernation", in which families rely on relatives or the state for support until conditions improve (Perry *et al.*, 2010a). If the change in the marine ecosystem persists or is large (such as a catastrophic collapse of a key stock), then uncertainty is increased because it may represent conditions not previously experienced, which forces the human social system to implement more significant adapting strategies. These include political actions to obtain more support from the state; education and retraining to update skills or for new opportunities; restructuring to reduce reliance on fisheries and marine products; and ultimately, if the collapse continues with no relief or alternative prospects in sight, abandonment of the community (Perry *et al.*, 2010a).

Quinoñes (2010; see also Leal *et al.*, in press) provides an example of the potential consequences of increased scientific uncertainty relating to climate change and fisheries. The jack mackerel (*Trachurus symmetricus murphyi*) stock in the south-east Pacific spawns far offshore of the coast of Chile. In 1997, juveniles dominated the catches, and major uncertainty arose as to whether the signs of stock decline were a result of overfishing or major changes in distribution of the stock due to the strong *El Niño* of 1997-98. In 2001, the Chilean government proposed major cuts in quota, triggering significant social disruption including riots in the streets. The differing scientific views as to the causes of the stock changes contributed to the social unrest (Quinoñes, 2010). This "jack mackerel" crisis, as it became known, was ultimately resolved by formation of a high-level government scientific panel to reach agreement on the abundance versus distribution debate, agreement on the necessary cuts in fishing capacity, and required flexibility in the responses by all sectors (Quinoñes, 2010).

Dealing with uncertainty in marine social-ecological systems

The key point to remember when considering the potential impacts of climate change on coupled marine social-ecological systems is that uncertainty is inherent. Climate change impacts include the current issues of observation, model, process and policy uncertainties, but will go beyond to produce, in many cases, situations for which past ("normal") experience is no longer a guide to future expectations. The question, then, is how are such coupled systems to deal with uncertainty that may go beyond their previous experience? Rather than building a system which is tuned to respond to *predicted* changes, it will be more important, and likely more practical, to enhance the existing capacities of marine social-ecological systems to adjust to variability and uncertainty, regardless of the cause.

This will require enhancing the adaptive capacities of both the human social *and* biophysical subsystems. Much of this existing adaptive capacity, of course, will be based on the conditions which human communities have experienced in the past, and how they have responded. Hamilton (2007) provides an example from Iceland in which one community thrived when fish distributions and abundances changed, because it had developed a broad-based fish catching and processing capability, whereas another community struggled when its primary species declined.

There are several policy options for enhancing the natural adaptive capacities of biophysical subsystems. These include reducing the overall fishing pressure, which would reduce one of the important factors that interact with climate change (Brander, 2008). In addition to reducing fishing pressure overall, an effort should be made to move away from a focus on biomass and to include maintaining the age distribution and life span similar to that of the unfished population as well as maintaining the diversity of sub-populations (Perry *et al.*, 2010b). A better match must be made to adapt fishing and stock rebuilding plans to the productivity conditions, including being alert for new fishing opportunities that may arise from changes in distributions.

There are several policy options for enhancing the adaptive capacities of human social systems to marine ecosystem changes. Many of these will also serve to enhance the capacities to adapt to changes in other sectors of human social systems, since climate change is expected to have multi-sector impacts (*e.g.* to agriculture and forestry). Policies to enhance human social system adaptations to climate change include adopting a livelihoods approach, in which fishing is one of several ways for people to obtain a living (Allison and Ellis, 2001). Such an approach is common among traditional fishing societies (*e.g.* Kalikoski *et al.*, 2010; Cinner *et al.*, 2009) but can also occur in unexpected ways, as for example in Ghana where an increase in the poaching of bushmeat from coastal national parks was observed concurrent with declines in coastal fishing opportunities (Brashares *et al.*, 2004). It is also important to recognise that current policies, for example specific management targets (*e.g.* limit and target reference points), which have been developed from time series during previous conditions, may not be appropriate for the new conditions with climate change. In addition, policies such as subsidies for fishing may retard a fishery from recognising that conditions have changed and from adapting to the changes. Increased uncertainty requires increased monitoring and reporting of environmental conditions (*e.g.* UNEP and IOC-UNESCO, 2009), so as to determine how conditions are changing. Increased uncertainty also requires more active, and more rapid, communications with stakeholders so that discussions about potential changes and how to respond can be worked out in advance, and that observations of new conditions and their implications can be communicated promptly. The U.S. National Weather Service is moving towards a process which explicitly includes uncertainties, and uses these uncertainties in a probabilistic context to assist with decision making (Table 4.1).

Table 4.1. Process proposed for use by the U.S. National Weather Service for explicit consideration of uncertainties in weather forecasts

"Old" paradigm	"New" paradigm based on explicit consideration of uncertainties
Focus only on reducing uncertainty	Focus on reducing and quantifying uncertainty
Single value "most likely" forecast	Most likely value and probabilities of other values
Decisions based only on "most likely" scenario	Decisions based on weighing costs and impacts of each possible scenario
Status quo socio-economic losses due to forecast error	Risk mitigation, socio-economic enhancements due to factor forecast errors into decision making

Source: modified from NOAA, 2009

Additional recommendations for dealing with uncertainty due to climate change include:

- *Observation uncertainty*: invest in monitoring, in particular of the critical components of the full social-ecological system. This means identifying appropriate indicators which include human social and natural ecosystem elements. Good progress is being made in the development of indicators for marine ecosystems (Link, 2005), although similar suites of indicators for human social systems within a marine ecosystem context are not as well developed (*e.g.* St. Martin *et al.*, 2007; deYoung *et al.*, 2008). In addition, statistical modelling could focus on forecasting near-future conditions, rather than making long-term projections for which the errors and uncertainties will compound.
- *Model uncertainty*: develop multiple, and fully coupled social-ecological, models for the same system, preferably with different underlying assumptions and structures. This will lead to an ensemble approach to assessing model predictions, which has proven fruitful for example in the Intergovernmental Panel on Climate Change process (Tebaldi and Knutti, 2007).
- *Process uncertainty*: invest in research to improve understanding of critical processes (and which processes are critical), to identify highly sensitive components and connections, and to identify important processes which are not included in the models.
- *Policy uncertainty*: invest in policy planning with stakeholders regarding how to respond to changes when they happen, monitor the implementation of the policies to ascertain if they are working as desired, and conduct periodic reviews as to whether the policy is still appropriate. Institutional changes may be needed to facilitate rapid responses, including increased flexibility regarding locations and species fished and an ability to alter management plans quickly as information is updated. Learning how to make decisions with reduced knowledge and greater uncertainty is a part of this process, but it must be recognised that each sector in fisheries, from fish catching, to processing, management, and investments (*e.g.* banks) will put their own interpretations on uncertainty relating to climate change, which can lead to conflicting goals (*e.g.* Broad, 2003).

Conclusions

Climate change is but one of many drivers of change in marine social-ecological systems. Fisheries systems have capacities to adapt to uncertainties due to environmental and human variability, which can be enhanced or suppressed by management and policy actions. It is important, therefore, to recognise the inherent uncertainties of observations, models, the underlying processes, and the application of policies. This will require a process of decision making under uncertainty. No matter how good the predictions, however, there will always be uncertainties and, consequently, "surprises". What is needed is to build and enhance the capacities of both the "natural" and human social systems which support adaptation to uncertainty and surprises.

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Chapter 5

Fisheries management and governance challenges in a changing climate

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The paper provides an overview of the key challenges facing the management of fisheries and aquaculture in a world increasingly characterised by a changing climate induced primarily by the anthropogenic emissions of carbon dioxide (CO2). The context of the assessment will be on the open ocean beyond national jurisdiction and on the coastal ocean within exclusive economic zones (EEZs).

The situations faced by large-scale capture fisheries and small-scale coastal fisheries and aquaculture will receive primary attention. The definition of "governance" to be employed is taken primarily from the Food and Agriculture Organization (FAO) Dept of Fisheries website (FAO, n.d.).

Introduction

The focus of the governance concept is the "…exercise of economic, political and administrative authority" and it includes:

- "guiding principles and goals, both conceptual and operational;
- the ways and means of organization and coordination;
- the infrastructure of socio-political, economic and legal institutions and instruments;
- the nature and modus operandi of the processes;
- the actors and their roles;
- the policies, plans and measures that are produced; as well as
- the outcomes of the exercise." (FAO, n.d.)

In this way, the "…overriding principles and objectives of the sector…" are established. Policy and regulatory frameworks are established at all levels, thereby connecting government with civil society and maintaining social order, legitimating the interaction of stakeholders and the enforcement of decisions and regulations. "Finally, it conditions the allocation of power, resources and benefits and maintains the governance system capacity to learn and change" (FAO, n.d.).

The existing literature on this subject since the 1980s shows that there is widespread agreement that the root causes of continued decline of commercially important fish stocks lie in failures of governance. Before an assessment of the large-scale environmental challenges is presented, it is necessary to assess what exactly are the major failures of fisheries governance and what actions are necessary to correct them. Failures of governance antedate the emergence of the current global environmental challenges, so to be effective, policy interventions must respond to both dimensions of the problems facing the management of fisheries within and beyond exclusive economic zones (EEZs).

Following an assessment of the major failures of fisheries governance into the first decade of the 21st century, the paper will focus on identifying and assessing the consequences of large scale environmental change in the ocean and, particularly, what is new about them from the perspective of governance systems for fisheries management. A critical element of this assessment will be a focus on two questions: what elements of traditional governance systems and fisheries management systems must be retained and why? And what new elements and activities must be introduced and why? The penultimate section of the paper will focus on two further questions: how can we assure that having made the recommended changes, governance systems will be able simultaneously to contribute to sustainable and responsible fisheries? And how can fishery policy making and management processes be strengthened, keeping in mind the key elements of fisheries governance and the political economy perspective?

Assessing the major failures of governance in fisheries management

Identifying the major failures

We can take the year 1976 as the threshold for the switch from the rules of a Grotian ocean (freedom of the seas), emphasising limited coastal state authority to manage living and non-living resources beyond a narrow area off its coasts, to the era of extended coastal state jurisdiction out to 200 nautical miles beyond the low water mark. The year 1976 is chosen because this was the year in which the United States Congress passed the Magnuson Fisheries Conservation and Management Act claiming an extended fishing zone of 200 miles. About 50 states followed the US, many of them claiming the broader authority of an exclusive economic zone before the Third United Nations Conference on the Law of the Sea (UNCLOS III) had completed its work.

This turn of events was welcomed by a predominant number of people from coastal states who were involved in exploiting, analysing, and developing policy for the management of fisheries. Natural resource economists were particularly prominent in providing the rationale for vesting property rights in fisheries in coastal states on the basis of the assumption that moving away from the highly decentralised management authority inherent in a Grotian ocean would curb the waste and constant conflict over international fisheries as common property resources (Gordon, 1954; Christy and Scott, 1965, 1972). With respect to the governance exercised by management regimes in this period, the following interpretation of the observational record was provided by Miles:

> *…the key question in the international management of fisheries is always control over the stocks. If the authority to manage is fragmented and participation in the management system is voluntary, with serious constraints on surveillance and enforcement, then biologic waste will be high, conflict will be endemic in the system, decision systems will be cumbersome, decision times will be protracted, and management effectiveness will be low. (Miles, 1993)*

Extended coastal state jurisdiction over fisheries out to 200 miles from the coast, brought into being by UNCLOS III, solved the problem of *fragmented authority* for virtually all the world's demersal, coastal pelagic, and shellfish populations (crustacea and molluscs) and about 60-65% of all pelagic species commercially fished, but it did not solve the problem of failures in national and international fisheries management systems on a global basis. Nor did it solve the problems of fisheries conducted either in the high seas areas beyond the 200-mile boundary or the problems of small scale fisheries within 200-mile zones. Within the EEZ the coastal state establishes the total allowable catch (TAC); decides on its own capability to harvest the yield and whether there is any surplus to be shared; and these decisions, lying at the heart of the discretionary authority of the coastal state, are non-reviewable by any third party. In this way the property rights (sovereign rights) were vested in the coastal state.

So has the *governance* of fisheries management improved dramatically, or even at all, in marine fisheries? While there are individual cases of success, the general answer to the question is a firm no. Why is this so? Because, in large part, *the practice of fisheries management* within the regime of extended jurisdiction has not been applied systematically to achieve the integrated level of fisheries governance as defined by FAO. Aquaculture has grown at the phenomenal rate of 8.8% per year since 1970 (FAO, 2009) and is now a major force in world fisheries production and trade, but it has done so

without the qualitative growth of an institutional infrastructure that can provide mature governance arrangements. Small-scale coastal fisheries also generally face serious capacity problems with respect to management and they are often of low priority to national governments.

The combination of continuing open access conditions on the high seas, combined with maintaining such conditions within EEZs for domestic operations is exacerbated by increasing subsidies for fishing fleets in the face of rising real prices for fish and fish products as a consequence of increases in world population. The result of this set of factors was significant overcapitalisation of the world fishing fleet and significant growth in aquaculture by the early 1990s (FAO, 1992). By 2006 aquaculture has outpaced population growth, emerging as the "…fastest growing animal food-producing sector…" (FAO, 2009). The Asia-Pacific region produces 89% of production as measured by quantity and 77% as measured by value (FAO, 2009). China alone produces 67% of global production in quantity and 49% of value. While the 1970s and 1980s witnessed significantly increasing rates of overfishing, "…the proportions of overexploited, depleted, and recovering stocks have remained relatively stable over the last 10-15 years" (FAO, 2009). In 2007, only 2% of stocks monitored by FAO were underexploited, 18% were moderately exploited, 52% were fully exploited, and 28% were overexploited, depleted, or recovering.

The problem of by-catch

Another serious problem facing fisheries management, which attracted a lot of attention from the 1980s on, has been the problem of by-catch which has many causes. By-catch tends to be wasteful and subversive of fisheries regulation and it can have "…significant consequences for food webs and ecosystems" (FAO, 2009). However, only a crude estimate of 20 million tonnes globally per year has been made. This amount is equivalent to 23% of marine landings (FAO, 2009). So seriously is this issue now regarded that global awareness has grown significantly, to the extent that a large consensus has emerged on the view that "…bycatch should be minimized to levels approaching insignificance" (FAO, 2009). This awareness has produced some serious results, for instance reducing turtle mortalities through expanding the use of excluder devices in the shrimp trawl fisheries. The fact that the United States has made such a policy a requirement for shrimp exports to the U.S. adds teeth to the global consensus against by-catch. Similarly, the promotion of using circle hooks in pelagic longline fisheries has also been a productive instrument in making inroads on the by-catch problem. However, where the species affected are less charismatic "…they remain a source of unregulated and unreported fishing mortality" (FAO, 2009). The campaign against by-catch has also benefited seabirds.

With respect to aquaculture, as demand grows, pushed by a growing world population, and production increases, the organization of the world aquaculture system has changed from one that was primarily market-driven to one which is heavily influenced by official governmental policy. Both the growth in population combined with demand and the consequent growth in production raise serious socio-economic issues for many governments. Consequently, subsidies now play an important role as governments pursue several objectives related to increasing employment, increasing economic growth, increasing a positive balance of payments position, and reducing poverty, *inter alia* (FAO/SOFIA, 2010).

The changing status of world fisheries, 1980-2000

The question of the status of world fisheries was a very contentious subject during the period 1980-2000 in the face of what appeared to be a series of serial depletions of fish stocks around the world. Analysing catch data from 1948-90, FAO (1992) showed declines in the rates of increases in total catch by comparing the 6% achieved in the period 1948-70 with the decline in growth rate to 2.3% between 1972 and 1990, triggered by the decline in the Peruvian anchovetta catch from a high of 12 million metric tonnes to ~2 million metric tonnes. 1990 exhibited the first decline in production since 1976, a drop of about 3%. The growth rate of the 1980s was achieved on the basis of primarily coastal pelagic species, 68% of which were caught in only four regions of the world. However, the growth in the world fishing fleet at the same time did not reflect the constraints and the potential instability reflected in the resource base. That mismatch, among other things, led FAO to declare in 1992 that sustainable development of fisheries "…cannot be achieved under open access regimes, whether they are within or outside EEZs" (FAO, 1992). But by 2008 the FAO *World Review of Fisheries and Aquaculture* noted that "The proportion of overexploited, depleted, or recovering stocks appears to have stabilized at between 25 and 30 percent since the mid 1990s." Even so, FAO also noted that certain thorny fisheries management problems continued. In particular, there had been no notable progress in achieving significant reductions of fishing capacity, curbing harmful subsidies, and matching fishing capacity with sustainable harvest levels.

Not surprisingly, over this same period of time, while the global catch showed some stability in amounts, there was considerable variability in performance at the regional spatial scale. The areas most hard hit were the high seas and EEZs in which coastal state capacity to engage in high order surveillance and enforcement activities was severely limited. Distant water fleets operating in the Southern and Indian Oceans particularly engaged in a substantial amount of illegal, unreported and unregulated (IUU) fishing (Vidas, 2004; Riddle, 2006; Berkes *et al.*, 2006). Berkes *et al* keyed their argument from a socio-economic perspective on a point made by Olson (2000) concerning the emergence of "roving bandits" operating in the commons. Olson's argument was another level down from the economists who had strongly supported the exclusive economic zone as a way of breaking the tragedy of the commons in fisheries, but by taking the argument down to the local level he made the concept equally applicable to internal regions within states as well as behaviour to be observed globally in both EEZs and the high seas.

The point, as summarised by Berkes *et al.* is that "…local governance creates a vested interest in the maintenance of local resources, whereas the ability of mobile agents [called "roving bandits" by Olson] to move on to other, unprotected, resources severs local feedback and the incentive to build conserving institutions". In the context of a global market powerfully supported by the new IT, new markets can develop rapidly in fisheries to the point where they induce serial depletions, defined as "…the spatially expanding depletion of harvested species" (Berkes *et al*., 2006). In this way, "…spatial expansions masked regional depletions", resulting in highly altered ecosystems.

The biological argument about serial depletions was made by Pauly *et al.* (2002) at the end of two decades of persistent overfishing. They characterised the pattern of large, industrial distant water fleets operating in the high seas and EEZs in which surveillance and enforcement were scarce "… fishing down marine food webs…" involving serious effects on ecosystems targeted. These effects included: the gradual removal of large, long-lived fishes; such removal often facilitates increases of previously suppressed species not all of which can safely be eaten by humans; and the simplification of food

webs by "…reducing the number and length of pathways linking food fishes to the primary producers…", which, in turn renders the remaining biomass strongly dependent on annual recruitment. Essington *et al.* (2006), on the other hand, provide a more complex perspective on the "fishing down the food web" argument. This is an important contribution because it leads to different policy prescriptions from those espoused by Pauly *et al.*

Essington *et al.* argue that there are two pathways through which fishing down the food web could occur. The first is identical to the single pathway adopted by Pauly *et al*., *i.e.*, through "…sequential replacement of high-value, upper-trophic-level species with less valuable lower-trophic-level species…." The other pathway is through "…the sequential addition of lower-trophic-level fisheries within an ecosystem." Essington *et al.* make the case quantitatively that while the first type of pathway is predominant in the North Atlantic, the second type is characteristic of the rest of the world, particularly the southern hemisphere. From a policy perspective Essington *et al.* point out that while the second type does not call for the dramatic interventions of the first, its consequences are also very difficult because it leads to development of fisheries which demand different ecosystem services. Governments, however, do not have a good record of making effective decisions when faced with difficult trade-offs between user groups.

The last major failure of governance in fisheries management to be discussed concerns the UN Code of Conduct for Responsible Fisheries (1995). The United Nations Conference on Environment and Development (UNCED) of 1992 devoted considerable effort to the management of the oceans in Chapter 17 of Agenda 21. With respect to fishing, there was great urgency attached to these efforts as a result of the intense period of serial depletions which had been experienced during the 1980s. As a result of those experiences, FAO was deeply involved in stimulating the development of both "soft" and "hard law" on the gaps that had emerged in the UN Convention on the Law of the Sea with respect to fisheries. The principal problems here were, first, the unfinished business of UNCLOS III relating to the management of straddling stocks and highly migratory fish stocks. These two issues were joined and an international (hard) law-making conference was convened by the United Nations on those two problems. The outcome of that conference was a treaty, which is focused on the implementation of provisions of the UN Convention on the Law of the Sea of 1982 (LOSC). This treaty is commonly known as the UN Fish Stocks Agreement (UNFSA) of 1995 (Meltzer, 2009). Even earlier, the FAO was hard at work on the issues of flag state responsibility for the control of their fishing vessels operating on the high seas. This agreement was completed in 1993 and entered into force on 24 April 2003 (Meltzer, 2009). This agreement is more commonly known as the FAO Compliance Agreement. The last part of this package of law-making is the result of another FAO initiative in the "soft" law category called the Code of Conduct for Responsible Fisheries, completed in 1995 and made part of the FAO Compliance Agreement. All of these instruments were targeting the operations of unregulated vessels on the high seas. The Code, in particular, sets minimum standards for achieving responsible fisheries in response to urging from the UNCED Conference of 1992.

The question to be raised here is to what extent has the Code actually increased compliance with its principles? Pitcher *et al.* (2009) have provided a quantitative evaluation of the performance of 53 countries accounting for 96% of the world catch (based on catches reported in 1999) and they find "dismayingly poor compliance". No country achieves a score in the "good" category. "Only six countries have overall compliance scores whose confidence limits overlap with 60% (Norway, the United States, Canada, Australia, Iceland and Namibia" (Pitcher *et al*., 2009). Countries scored worst on

the following items: "…introducing ecosystem-based management, controlling illegal fishing, reducing excess fishing capacity, and minimizing bycatch and destructive fishing practices." With respect to controlling illegal fishing practices, the major advances in law-making have together virtually done away with the status of fishing on the high seas as a traditional freedom of the sea. All high seas fishing is now subject to the authorisation of the flag state; the flip side of that achievement means that illegal activities of fishing vessels on the high seas are state failures or lack of capacity or will to control such activities.

The new challenges facing fisheries governance, fisheries management and aquaculture in the twenty-first century

Multiple stresses: global population growth and changing patterns of coastal land use

There is already a very large literature on the first new challenge to fisheries management on a global scale, which is a step-level increase in the scale of the multiple stresses problem combining high levels of overfishing with massive human development of the coastal zone. At its base, this problem is a combination, once again, of rates of population growth plus unsustainable land use patterns of human settlement. This problem had been tracked collectively by the inter-agency Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) sponsored by the International Maritime Organization (IMO) for some time (GESAMP, 1990, 1991), but also individually by FAO (FAO, 1992) and UNEP (2006, 2008) (which are also members of GESAMP). What is new about this driver of change is an understanding that, by 2050, world population is projected to be about 9 billion people, as compared to 6.3 billion in 2003, and to stabilise at somewhere between 11-12 billion people by 2100 (Cohen, 2003). Those rates of increases, from 29.2% to 42.7%, represent a massive increase in one of the principal drivers of unsustainable demands on the planetary biosphere. UNEP (2008) catalogues what the observable effects are at the present time: 60% of the waste water discharged into the Caspian Sea is untreated. The comparable estimates for Latin America, the Caribbean, and large parts of Africa and Indonesia is 80-90%.

The poor management of sewage represents significant threats to both human social systems and marine ecosystems in the coastal zone. So far, it has not been possible to achieve effective control over this problem. In addition, human actions trigger "…oil spills… heavy siltation, eutrophication (nutrient enrichment), invasive species, persistent organic pollutants (POPs), heavy metals from mine tailings and other sources, acidification, radioactive substances, marine litter, overfishing and destruction of coastal and marine habitats." (UNEP, 2008). Of all of those adverse impacts on the global marine environment, only the discharge of POPs has been reduced substantially. UNEP (2008) also projects that, by 2050, 91% of all coasts in the tropics and in the temperate zone will be inhabited and that this will lead to major increases in marine pollution, more than 80% of which will be land-based. Moreover, the number of "dead zones" (hypoxic areas deficient in oxygen) in the world ocean has already increased from 149 in 2003 to more than 200 in 2006. The massive increases in projected human population by 2050 and 2100, which have been described above, will make this problem much worse.

Land-based pollution of the global ocean is by itself a super-driver of multiple stresses on the marine environment, on marine ecosystems, and on the provision of

ecosystem services from both terrestrial and marine ecosystems. But land-based pollution of the coastal ocean has now been joined by two other super-drivers: changing ocean thermal structure and increasing acidification of the world ocean. There are then three super-drivers of change acting simultaneously and synergistically at all scales: global, regional, national, and local. Multiple stresses, not even of this magnitude, produce both different magnitudes of change and changing rates of change of varying intensities at different scales. Socio-political systems experience great difficulty in responding appropriately to both the magnitude and varying rates of change. Confronting three super-drivers simultaneously, therefore, constitutes a tremendous challenge.

Global climate change

Global climate change is a problem of long timescale that must be defined in terms not only of the amount of carbon dioxide (CO_2) and other greenhouse gases released by humans, marine and terrestrial ecosystems, but also of the timescales of residence of these gases in the atmosphere and the timescales of the global carbon cycle. The latter are determined by the exchange between the atmosphere and the ocean. Under these conditions, all policy measures will be indeterminate in their ultimate impacts, and indeterminacy, when linked to issues of costs, changing lifestyles, and distributive inequities, creates large obstacles to significant short-run policy action. When the timescale of nature runs the gamut from seasonal inter-annual variability through decadal to centennial and even millennial timescales, the assumptions and procedures of benefit-cost analyses always tend to discount the future very heavily beyond two decades.

The conclusions of the Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC, 2007) can be summarised briefly as follows:

- Global atmospheric concentrations of CO_2 , methane, and nitrous oxide have increased markedly as a result of human activities since 1750, to a level far surpassing pre-industrial levels. The drivers of the CO_2 concentration are principally anthropogenic fossil fuel use and land use change. This level of carbon dioxide has been the highest at least in the last 650 000 years.
- There is very high confidence (= 9/10 chance) that it is the greenhouse gas increase that results in the observed planetary warming with a radiative forcing of 1.6 watts per square meter. That estimate is embedded in a range of uncertainty of +0.6 - + 2.4 watts per square meter.
- This warmth in the last half of the 20th century is unusual in at least the previous 1300 years.
- For the next two decades, the IPCC projects a warming of 0.2° C per decade.
- Sea level projections do not include the full effects of changes in ice sheet flow because the basis for such a judgment in the published literature is lacking.
- It is very likely that hot extremes, heat waves, and heavy precipitation events will become more frequent.

What then are the policy implications of these conclusions? First, that unless states can agree quickly on a series of measures to reduce the anthropogenic rate of carbon dioxide emissions, the consequences initially will be experienced in faster and larger magnitudes of change. These consequences, in turn, raise questions about feedbacks in

the planetary climate system, non-linear change, and tipping points for both the climate system and natural ecosystems according to their different dynamical modes. Secondly, most of the non-linearities are probably not predictable, so most of the analytical effort should go towards understanding where the thresholds or tipping points are. These should then constitute the core of risk assessment and risk management approaches to be adopted. Thirdly, each of the major stresses needs to be tackled separately while at the same time trying to identify their interconnections and the synergies between them. Population growth is an especially powerful and multivalent driver, which spins off severe questions about urbanisation, demands on energy and environmental security. These, in turn, touch questions relating to food supply, water supplies, public health, pressures on the poorest states, migrations, and societal instabilities.

Thresholds are important because the rate of growth in carbon dioxide emissions appears to be greater than has been expected. At a concentration level of 380 parts per million by volume (ppmv) of carbon dioxide in the atmosphere, a very substantial increase of heat in the surface and subsurface heat of the oceans was detected (14.5×10^{22} joules) (Levitus *et al.*, 2000, 2005). Significant decreases in pH (or alkalinity) were also detected at about the same period in time (Feely *et al.*, 2004; Sabine *et al.*, 2004). Both of these stressors acting together would dislocate marine ecosystems at many trophic levels and they would combine again with overfishing to deliver a "triple whammy" of multiple stresses. As carbon dioxide concentrations increase in the atmosphere, it is not yet known precisely if and at what point the uptake of carbon by oceanic and terrestrial sinks would begin to slow down and whether large sinks would become large sources. There is, though, considerable consensus in the literature concerning the increased probability of extremes of both hot and dry and cold and wet episodes. It is clear that precipitation events are increasing in both frequency and intensity and that the intensity, though not the frequency, of hurricanes and typhoons is increasing (Emmanuel, 2005; Webster *et al.*, 2005). These developments, combined with the occurrence of sea level rise, do raise serious questions about coastal hazards, which include coastal erosion and the destruction of wetlands and other coastal marine habitat. Coastal hazards combine with all the effects of land-based pollution to subject coastal marine ecosystems to even more severe levels of stress.

Determining what elements of traditional governance systems should be retained and what new elements introduced

So what elements of traditional governance systems must be retained and why in the context of these new super-drivers of change and what new elements need to be introduced and why? Because the super-drivers generate large-scale effects which cut across bureaucratic sectors and wide ranges of human activities, it is imperative that the "…exercise of economic, political, and administrative authority", that is to say governance, become more integrated. Managing coastal ecosystems and coastal development are not separate activities any more, if they ever were. Ecosystem management and coastal development must be merged because the latter can destroy the former and, in the face of a growing population, fisheries production will become a critical component of food security for states. The objectives, policies, and plans and the ways and means of organisation and co-ordination of fisheries management must be changed to be more appropriate to respond to the challenges that must be faced.

One way of combining ecosystem management with coastal development is by the adoption of marine spatial planning as a critical tool with high potential payoff for

effective management (Young *et al.*, 2007). A focus on place-based management, particularly on regional to local scales is a prerequisite for effective use of marine spatial planning. This constitutes a significantly broader approach than just concentrating on ocean zoning because it is both comprehensive and integrated. The criteria of success in performance include a heavy emphasis on adaptive management, which is defined here as a capacity "…to monitor changes closely, adjust existing practices to changing circumstances, and cope with relatively high levels of uncertainty." (Young *et al.*, 2007). Adaptive management must be able to observe feedback between decisions taken and implemented and system responses. System responses go beyond the effect of decisions to include natural variability and external forcing (Young *et al.*, 2007; Bottsford *et al.*, 1997). It is expensive to acquire the capacity to monitor changes at that level, but costs can be minimised through a reliance on place-based management (Young *et al.*, 2007).

The capacity of states to manage fisheries must be developed so that they are able to engage in precautionary ecosystem management. Ecosystem management begins with increasing our understanding of planktonic ecosystems as the components of net primary productivity (NPP). But, we should note fish production is only weakly related to NPP because the variability in both the number of trophic steps and the transfer efficiency is considerable (Brander, 2007). That variability is important for the ways in which precautionary ecosystem management is likely to develop. The focus will be on specific communities, stock complexes, and the ecosystem services they deliver. Planning will therefore have to develop in an explicitly spatial fashion, with all the detail derived from the specific locations of interest along with their characteristic physical, chemical, and biological signatures treated in an integrated fashion, and with patterns of variability appropriate to that place. Human societal connections will have to be built in as well to link what is being done in the marine environment to operations of fishing fleets, aquaculture production, and trade in fish and fish products in specific places. Simply said, "[g]overnance systems in such dynamic settings must pay particular attention to avoiding spatial and temporal mismatches,. They must be responsive to local conditions but also pay attention to large-scale processes….Similarly, they must be sensitive to sudden shocks…while keeping track of long term factors…."(Young *et al.,* 2007).

The points made above clearly indicate that major changes are required in patterns of governance in fisheries management, particularly so because the growth in demand for fish and fish products has tightened the links between capture fisheries and aquaculture. Given the driver of population growth, there is a looming question whether at some point in the growth of aquaculture production, there will be a clear trade-off between increasing such production further versus maintaining and/or increasing production from capture fisheries. The link here is created by the size and age structure of individual species demanded by their respective markets and the question is whether increasing the take of forage fish to make food for aquaculture will produce adverse consequences for larger size adults which are the prime targets of capture fisheries. Furthermore, Brander (2007) makes the point that "[f]ishing is the greatest threat to future fish production" because it changes both the size and age structure of the population, which results in greater variability in annual recruitment. Changing both of those effects makes fish populations more sensitive to climate fluctuations. The rule he derives from this condition is that sustaining the resilience of fish populations requires that we seek to preserve their age and geographic structure rather than manage only their biomass. Such a shift in management objectives would be another major change in governance.

We do not underestimate how difficult it will be to achieve such changes. Recall one of the conclusions of the FAO (2008) that to date there has been no notable success in

achieving significant reductions of fishing capacity in the world fishing fleet, in curbing harmful state subsidies for building larger fleets, and in matching fishing capacity with sustainable harvest levels. We note too the most important failures of state signatories to the FAO Code of Conduct for Responsible Fisheries. The standards most frequently not upheld include: introducing ecosystem-based fisheries management, controlling illegal fishing, reducing excess fishing capacity, and minimising by-catch and destructive fishing practices (Pitcher *et al.*, 2009). In addition to the above, fisheries governance as a system must develop the capacity, and therefore the flexibility, to manage adaptively for long-term sustainability (Levin and Lubchenco, 2008). Such a capacity includes as a prime objective maintaining functionality in the face of disturbance in the ecosystem by managing both short and long-term timescales over spatial scales of varying magnitude.

Seeking a classification of broad groupings of strategies that would apply to all states, those with high adaptive capacity, and those with low adaptive capacity, Johnson and Welch (2010) provide a most useful contribution in the taxonomy shown as Table 1 in Appendix A to their paper. The details of this table indicate specific directions in which systems of fisheries governance should change for the three classes of states. Specification of the new directions will be provided later in this paper. Though this table is arrived at from a different direction, the recommendations conform to all the others, which have been mentioned above. This is evidence for a growing consensus at the global level on the nature of the paradigm shift that must be made in fisheries management.

Changes in aquaculture

With respect to aquaculture, let us return to its institutional immaturity as pointed out by FAO (2009) and Smith *et al.* (2010). It was born and grew up in a private sector culture dominated by for-profit incentives in a highly decentralised context. Seafood for the export trade dominated the business in countries that were undernourished for animal protein intake. In countries that were not undernourished, like the US, Canada, EU countries, Australia, and New Zealand, effective governance systems developed. But elsewhere, the combination of high undernourishment combined with weak governance structures led to serious problems (Smith *et al.*, 2010). Smith *et al.* assert that the global situation of aquaculture is precarious because external problems ("…a tight coupling to ecosystems combined with dependence on common-pool resources"), a high vulnerability to exogenous shocks, and poor management threaten its long-term future. These challenges are exacerbated by internal problems like poorly defined property rights, seriously adverse environmental effects, and inadequate controls on disease.

How can we assure that, with the changes being made, governance systems will be able simultaneously to contribute to sustainable and responsible fisheries and to aquaculture? How can the fishery policy-making process be strengthened, keeping in mind the key elements of fisheries and the political economy perspective?

The questions posed above are big questions about apparently intractable problems. Rather than thinking about solving problems completely, the questions stated above ask us to think about making progress in the form of contributing to sustainable and responsible fisheries and aquaculture. This is within the realm of possibility because, in the face of big problems – overfishing, achieving significant reductions of fishing capacity, curbing harmful subsidies, and matching fishing capacity with sustainable

harvest levels – there are now modest hopeful signs. We are ten to fifteen years away from the serial depletions of the late 1970s to the late 1990s. In a significant number of regions, not only has the rate of stock declines been stabilised, but there is evidence of rebuilding of stocks based on new learning about management approaches, including the design and use of new "tools" of management (Worm *et al.*, 2009, especially Table 1, p. 583). The picture presented in the latest assessment of world fisheries completed by Worm *et al* (2009) compares well with the earlier assessment presented by FAO in 2008. This time, amongst the gloom of the trends of the global assessment, there are hopeful signs of stability and rebuilding in a number of regions/countries in the world ocean. In other words, scale matters a lot relative to the picture one gets.

The authors argue that reducing the exploitation rates of fish stocks is the most effective tool one can apply to reduce total allowable catches and that this result has been achieved in the Bering Sea/Gulf of Alaska, in the North Sea/Celtic-Biscay region, in Iceland, the South-East Australian Shelf, and in New Zealand. Total fishing effort has been reduced only on the North-East US Shelf but closed areas have been the tool of choice in the California Current. Catch shares have been an essential tool in the Bering Sea/Gulf of Alaska, Iceland, the South-east Australian Shelf, and in New Zealand, while community co-management has been the most effective management tool for the artisanal fisheries of Kenya, Chile, and Mexico. Gear restrictions have been another essential tool for the artisanal fisheries of Chile and Mexico and an important tool in the artisanal fishery of Kenya, and on the Northwest Australian Shelf. Finally, capacity reductions have been an important tool in the Bering Sea/Gulf of Alaska, the California Current, and the North-East US Shelf. While the effectiveness with which one can use these management tools will vary with "…the local characteristics of the region, ecosystem, and governance system (Worm *et al.*, 2009), the authors emphasise that "…[r]ealigning economic incentives with resource conservation…is increasingly recognized as a critical component of successful rebuilding efforts. These rebuilding tools of management are quite compatible with a new trend of management which combines ecosystem-based management embedded within a comprehensive marine spatial plan for a particular region in the world ocean as discussed above.

With respect to the development of aquaculture, the FAO is quite explicit and detailed about the changes that appear to be necessary. Similar changes are also suggested by Smith *et al.* (2010). For entrepreneurs, "good governance" would involve drafting a legislative framework, which, among other things, ensures property rights, and is explicit about licensing, monitoring, and control. Regulations need to be administered transparently and the processing of licenses should be rapid and equitable. Self-regulation through voluntary codes of practice should also be encouraged but there should be governmental regulations which deal with planning and access , with water and waste water, seed, feed, investment and fish movement for purposes of disease control. It may sometimes be necessary to quarantine brood stock, but at all times environmental sustainability and social responsibility should be emphasised (FAO, 2009). No system will work effectively unless there are skilled government personnel with adequate financial resources to monitor and enforce the legislation and the regulations that flow from there (FAO, 2009). Some important regulation will also come from outside the national system. One example is the development of a ban on subsidies, which contribute to overfishing and overcapacity, by the World Trade Organization (WTO). Regional trade agreements are another source of external regulation.

For fisheries as well as for aquaculture, setting out a design for change to enhance prospects for sustainable development is one thing. Implementing that design is usually a

very difficult hurdle to get across. One idea that has been developed by Grafton *et al.* (2007) has been called "Benchmarking for Fisheries Governance." The five core components of the approach recommended by Grafton *et al.* include: "…accountability, transparency, incentives, risk assessment and management, and adaptability". The framework is at the same time a *de minimis* list of things a management system must do and a capability it must develop to keep abreast with dynamic changes in the populations and fisheries for which it holds the management responsibility. This approach then breathes life into FAO's definition of governance quoted at the beginning of this paper. The authors make the point quite clearly: "Fisheries governance involves two key challenges. The first is the need to understand the current state of the world, and especially the principal feedbacks of fisher and ecosystem dynamics. The second is the necessity to translate this knowledge into effective governance to achieve biological, social, and economic goals (Grafton *et al.*, 2007)." They begin with the precautionary principle, but make clear its constraints. This elaboration is then linked to the issues of reference points and target reference points in fisheries management. The latter will fail unless they are connected to instruments, or decision and management tools for realising stated goals and objectives. They go beyond that to "…explain why incentives-based approaches alone cannot resolve the challenges that hinder effective fisheries governance".

The authors begin with an analysis of the ways in which substantial uncertainties about the status of particular stocks constrain the achievement of target reference points. As a result, it is often the case that political and/or economic forces push allocation decisions to be at higher levels than they should be. The authors wish to infer a larger point from this discussion, which is: "…without structural change in how fisheries are governed the precautionary principle, by itself, will fail to present risk-prone decisions". The use of fixed reference points is not recommended either since they may lead to unnecessary caution in management decisions or they do not really remove all elements of qualitative judgments and discretion from managing fisheries. The authors argue that reference targets do not represent, by themselves, the major failures in fisheries management. The source of the major failures lies in ineffective instruments which are used to achieve stated goals. Instruments must be appropriate to fisheries in particular places but they also need suitable targets. Suitability is a judgment to be derived only from the study of a comparative universe of examples. Incentives are important here, even if they are not THE key to success. Incentives provide a mechanism by which "…fishers' interests become closer aligned to societal objectives, such as sustainability (Grafton *et al.*, 2007). "Sustainability as an objective of fisheries management can be achieved if there is effective governance and oversight, incentives-based approaches, and a shift to ecosystem approaches to fisheries management (EAF) embedded within marine spatial management."

Given the complexity of this approach, the real issue is: "…how to effectively manage uncertainty and connect higher level goals, such as ecologically sustainable development (ESD), to day-to-day management decisions". The benchmarking approach posits the achievement of resilient marine ecosystems and sustainable fish stocks as the overriding objective and managers must be accountable for judgments about uncertainty, risk assessment, and risk management. Accountability requires performance indicators at various levels, a bottom-up managerial approach, and full transparency at all levels. Finally, to be resilient in the face of change requires adaptability, which, in turn requires institutional flexibility. These qualities must also be infused with the understanding that

management actions should differ across fisheries in terms of their "…current state, history, level of exploitation, and institutional capacity…" *inter alia.*

Summary and conclusions

The elements of traditional governance systems in fisheries management that should and will be retained relate to the regulatory and assessment infrastructure used to establish total allowable catches, gear restrictions, closed areas and the like. However, the focus must shift from individual species or species groups to whole ecosystems. Economic incentives must not only be retained but must grow. Individually transferable quotas as a means of arriving at catch shares have proven to be a powerful tool for effective fisheries management. What has to change is the approach to designing fisheries governance systems. There is widespread agreement among the community studying these problems in a large number of countries that the present pattern of fisheries governance has largely failed. The major failures include: the lack of controls over domestic fishing effort, counterproductive subsidies leading to severe overcapitalisation of fishing fleets, a widespread inability to match fishing effort dynamically to sustainable harvest levels, and generally inadequate management infrastructure. How then shall we do better? What new approaches and techniques must be introduced and why?

Let us first answer why we must do better now. The traditional super-drivers of world fisheries have been only two large forces: global population growth, with its effects on the growth in demand for fish and fisheries products, and land-based pollution of the coastal ocean, with its adverse impacts on habitat in particular. We have not done a good job of responding to these two drivers. Now, however, we are faced with three more drivers which are derivatives of the combination of population growth and the growth in industrialisation fuelled by fossil energy. The three new super-drivers are: the large and increasing magnitudes of CO_2 emissions as a function of economic growth, changing ocean thermal structure, and increasing acidification of the world's oceans. Confronting these new challenges is a major hurdle in any respect, and particularly so in fisheries with the serious difficulties it already faces. For developing countries with limited infrastructure and capacity to manage, this combination of forces presents an almost insuperable difficulty. A survey of the literature which has emerged over the last two decades leads one to conclude that fisheries management has to become more integrated, given the larger global environmental challenges we now face. There must be strong links between coastal development planning on the terrestrial dimension and coastal fisheries development and management. The focus on fisheries management in all areas is increasingly seen as combining ecosystem-based management embedded in marine spatial planning. This planning must be place-based and there appears to be a tendency to focus on the regional spatial scale as the most appropriate one. Above all, the need to develop flexible response capacity demands learning of suites of strategies which facilitate adaptive management.

Growth in demand for fish and fish products has tightened the links between capture fisheries and aquaculture. Aquaculture has to be managed and regulated to achieve sustainable harvests in both areas. Johnson and Welch (2010, Table 4), outline the ways in which fisheries management has to change in terms of three classes of requirements. In the broadest class, and applying to all states, the "must do" strategies are preserving age structures of commercially fished populations across their geographic ranges; facilitating the learning of flexible, adaptive management; integrating social, economic, and ecological values into all fisheries; adopting a long-term outlook; and reducing

overcapacity. For states with moderate to high capacity, their additional responsibility is to adopt precautionary catch and/or effort quotas and engage in differential management for different ecological roles. The authors admit that the former requirement requires a shift in the management paradigm. For states with low adaptive capacity, the authors recommend: building social and economic resilience; diversifying fishing strategies to multi-species utilisation; facilitating greater access to markets; promoting flexible livelihood strategies; facilitating institutional change (*e.g.* higher levels of community co-management); and seeking adequate implementation assistance.

For all categories, the authors suggest that they take advantage of a growing interest in rebuilding stocks and seeking sustainability. Again they note the growing consensus on combining precautionary ecosystem management in place-based systematic marine spatial planning. Aquaculture requires more attention to be paid to designing good governance systems. Characteristics of mature systems have already been noted in terms of the FAO's advice referred to earlier in the text. For both capture fisheries and aquaculture, they require not only flexible management systems, but also system components that can learn from experience and adapt lessons learned to a changing reality. Finally, authorities need to be able to control management systems to the point of implementing strategies which have been decided. For this to happen, one needs a monitoring capability and capacity for evaluating performance effectiveness dynamically. Grafton *et al.* (2007) demonstrate what such a capability consists of by use of a framework for "benchmarking" fisheries governance. This framework is based on six criteria: accountability, transparency, incentives, risk assessment and management and adaptability.

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Chapter 6

Is the current fisheries management toolbox sufficient to address climate change?

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This report is presented in response to the request by the Fisheries Committee of the OECD as a submission to the international workshop on "The Economics of Adapting Fisheries to Climate Change" to be hosted the OECD Committee for Fisheries and the Fisheries Policies Division and held on June 10-11, 2010 in Busan, Korea. The workshop addresses what fisheries policy makers should do in order to develop adaptive and flexible fisheries management regimes to the changing climate and help the transition of fishing industries and communities.

This paper examines current fisheries and aquaculture management methods and their strengths and weaknesses, successes and failures with dealing with the potential risks and pressures posed by climate change. The paper also addresses how fisheries management deals with uncertainty in planning fisheries management strategies and examines management responses to climate change threats and impacts. Finally, the paper discusses fisheries management methods alignment to adapt to pending climate change.

The paper concludes that what is required is an evolving, responsible, and resilient fisheries management system that establishes a contextual and participatory governance framework characterised by flexible, and adaptive operational and strategic decision making. Decision support tools featuring operational targets and decision rules are presented to illustrate adaptive fisheries management.

Introduction

Signs of the changing climate are increasingly visible and the trends are undeniable. Rising temperatures are melting polar ice and together with thermal expansion of water are contributing to sea level rise, changing precipitation patterns, more frequent intense weather events, storm surges and flooding, coastal erosion, increased sedimentation of coastal waters, and pollution from flooded or destroyed infrastructure and storm runoff (IPCC 2007a, 2007b; IISD, n.d.; FAO, 2007; UNEP, 2008).

In capture fisheries and aquaculture, climate change impacts are evident by changes in the aquatic ecosystem, including swings in primary productivity, species interactions and predator-prey relationships, spatial and abundance shifts in stock distribution through changes in recruitment, growth rate and natural mortality rates. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change States that with "high confidence" changes will occur in marine biological systems due to rising water temperatures affecting shifts in pelagic algae and other plankton, and fish abundance in high latitudes (IPCC, 2007a). Migratory patterns of stocks are expected to alter due to modified seasonality of marine and freshwater systems. Traditional fisheries and fisheries management in this shifting system need to be similarly adjusted thereby incurring increasing costs for administration, science, monitoring and observation systems as well as rising uncertainty and input costs to the commercial fisheries. These aggregate changes as a result of the changing climate are expected to increase in intensity in the coming decades of the 21st century (Grafton, 2009; FAO, 2008a, 2008b, 2007b).

As is noted in the *State of Fisheries and Aquaculture* report for 2008, increasing energy and food prices as well as the threat from climate change mean that

The conditions for capture fisheries and aquaculture are changing. That said, the combined effects of rising prices and climate change are complex, and they affect a very large number of fisheries and aquaculture operations in a mosaic of natural, social and economic contexts. Hence, it is too early to have a clear understanding of the cumulative impact worldwide on fisheries and aquaculture. (FAO, 2009, foreword)

Considerable analysis had been done to analyse the potential impacts on fisheries and aquaculture systems due to pending climate change. Studies include:

- PICES International Symposium on Climate Change Effects on Fish and Fisheries*:* Forecasting Impacts, Assessing Ecosystem Responses, and Evaluating Management Strategies, April 25-29, 2010, Sendai, Japan.

- U.S. National Research Council of the National Academies of Sciences Report on *America's Climate Choices* (May 19, 2010 release), Washington DC.

- Special Issue of the *Journal of Marine Systems* on the Impact of climate variability on marine ecosystems: A comparative approach, February 2010, Volume 79.

- Royal Swedish Academy of Agriculture and Forestry Report on *Fisheries, Sustainability, and Development*, October 13, 2009.

- North Pacific Climate Regimes and Ecosystem Productivity (NPCREP) program, Bering Sea Ecosystem Study (BEST), Northeast Pacific Program (NEP), June 2009 involving PICES, USA, Korea.

- The Institute of Public Works Engineering Australia (IPWEA) National Conference on Climate Change: *Responding to Sea Level Rise*, IPWEA (2008), Coffs Harbour, New South Wales, 3-5th August 2008.

- U.S. Global Ocean Ecosystem Dynamics Program (GLOBEC) and GLOBEC International, Integrating Climate and Ecosystem Dynamics in the Southern Ocean, July 2008.

- High-Level Conference on World Food Security: the Challenges of Climate Change and Bioenergy at FAO headquarters in Rome from 3 to 5 June 2008 and the Expert Panel 7-9 April 2008.

- PICES 2008 Workshop, Forecasting Climate Impacts on Future Production of Commercially Exploited Fish and Shellfish on July 19–20, 2007, in Seattle, USA.

- The Fourth Assessment of the Intergovernmental Panel on Climate Change, AR4, (IPCC, 2007a, 2007b); AR5 pending release (IPCC, 2013).

Despite this extensive body of mainly scientific work, uncertainties persist and implications have not been made yet at the local, operational level for managing fisheries. Coastal communities, for example, have not developed effective means to mobilise people, institutions, and commercial enterprises – notably the fisheries and aquaculture sector – to prepare for warming, increased storm frequency and sea level rise in order to adapt to the pending changes and impacts to the coastal zone and production.

Fisheries management plays a crucial role in adapting fisheries and aquaculture to the changing climate of coastal communities. Effective fisheries management systems are characterised as being adaptive, flexible, and participatory. Effective fisheries management decision making under uncertainty is based on precautionary and whole ecosystem approaches to problem solving taking into account multiple stakeholders and the multiple criteria of ecosystem, social, economic and administrative consequences. The challenge of developing and assessing policy options and operationalising strategies represents the real challenge for adaptive fisheries and aquaculture management at the local community, regional, and national levels.

Against this background, the OECD Committee for Fisheries and the Fisheries Policies Division presented the international workshop on "The Economics of Adapting Fisheries to Climate Change" to address what fisheries policy makers should do in order to develop adaptive and flexible fisheries management regimes and help the transition of fishing and aquaculture industries and coastal communities.

This paper addresses the question of whether the current fisheries management toolbox is sufficient to address climate change. The paper discusses the elements and the strengths and weaknesses of the current fisheries management toolbox in terms of dealing with potential additional risks and pressures posed by climate change. This discussion is followed by a consideration of the impacts on fisheries and aquaculture that are expected from the suite of changes to the climate including increased frequency of severe events in the short-term, and reduced longer-term productivity of aquatic ecosystems (FAO, 2008). The responsiveness of the current management systems to the climate change impacts is examined.

While the paper confirms the more theoretical capabilities of the fisheries management toolbox to respond to climate change, it also notes its operational deficiencies in adapting to change in practice. Finally, the paper offers some thoughts on the transition to adaptive fisheries management including ways and means of dealing with uncertainty in planning fisheries management strategies through evoking intuitive solutions, developing our ecosystem observation and learning processes, clarifying ecosystem objectives, and engaging local communities and stakeholders more directly in the decision making process.

The current fisheries management toolbox

The current fisheries management toolbox includes a range of output and input controls often combined with technical measures in dealing with the different scales of the fishery including commercial, artisanal, and recreational fisheries and aquaculture sectors and the additional risks associated with uncertainty in management. This section presents a summary of the fisheries management toolbox generally used worldwide to apply fisheries management administration and discusses its strengths and weaknesses and its responsiveness to the uncertainty of the pending impacts of climate change.

Characterising the current fisheries management toolbox

The fisheries management system or "toolbox" is characterised by several key elements that define it, including:

1. general objectives of the fisheries management system;
2. management measures (input controls, output controls and technical measures);
3. institutional arrangements, support structures for scale of management and user participation.

Each of these elements is described briefly below.

General objectives of the fisheries management system

Countries' mandates and policy directions for fisheries management systems have typically evolved from a focus on resource development and conservation, expanding over time with varying levels of emphasis on socio-economic dependence and community benefits from fishing and aquaculture operations. The Code of Conduct for Responsible Fisheries (FAO, 1995) highlighted the common theme in its call for responsible and sustainable management of fisheries. Recently, fisheries management objectives are under criticism in regimes experiencing declining fish stocks, falling catches, and the anticipated negative impacts of climate change on the status of our oceans and waters.

Some countries' major legislation and guidelines have attempted to create lasting policy ties between resource conservation, sustainability and wealth generation associated with exploitation by the country's commercial fishery and aquaculture sectors all the while recognising the reality of the inherent conflict between conservation and exploitation. For example, the government of Canada recently embarked on a policy of "Fisheries Renewal" with renewed objectives for the fisheries management system. The renewed statement of the fisheries management objectives is:

- Long term sustainability - By enabling resource users to achieve strong conservation outcomes through risk management frameworks incorporating the ecosystem considerations and precaution.

- Economic prosperity - By aligning fisheries policies and decision-making processes to aim to achieve economic prosperity working with stakeholders throughout the seafood value chain through an Ocean to Plate Approach.

- Improved governance - By increasing stability, transparency and accountability and by promoting shared stewardship with resource users and others with an interest in the resource. (source: DFO website: www.dfo-mpo.gc.ca/fm-gp/peches-fisheries/fish-ren-peche/index-eng.htm. Accessed May 19, 2010).

These objectives are aligned with that of most developed and developing countries. In the European Union, the objective of the Common Fisheries Policy (CFP) is "to provide for sustainable exploitation of living aquatic resources and of aquaculture in the context of sustainable development, taking account of the environmental, economic and social aspects in a balanced manner" (Holden, 1994). As in Canada, recent reform of the CFP also seeks to improve fisheries governance – a common lament given unrealised objectives – through enhanced stakeholder engagement. As stated in the CFP Green paper:

Pollution from industrial and other human activities, and climate change have also contributed to stock decline or lack of fish in some areas. Measures to counteract the effects of these factors on stocks are urgently needed otherwise conservation and management policy for the fishery resources will be constantly undermined. (Commission of the European Communities, 2001, p.10)

In summary, countries' fisheries management systems objectives may be characterised by:

- Ecological sustainability and ecosystem conservation: as expressed in biodiversity goals

- Economic viability and social stability: objectives related to sustainable development and socio-economic support

- Responsibility: shared stewardship and partnership with fisheries system stakeholders

Clearly stated objectives and their realisation in policy have important implications for an effective fisheries management system adapted to climate change.

Management measures

Sutinen's work on the 1994-96 OECD Fisheries Committee work program was presented under the title of "economic aspects of the management of living marine resources" (OECD, 1997). In that work, management instruments are reviewed and assessed with the objective of facilitating appropriate economic analysis useful for fisheries management decision making. Tables 6.1 to 6.4 below summarise the management measures of the fisheries management toolbox in effect for today's commercial marine fisheries and aquaculture systems. Table 6.1 summarises the output,

input, and technical measures, while Tables 6.2 through 6.4 focus on controls and measures and their expected and practical consequences.

Input control systems limit access to fisheries and restrict the use of capture devices (gear) in order to conserve exploited resources while attempting to equalise fleet activity through overall or individual vessel fishing effort control. Prior to the 1970s, input controls were prevalent in commercial fisheries, and were applicable nationally and internationally. Fishing effort restrictions began with aggregate measures to limit fleet and vessel numbers through limited licensing programs. Gradually, these measures became more restrictive and more directly applicable to individual fishermen with respect to a limit quota on total fishing effort (*e.g.* days fishing), and on individual vessel's size, weight, configuration, and gear, *e.g.* net size and shape (diamond or square mesh, soak time limits for passive net gear, limit numbers of hooks used).

Output controls restrict the controlled delivery of exploited marine resources on the aggregate capture of whole fleets (*e.g.* total annual or seasonal catches, TACs), on the designated subset of fishing fleets assigned quotas to be shared among themselves (*e.g.* catch shares or community quotas), or on individually licensed vessels or operators (*e.g.* individual quotas either transferable or not transferable among fishing units). Historically, output controls were established globally (only since the 1970s) in response to the apparent ineffectiveness of combined input controls and technical measures that had been in place to this point to sustain exploited fish populations. The popular trend in output controls is away from purely aggregate fleet output controls (*e.g.* TACs) and toward more specifically applied output controls to individual vessel operators (*e.g.* individual transferrable quotas [ITQs], or individual vessel quotas [IVQs]). This transition has been identified with enhancing fisheries access and allocation as a property right, and is applied as a consequence of the difficulties and ineffectiveness of controlling only aggregate outputs.

Technical measures define the acceptable limits of captured marine resources both in terms of units captured and their spatial and temporal characteristics. Technical capture regulations may be applicable to the allowable size, sex, space, and time for stock exploitation. In recent years, the definition of spatial-temporal Marine Protected Areas (MPAs) have become a popular technical measure. MPAs often designate "no take" areas, although some MPAs are designed as multi-use zones with defined time-area uses.

Table 6.1. Management measures toolbox

Application target	Input controls	Output controls	Technical measures
Aggregate fleet	1.Total allowable fishing effort limits/limited licences	1. Total allowable (seasonal) catch limits (TACs)	1. No take zones (strict MPAs)
Individual vessel /operator	2. Individual fishing effort quota restrictions	2. Individual operator quotas (IQs), Individual transferable quotas (ITQs), catch shares	2. Time-area closures (multi-use MPAs)
Combined fleet and operator	3. Vessel and gear restrictions	3. Vessel catch limits	3. Output selectivity restrictions (for size and sex)

Source: Adapted from OECD (1997), Table 1, p.13.

Most modern fisheries management systems utilise all of these management measures identified in Table 6.1 as part of their overall application of the modern toolbox for achieving the fisheries and aquaculture system objectives. Table 6.2 below presents details on the input control measures of the toolbox along with the expected and actual (critical) consequences of these controls.

Input controls provided managers with direct fishing effort reduction on vulnerable stock components, particularly juvenile fish. Effort controls promised resource recovery and improved sustainability for the exploited stocks. Individual vessel effort controls were designed to mitigate the fleet's tendency to "race for fish" under a limited global quota regime such as TACs.

In practice input controls were initially effective for limiting licences and the number of vessels and fishermen by restricting direct access to the commercial fisheries. However input controls expressed as operational conditions (*e.g.* the restricted use of gear) proved to be difficult to monitor and enforce in practice. As well, the difficulties of establishing measures and effectiveness of fishing effort became onerous such that the application of input restrictions were easily circumvented and less effective than anticipated. All effort restrictive approaches increase operating costs and reduce efficiencies of production and lower profitability.

Table 6.2. Input controls

Input control	Expected consequences	Practical consequences
1.Total allowable fishing effort limits/limited licences	Direct effort reduction; Resource recovery and improved resource conservation.	• Established licence/vessel number limits while excluding fishermen, and defining barriers to entry and the need for buy-back programs; • Economic inefficiencies, higher costs of production; • Capital stuffing from new and uncontrolled other inputs; • Initial trend in total effort decreases then increase among limited fleet/licence holders; • Difficulty in monitoring and enforcing in operational (real) time conditions and neglected reporting of outputs; • Evidence of discarding and highgrading to assign effort limits to most valuable outputs.
2. Individual fishing effort quota restrictions (transferable or non-transferable)	Direct effort reduction; Resource recovery and improved resource conservation; Mitigates the "race for fish".	• Problematic setting of effort units and individual limits; • Exclusive fishermen, barriers to entry; buy-back costs; • Economic inefficiencies, higher costs of production; • Improved technology and capital stuffing from new and uncontrolled and combined other inputs; • Difficulty in monitoring and enforcing in (real) time conditions and poor reporting of outputs; • Evidence of discarding and highgrading to assign effort limits to most valuable outputs.
3. Vessel and gear restrictions	Effective effort and catchability reduction; Resource recovery and improved resource conservation and reduced fishing mortality on targeted stocks components.	• Problematic setting of effort units and limit levels; • exclusive fishermen, barriers to entry; buy-back costs; • economic inefficiencies, higher costs of production; • improved technology and capital stuffing from new and uncontrolled and combined other inputs; • difficulty in monitoring and enforcing in operational (real) time conditions poor reporting of outputs; • evidence of discarding and highgrading to assign effort limits to most valuable outputs.

Source: Adapted from OECD (1997), pp.88-100.

In general terms, the input controls of Table 6.2, by themselves, are not sufficient to reduce exploitation and improve stock conservation. Moreover, the absence of focus on output creates an unknown for stock management and assessment. In practice, the expected success of input controls is reduced in isolation with other management measures (output controls and technical measures). As noted previously, to be effective, input controls need to be combined with other measures (output controls, and technical measures).

Table 6.3 below presents details on the output control measures of the toolbox along with the expected and actual (critical) consequences of these controls.

Table 6.3. Output controls

Output control	Expected consequences	Practical consequences
1. Total allowable (seasonal) catch limits (TACs)	Direct limit on aggregate output and fishing mortality; Resource recovery and improved resource conservation.	• Problematic setting of aggregate total; • Difficult to enforce aggregate due to data recording delays; • Unintended season shortening – "race for fish" with over-investment in fishing capital ("capital stuffing"), higher operating costs; • Rent dissipation with free entry and exit; • Safety concerns re "race for fish"; • Market gluts at peak output, unstable supply; • Evidence of highgrading problems.
2. Individual operator quotas (IQs), Individual Transferable quotas (ITQs), catch shares	Direct limit on individual output and fishing mortality; Resource recovery and improved resource conservation; Eliminate "race to fish"; Generates resource rents by removing inefficient input controls.	• Problematic setting of vessel quota allocations (absolute share versus proportion of TAC); • Difficult to enforce individual quota to data recording delays; • Rent dissipation with free entry and exit; • Evidence of highgrading problems; • IQ as property – issues of duration, flexibility, transferability, divisibility; in-season transfers; initial allocation problems; • Difficulties in enforcement and compliance.
3. Vessel catch limits	Direct control on landings /vessel per trip; reduced landings, total fishing effort; smooth landings, effort distribution; eliminate "race to fish"; Control exploitation	• Increased discards and underreporting; • increased enforcement costs due to increased control; • highgrading problems and incentives; • difficulties in enforcement and compliance.

Source: Adapted from OECD (1997), pp.72-88.

In general terms, output controls, by themselves required enhanced monitoring and enforcement. In practice, where these enhanced services were not in place, then the expected success of output controls was reduced. As noted previously, output controls were often used in conjunction with other measures (input controls and technical measures).

Table 6.4 below presents details on the technical measures of the toolbox along with the expected and practical consequences of these controls.

Technical measures were designed to protect sensitive areas from fisheries exploitation by imposing direct closures entirely or in part. Designating whole areas as marine parks or protected areas does not prevent "leakage" of resource units into contiguous grounds. MPAs deflect fishing effort, and do not necessarily eliminate it. Increases in effort outside the MPA may have unforeseen impacts on other parts of the marine space. Similarly, a deflection of selectivity to protect vulnerable segments of the population may create related problems of how the unused effort is misdirected or misreported.

Table 6.4. Technical measures

Input control	Expected consequences	Practical consequences
1. No take zones (strict MPAs)	Eliminate fishing mortality in an area; protect designated marine ecosystem and vulnerable (spawning, juvenile) stock units.	– Fishing effort shifted to adjacent (spill over) areas; – Does not account for transboundary/trans-ecosystem movement; – Increases costs of fishing effort due to space-time restrictions; – Increased misreporting; – increased enforcement costs.
2. Time-area closures (multi-use MPAs)	Protect vulnerable (spawning, juvenile) stock units.	– Increases costs of fishing effort due to space-time restrictions; – Increased misreporting; – Increased enforcement costs.
3. Output selectivity restrictions (for size and sex)	Protect vulnerable (spawning, juvenile) stock units by controlling exploitation.	– Increases costs of fishing effort; – Increased misreporting; – Increased enforcement costs; – Highgrading problems and incentives.

Source: Adapted from OECD (1997), pp.100-111.

In general terms, technical measures taken by themselves do not necessarily achieve their expected consequences. In practice, it is difficult to determine the effectiveness of closed areas, especially considering the impact of displaced fishing effort. However, as with the other management measures, the combination of output controls, input controls, and technical measures can be effective in delivering management objectives and sustainable fisheries and aquaculture.

Institutional arrangements, support structures for scale of management, and user participation

The institutional arrangements in place in the fisheries management system are fundamental to the effective delivery of the toolbox. Ostrom defines an institution as: "simply the set of rules actually used (the working rules or rules-in-use) by a set of individuals to organize repetitive activities that produce outcomes affecting those individuals and potentially affecting others" (Ostrom, 1992). Ostrom's rules are formalised as institutional arrangements. Nielsen and Vedsmand (1995) define specific sets of organisational and institutional arrangements which define government-citizen co-operation and are influenced by:

- scale of management, *e.g.* local (artisanal, recreational), regional (sectors), national, and international participation and characterisation of fisheries
- management measures and the structure of property rights
- user group involvement in decision making

Jentoft and McCay (1995) characterise user participation within the implementation of fisheries management on a spectrum related to the role of governments and the increasing contribution and power of stakeholders. The highest level of government control or top-down hierarchy with minimal user responsibility is denoted as "informational". A "consultative" arrangement formalises user input but does not necessarily commit the responsible government authority to act accordingly. Consultation is seen as a means of demonstrating transparency in government decision making. Finally, the bottom-up approach is designated as "co-management" whereby the government devolves authority for decision making and responsibility to users who are then able to apply traditional and communal rights systems.

Table 6.5 below characterises fisheries management by virtue of the scale of operations, associated management measures and the degree of user participation.

Table 6.5. Management scale, measures and participation

Scale	Measures	User participation	Characterisation
Local (small)	Limited restrictions; few barriers to entry; open access.	User-based but with little management; limited government involvement; minimal government lobbying.	• Manual, simple technology (passive gear), fishing • Limited to local waters; • Low capital requirements (many small boats, artisanal, recreational); • Low cost access (minimal licensing); low returns; • practised mostly by developing countries; • Near-shore marine and inland waters; • Generalist, flexible fleet, many species; • Full and part time, often poor, subsistence income; • Fishing communities remote from government, limited or no scientific information available.
Regional	Limited licences.	Mainly consultative, shared management with fishermen, communities, regional government	• Limited barriers to entry; • Near-shore marine and inland waters; • Generalist, flexible fleet, multiple gear types (fixed and mobile); • Fishing communities linked to regional governments, some but limited scientific capacity.
National	Limited licences; TACs; Effort limits; Individual quotas.	Consultative and informational; national government priority; formalised engagement of stakeholders (ENGOs, industry); organised lobbying.	• Larger vessel, specialised (mobile) fleets, few species; • Industrial, organised sector; • Domestic enforcement; • Mostly marine (often oceanic) waters; • Practised mostly by developed countries; • Mechanised, advanced technology, possess distant water, mobile gear fleet not limited to local waters; • National, government supported scientific capacity.
Inter-national (large)	Limited licences; TACs; effort limits; IQs; Restrictive measures on gear and vessels.	Informational, consultative, formalised engagement of industry toward co-management; professional government lobbying.	• High capital cost; barriers to entry; oligopolistic; • Shared international enforcement (coastal state); • International agreements, e.g. ICAAT, RMFOs (NAFO); • Mostly marine waters; • Practised mostly by developed countries; • Mechanised, advanced technology, possess distant water, mobile gear fleet not limited to local waters; • Homogeneous, specialised fleet, few species; • Full-time, professional fishermen; • Large management bureaucracies, extensive scientific attention and capacity.

Sources: after Berkes *et al.*, 2001; Pauly, 2006; and Baelde, 2007

In general, the smaller the scale of the fisheries or aquaculture operations, the less organised the sector, with little government intervention. Globally, it is estimated that small scale operations use one-tenth less carbon-based fuel than industrialised fisheries. This is combined with low relative catches per unit effort of fishing. The catches are mainly for food as in artisanal fisheries. Globally, small scale fisheries involve tens of millions of people, mainly in developing coastal regions of the world.

At the other end of the scale, fully industrialised international fishing fleets use high levels of fuel in catching approximately ten times the catch volume with 1% of the labour of the small scale fisheries. In comparison with small scale operations, catches per unit

fuel use is approximately equal (2-5 tonnes per tonne of fuel). Industrialised fisheries produce for higher valued international markets for food, and bulk quantities for reduction to fishmeal for aquaculture operations (Berkes *et al.*, 2001; Pauly, 2006; Baelde, 2007).

Finally, Table 6.6 identifies the basic (scale independent) set of operational tasks of the fisheries management system and the associated engagement and user participation in these tasks.

Table 6.6. Fisheries management operational tasks and user participation

Fisheries Management Tasks	Discipline	Responsible	User Participation
Stock assessment	Fisheries science	Fisheries scientists	Informational
Fishing access	Fisheries management	Fisheries managers	Consultative
Fishing allocation	Fisheries economics/policy	Fisheries managers	Consultative
Monitoring & enforcement	Fisheries officers	Fisheries managers	Informational
Fisheries policy/ decision making	All	Government leader	Consultative

The history of the fisheries management toolbox has been driven by the apparent inability to maintain resource sustainability over time amid improved fishing technologies and capacity. Over time, management measures have needed to "ratchet up" control by applying further restrictions to fishing inputs in the aggregate, and later to individual fleets sectors and vessels. Input inefficiencies and continued resource problems led to aggregate output controls followed in turn by fleet sector and individual output restrictions, leading finally to specific management measures denoting ultimate restrictions via closed and protected areas. Arguably, to date, the fisheries management toolbox has experimented with the full spectrum of management controls. It is noted that the modern toolbox represents a diversity of management approaches that are most effective when operated jointly and designed specifically and uniquely for the context and fishery in question.

The responsiveness of the modern fisheries management toolbox to address climate change is linked to the basic characteristics of the toolbox, and the ability of governments and users to manipulate these tasks in developing adaptation strategies. The fisheries management toolbox exhibits strengths and weaknesses with regard to dynamic changes in the complex environments in which it operates. These are discussed below.

Strengths

The ability of the fisheries management toolbox to adapt to change in the marine and freshwater systems environment is a function of its informational gathering capabilities, innovation and responsiveness, and its command and control of its user base.

Local knowledge and governance

Regional, national, and international fisheries generally provide clear provision in government-controlled legislation for formal governance mechanisms. The EU RACs, the US Regional Fisheries Management Committees (RFMCs), the Australian Management Advisory Committees (MACs), and the Canadian Fisheries Resource Conservation Council (FRCC) in the Atlantic and Pacific are formal, legitimised structures established as intermediaries to acquire local knowledge. These groups have precipitated well-organised fisheries associations and stakeholder and community groups with platforms to present options to government representatives in the critical issues of accessibility to the fishery and allocations of the resources. These mechanisms, typical of modern fisheries management systems, provide a direct connection from the local community to governments and give the impression of transparency and democracy through consultation. Accordingly, they are meant to provide the means for government decision makers to respond and adapt to the changing environment.

The adoption of the precautionary approach

Since the mid-1990s, fisheries management systems have struggled with dealing with uncertainty in the complex marine and freshwater environments. The FAO has been instrumental in promoting countries to adopt the precautionary approach (PA) as the effective response to uncertainty (FAO, 1995). The PA mantra that "the lack of information is not justification for taking action" is clear and motivating. With regard to climate change, the potential is for the PA to define conservative, risk-averse decision making in the face of potential negative implications of change.

Fisheries and aquaculture carbon footprint

The fisheries management toolbox can be used to improve carbon-based fuel efficiency for the sector as a whole by using management measures to reduce overcapacity and excess effort thereby improving fuel efficiency by promoting specific gears. Support programs for reducing greenhouse gases (GHGs) for new technologies and innovation for fisheries operations and the transport, processing and storage of fish can be developed under suitable management measures from the existing toolbox.

International associations and agreements

Fisheries management is a globally recognised field of study supported in large part by governments and disciplinary associations such as the International Council for the Exploration of the Sea (ICES), the international Code of Conduct for Responsible Fisheries and special studies, notably the OECD work programs of 1994-96 and 1997-2000 (OECD, 1997, 2000). The Code of Conduct for Responsible Fisheries was adopted by the FAO in 1995 (FAO, 1995). Under Section 12 of the code, "Future Research", the code specifically identifies the changing climate as a priority:

> *States should be able to monitor and assess the state of the stocks under their jurisdiction, including the impacts of ecosystem changes resulting from fishing pressure, pollution or habitat alteration. They should also establish the research capacity necessary to assess the effects of climate or environment change on fish stocks and aquatic ecosystems. (Article 12.5, p.32)*

The OECD studies highlighted the objectives of responsible and sustainable management of fisheries in the face of overexploited stocks and noted the need to harmonise efforts with the environment:

> *The main issue in fisheries management is how to restore fish stocks to environmentally, economically and socially sustainable levels. Some countries consider that fisheries management can be improved, under the responsibility of the administration, by the active participation of management bodies and by the use of management instruments that enhance fisher's sense of shared involvement in solutions. For some other countries, co-management frameworks that provide for input from fishers are considered to be valuable by providing improved user right and stewardship over the resource, in addition to being a valuable source of information. However, all aspects of fisheries – from harvesting to marketing to consumers – should be considered in a comprehensive way for a successful transition process to responsible fisheries. In this regard, it would seem that more effort is needed on consulting a broader set of fishing industry stakeholders. (OECD, 1997, p.7)*

In theory, the fisheries management toolbox has been conceived as a flexible and adaptive system to respond to the complex setting of the natural marine and freshwater environments. However, whether the toolbox is capable of meeting its objectives (see above) in practice is an open question. In this regard, weaknesses of the toolbox are itemised below.

Weaknesses

The ongoing national and international fora on improving fisheries management toward achieving sustainability and injecting responsibility and stewardship in the fishery provide evidence of the need to address the weaknesses in fisheries management toolbox. A list of these weaknesses is presented below.

Consultative governance systems and governmental command and control

As noted in Tables 6.5 and 6.6 above, user participation in fisheries management has tended toward government controlled consultative arrangements. Government controlled systems reflect the "tragedy of the commons" (Hardin, 1968) that provides the impetus behind the modern role of governments in command and control of the fisheries and aquaculture sector. However, as Ostrom *et al*. (2007) note, appropriate governance of all fisheries systems requires a range of context-driven applications and options. They argue that there is no panacea, "one-size-fits-all" approach for application of the fisheries management toolbox. When there is no authority for local knowledge to act, it diminishes the responsibility and opportunities to engage the local community and stakeholders. Most country management regimes, *e.g.* the EU, and Canada, instill power in the government responsible minister and are known as fisheries that are "run from Brussels" in the case of the EU with "European Competency", and for Canada fisheries as "Ottawa run". These government based paternal systems are typically based on operational disciplinary tasks, *e.g.* fisheries science, management, and policy, from government developed and funded expertise. Stakeholders, industries, communities are typically provided merely a consultative role. This is seen as a weakness in instilling responsibility to users in the command and control system.

Data deficiencies in ecosystem observations and monitoring

Consistent with the major government role, ecosystem observations tend to be controlled and processed by the government agencies to support command and control. Local, regional, national, and international fishermen are often mandated to provide information and observations as part of their licensing agreements. However, the information flow is such that governments tend to use data for their own planning purposes and without a clear and directed communication to users about how the information is compiled and analysed. It is a weakness that resource users' additional observations that may not conform to standard data and model requirements and often gets labelled as "anecdotal information" and are accordingly minimalised or ignored.

Undefined objectives, targets and space in multicriteria decision making

The complexity of the fisheries management toolbox and the myriad of resources require a similar long task list for assigning access and allocation to fishery units in marine space. This requires extensive ecosystem and stock assessment estimates for the resources and associated target and objective setting in the marine space including socio-economic considerations. Government-led initiatives are generally not effective in declaring the full suite of objectives and accountable targets for socio-economic as well as resource status in defined marine areas. It is a weakness that government decisions, while based on the objectives of resource sustainability and socio-economic prosperity, are not clearly defined with respect to how they apply in the marine space and with respect to the multiple and conflicting criteria of fisheries and aquaculture resource systems.

Problems operationalising the PA

Despite well-known and principled approaches to ongoing stock declines, and risk-averse responses to uncertainty, the PA has not resulted in an improved sustainability performance primarily due to the unclear and wide interpretation of how to operationalise the PA in access and allocation decisions. The wide range of PA actions, consistent with environmental variability, invites a range of actions that overall do not reduce downside effects of uncertainty. Moreover, actions taken in the name of the PA do not necessarily translate into improved ecosystem performance due to the complexity of the system and the multiple and conflicting criteria of decisions. Despite the acknowledgement that science cannot fully inform decision makers, it is a weakness of fisheries management that there are significant difficulties with the application and operationalisation of the precautionary approach.

Government lobbying

Large scale international fisheries typically involve a small number of commercial entities (Table 6.5 above). Collectively, these entities may exert a significant force on government lobbying, bilateral agreements, and political interference. Under the current management toolbox characterised by government control systems, the incentives for big business are to maintain productivity, reduce costs, and increase profitability. These incentives tend to promote continued exploitation, the advancement of socio-economic considerations at the expense of resource sustainability, and may undermine potential ecosystem sustainability concerns.

Fisheries and aquaculture carbon footprint

Fisheries and aquaculture activities contribute to greenhouse gas emissions during production operations and the transport, processing and storage of fish and differentially by species and regions. Overcapacity and excess effort lead to lower fuel efficiency. Protein, energy consumption, and peripheral effects consumed in producing fish food from aquaculture varies significantly. Estimates of the ratio of edible protein energy output to industrial energy inputs varies considerably to the point of questioning the sustainability of aquaculture. Post-harvest activities entail stocking, packaging, transport and post-consumption waste are also linked to increased GHG emissions. International trade in fresh fish products by air freight produce high emissions that are estimated to be nearly 4 times higher than sea freight, and almost 100 times that from local transportation of fish consumed locally. As the global commercial fishery trade seeks higher value, continuing internationalization is important to developing nations that depend on valuable export earnings. Consequently, GHG emissions are expected to increase. The recent FAO State of the Fisheries and Aquaculture report for 2009 noted the weakness of the trade-offs between developing-country export benefits and air transport mitigation efforts (FAO 2009, p.87ff).

Fisheries management in practice

A fundamental weakness of the fisheries management toolbox is its inability, in practice, to realise its objectives of ecological sustainability and ecosystem conservation, economic viability and social stability, and responsibility. These objectives remain largely unfulfilled as evidenced by the global response to persistent overexploitation by national and international fishing fleets, and the persistent policy of states' subsidisation of fisheries and aquaculture operations in the guise of social stability and economic viability.

In light of this description of the modern fisheries management system, the following section examines the pending impacts on the system from climate change and the response of the system to these impacts.

Climate change impacts and response of the fisheries management toolbox

This section discusses the requirements of adaptation strategies within the contexts and spatial specifics of the fisheries management toolbox summarised above. It also examines anticipated climate change impacts on the fisheries and aquaculture sectors. Finally, responses to climate change impacts of the fisheries management system in place are examined.

Environmental impacts

The High-Level Conference on World Food Security: the Challenges of Climate Change and Bioenergy at FAO headquarters in Rome (FAO, 2008a) concluded that in terms of physical and biological impacts, climate change is modifying the distribution of marine and freshwater species. Warm-water species are being displaced towards the poles with changes in fish size and stock productivity, ecosystem productivity is reduced in tropical and subtropical oceans, in the seas and lakes, and increased in higher latitudes. Temperature increases are also affecting fish physiological processes resulting in both

positive and negative effects on fisheries and aquaculture systems depending again on the region and latitude.

Differential warming between land and oceans and between polar and tropical regions affect the intensity, frequency and seasonality of climate patterns (*e.g. El Niño*) and extreme weather events (*e.g.* floods, droughts and storms). These events impact the stability of related marine and freshwater resources and have unpredictable consequences for fish production due to changes in the seasonality of marine and freshwater food webs and resource biological processes. Species invasions and spreading of vector-borne diseases increase the unpredictable risks of expected changes.

Sea level rise and land subsidence, glacier melting, ocean acidification, and changes in precipitation affecting groundwater and river flows significantly impact the productivity of coral reefs, wetlands, rivers, lakes and estuaries.

The conference also reported that extreme events impact coastal infrastructure, ranging from port landing and fish farm sites to post-harvest facilities and transportation routes. Safety at sea and coastal settlements and communities living in low-lying areas are at increased risk. Water stress and competition for water resources affect aquaculture operations and inland fisheries production, and increase conflicts among water-dependent activities.

A number of recent studies have been undertaken to detail climate changes and their impacts on fisheries and aquaculture. Notably, the work of Brander (2007, 2010) including his work in the collection of studies appearing in the recent special issue of the *Journal of Marine Systems* (Drinkwater *et al.*, 2010; Emeis *et al.*, 2010; Jennings and Brander, 2010; Ottersen *et al.*, 2010; Overland *et al.*, 2010; Perry *et al.*, 2010; Planque *et al.*, 2010; Schwing *et al.*, 2010) discuss the impacts of climate change on global and regional fisheries. Cheung *et al.* (2009) project impacts on global marine biodiversity under climate change. Turner's (2000) work examines the socio-economic impacts of change in the coastal zone.

Table 6.7 summaries the effects of anticipated climate change from this literature with acknowledgement to the work of Cochrane *et al.*, (2009), Sherman *et al.*, (2000), O'Reilly and Hyde (2009), Allison *et al.*, (2009), FAO (2007), and Gallardo and Yakupitiyage (2009). As noted, this work is considerable and Table 6.7 fashions a summary with focus on fisheries and aquaculture impacts in order to address the toolbox response.

Table 6.7. Direct and indirect effects of climate change on fisheries and aquaculture

Description	Physical impacts	Observed impacts on fisheries and aquaculture
Warming – increasing heat content and rising temperatures	Increased oxygen demand, decreased pH; warming surface waters and deep warming (Atlantic Ocean).	Oxygen demands cause stress in fish stocks interrupting reproductive success.
	Moderate to strong warming in freshwater lakes, decreasing levels.	Delayed diatom spring bloom and peak biomass reduced; changes in the dominant phytoplankton; deep tropical lakes experiencing reduced algal abundance, declines in productivity from reduced resupply of nutrients; changes in freshwater and marine species planktons.
	Increased river run-off at higher latitudes; decreases in West Africa, southern Europe and southern Latin America; decreasing rainfall and evaporation in African lakes.	Rapid changes in fish (pelagic) communities, vertical movements to counteract surface warming.
	Contraction of marginal sea ice biome and seasonally stratified subtropical gyre.	Species (terrestrial and marine) ranges driven toward the poles, expanding the range of warmer-water species, contracting colder-water species; reduced species diversity in tropical waters; populations at the poleward extents of their ranges tend to increase in abundance with warmer temperatures (achieved when food supply is adequate); populations near the equators decline in abundance as temperatures warm.
	Reduced ice cover in high-latitude, high-altitude lakes, longer growing season, increased algal abundance and algal blooms, increased invasive species, and diseases.	Marine and freshwater trophodynamics altered by ocean warming through predator-prey mismatch and reduced production and biodiversity and increased variability in yield.
	Anthropocentric concentration of GHG emissions by fisheries and aquaculture sectors.	
Changing ocean salinity, water column stratification; mixing of water in lakes and oceans	Increased salinity in surface ocean waters, decreasing in high latitudes.	Increased vertical stratification and water column stability in oceans and lakes reduce nutrient availability to the euphotic zone affecting primary and secondary production; distribution shifts due to tight trophic coupling adversely affects fisheries, reduction in prey and in primary productivity.
	Combined temperature and salinity changes reduce density of the surface ocean, increase vertical stratification, and change surface mixing with some geographical differences.	In high latitudes the residence time of particles in the euphotic zone will increase, extending the growing season and small global increase in primary production with large regional differences.
	Decrease nutrient supply to surface waters due to increased stratification.	
Changing ocean circulation and coastal upwelling changes in timing and latitude	Reductions in the ocean currents expected from freshwater input in the Arctic and subarctic, increased stability of the surface mixed layer, reduction in salt flux, reduced ocean convection and less deepwater formation.	Intensification of hydrological cycles influence limnological processes, increased run-off, discharge rates, flooding area and dry season water levels boost productivity at all levels (plankton to fish); changes in timing of floods may trigger production at the wrong time and flush biological production out of its habitat with important food web consequences.
	Upwelling seasonality affected.	Nutrient supply in surface waters altered, primary productivity reduced; changes in open sea fish and pelagic fish distribution and reduced coral-reef fisheries productivity.
	Changes in lake water levels and dry water flows in rivers.	

Table 6.7. Direct and indirect effects of climate change on fisheries and aquaculture (*cont.*)

Description	Physical impacts	Observed impacts on fisheries and aquaculture
Sea level rise, land subsidence	Rise in global average sea level rates accelerating since 1993 to about 3.1 mm per year. Losses expected in Atlantic, Gulf of Mexico, coasts of the Americas, Mediterranean, Baltic and small-islands; intertidal and coastal wetland habitats substantially reduced. Coastal profile changes, loss of harbours, homes; increased exposure of coastal areas to storm damage; increased vulnerability of coastal communities and infrastructure to storm surges and sea level.	Reduced production and yield of coastal and related fisheries due to loss of coastal fish breeding and nursery habitats, *e.g.* mangroves, coral reefs, and reduced area available for land-based aquaculture. Increased risks associated with fishing, higher insurance, more days at sea lost to storms, higher risks of accidents and damage to gear and aquaculture installations, less viable livelihood options for the poor, higher costs, reduced profitability. Salt water intrusion damage to land-based water systems, wells, and aquifers. Reduced freshwater availability for aquaculture.
Ocean acidification, increased CO_2	Decreased surface seawater pH. Impacts of ocean acidification uncertain, severe for shell-borne organisms, tropical coral reefs, and cold-water corals in the Southern Ocean.	Reduced production for calciferous marine resources, *e.g.* molluscs, crustaceans, corals, echinoderms, phytoplankton, calciferous marine resource species; coral bleaching and mortality; reduced coral calcification and enhanced reef erosion. Changes in surface water availability threat to fisheries production.
Atmosphere-ocean, land-ocean exchanges	Hydrological impacts of land-use change with consequences for ecosystem production, changes in sediment loads, damned water flows, and physico-chemical consequences (hypoxia, stratification and salinity changes)	Ecosystem community composition impacts, production seasonality shifts in plankton and fish. Pressure on inland fish and land-based, water intensive, food production systems (*e.g.* rice), particularly in developing countries; reduced diversity of rural livelihoods, less predictable rain/dry seasons and decreased ability to plan.
Low frequency climate variability patterns	Increase in the intensity and frequency of atmospheric patterns: North Atlantic Oscillation (NAO), El Nino-Southern Oscillation (ENSO) events. Warming trend throughout the ocean basins. Reduced water flows and increased droughts	Changes in species sex ratios associated with event timing and altered times of spawning, migrations, peak abundance of juvenile fish leading to reduced productivity overall. Changes in lake water levels, dry water flows in rivers leading to reduced productivity freshwater systems; increased invasive species, diseases and algal blooms and parasites; changes in fisheries and aquaculture infrastructure and operating costs from infestations of fouling organisms, pests, nuisance species, predators.
Increased frequency of extreme weather	Large waves and storm surges. Inland flooding from intense precipitation.	Salinity changes; introduction of disease or predator; loss of fishing gear, damage/loss of aquaculture facilities and aquaculture stock; increased costs needed to construct and secure wharvage, cages.
Combined climate changes leading to “regime shifts” with increasing	Amplification of combined climatic signals provoke short term, unpredictable biological responses as ecosystems shift from state to state. Large-scale changes related to	Regime shifts in the North Atlantic, North Pacific oceans affecting productivity. “Rapid” time scales (years): changes in distributions of both freshwater and marine species, changes in abundance from recruitment failure; changes in the timing of life history, rapid turnover species, *e.g.* plankton, squid

regional climate variability	temperature, winds, freshwater availability, and acidification, longer growing seasons, decreased ice cover, changing levels of precipitation (more droughts or floods), changes in sea level, and increased frequencies of extreme events (such as flooding and storm surges).	and small pelagic. Intermediate time scales (decades): temperature-mediated physiological stresses and phenology changes impact recruitment success and abundances. Long time scales (multidecadal): decreasing primary production with regional variability; reduced ecosystem resilience to climate variability as a result of changes caused by fishing. Increased intensity and duration of floods, shifts to freshwater fish species adapted to migration, spawning and transport of spawning products; lower water quality and increased production costs as freshwater aquaculture compete with changes in availability of freshwater due to agricultural, industrial, domestic and riverine requirements.

Table 6.7 summarises the anticipated climate changes and the potential impacts on the fisheries and aquaculture sector. It is recognised that the cause-effect of these climate changes in the complex marine and freshwater systems have direct and indirect cumulative impacts on these sensitive ecosystems. As such, these impacts are taken from observations. No functional response or predictable impacts can effectively be determined for the climate change impacts on fisheries and aquaculture. Nevertheless, it is instructive to postulate how the current fisheries management toolbox may respond to the pending changes. The following section examines the response of the fisheries management system for the anticipated impacts of Table 6.7 above.

Fisheries management toolbox response

By virtue of the recognised historically weak performance of the current fisheries management toolbox amid declining stocks, falling catches and catch rates, the evidence is that the response to change is lacking in practice (FAO, 2009; OECD, 1997, 2000). In this section, the climate change impacts summarised in Table 6.7 provide the focus for how the fisheries management toolbox may be expected to respond to the pending changes due to climate shifts. This exercise identifies the gaps in the applications and practical consequences of the fisheries management toolbox. The results direct us toward a more adaptive fisheries management system that is designed to deal with the complexities of climate change.

Table 6.8 below associates the key elements of the current fisheries management toolbox with the anticipated climate changes presented in Table 6.7 above. The "response" suggests how management measures, operational tasks, and governance approaches within the capacity of the current system can be called on, at least theoretically to address the pending impacts. Columns 1 and 2 of Table 6.8 are taken from the Table 6.7 description and impacts of anticipated climate changes, respectively. The last column of Table 6.8 applies relevant management measures and operational tasks of the fisheries management toolbox to the identified changes and their impacts.

Table 6.8. Fishery management toolbox response to climate change impacts

Description	Impacts on fisheries and aquaculture	Fishery management toolbox response
Warming – increasing heat content and rising temperatures	Stress in fish stocks interrupting reproductive success.	Protection of spawning grounds using technical measures, MPAs, time and area closures, improved fisheries science on the migration and timing of species' life cycles.
	Delayed algae blooms and changes in abundance and timing.	Enhanced systems for observation, monitoring, improved science of the migration and timing of species life cycle.
	Changes in fish (pelagic) communities, and behaviour; changes in species ranges.	Fishery behaviour tracking and ecosystem observation; catch statistics review including location of capture and analysis.
	Fisheries and aquaculture industry anthropogenic contribution minimal.	Shift to fixed or passive gear, versus mobile gear, new technology for reducing emissions.
Changing ocean salinity and water column stratification	Increased vertical stratification and water column stability reduced nutrient availability	Longitudinal observation system from surveys, timing of fish runs, more science on behaviour of fish from deputised fisheries observations.
	Reduction in prey and reductions in primary productivity	Improved and direct science surveys on ecosystem monitoring.
Changing ocean circulation and coastal upwelling changes in timing and latitude	Increased run-off, discharge rate; changes in the timing of floods.	Observations, ecosystem monitoring systems, comparative analyses.
	Nutrient supply altered, primary productivity reduced.	Improved and direct science surveys on the ecosystem monitoring.
	Changes in open sea fish and pelagic fish distribution and reduced coral-reef fisheries productivity.	Science tracking systems; assistance of fisheries observations with Science-aided information gathering.
	Loss of coastal fish breeding, nursery habitats, reduced area for aquaculture.	Ecosystem observations, shore and fisheries based.
Sea level rise, land subsidence	Increased risks; more days at sea lost to storms, higher risks of accidents and damage, reduced profitability.	Analysis and tracking evidence: information gathering; financial information analysis.
	Salt water intrusion damage to land-based water systems.	Integrated tracking of coastal water systems.
Ocean acidification, increased CO2	Reduced freshwater availability for aquaculture.	Policy adjustment from evidence to shift to brackish water species.
	Reduced production for calciferous marine resources.	Science and enhanced stock assessment of affected resources; ecosystem observation.
	Reduced coral calcification and enhanced reef erosion.	Development and maintenance of longitudinal records, trends.
Atmosphere-ocean, land-ocean exchanges	Changes in surface water availability.	Improved science information and monitoring.
	Shifts in production and seasonality processes in plankton and fish	Enhanced information and ecosystem monitoring observation systems.
	Pressure on water use	Development of integrated overall water use.
	Reduced diversity of rural livelihoods	Establish measures of local, regional dependence on fisheries and aquaculture.

	Altered times of spawning, migrations, and peak abundance of juvenile fish.	Improved analysis of catch observations, timing, life history and spatial range; technical measures applied to spawning and juvenile rearing areas.
Low frequency climate variability patterns	Reduced freshwater productivity.	Integrated analysis of water use and flows.
	Increased invasive species, diseases and algal blooms and parasites.	Enhanced ecosystem monitoring and observations.
	Increased costs from pests, fouling organisms, nuisance species, predators.	Observations and access and allocation management to remove organisms, reduce pests.
Increased frequency of extreme weather	Salinity changes, disease, predators	Improved ecosystem monitoring and observations.
	Loss and damage to gear, loss of aquaculture stock	Improved science and engineering for advanced technology and innovation on materials and gear.
Regime shifts	Regime shifts affecting productivity, pelagic, demersal species dominance.	Enhanced science and ecosystem modelling, observation, and systems analysis.

Table 6.8 suggests how the existing fisheries management toolbox can be expected to respond to the anticipated climate changes impacts. The table identifies those functions, measures and activities that are part of the toolbox and that need to be generally enhanced in the existing system in order to address the designated impacts. From Table 6.8 the following management toolbox responses are noted:

- **Enhanced ecosystem observation systems**: the most prevalent requirement to respond to the suite of climate change impacts is to establish enhanced systems for ecosystem modelling, observation, and analysis of species' status. This also requires enhanced science of the understanding of species' life cycle (migration and timing and fish behaviour), spatial and temporal analysis of the fishery, review and analysis of spatial-temporal catch statistics, and ongoing predator-prey relationships.

- **Protection of vulnerable species components**: species productivity and timing impacts require the protection of vulnerable spawning stocks and spawning events, and juvenile rearing areas to relieve stress and toward improving recruitment success using technical measures, *e.g.* MPAs, time and area closures.

- **Integrated tracking of coastal water systems**: integrated analysis of water use and flows in freshwater and marine systems including all sources and uses in a regular accounting and tracking of water use.

- **Gear shifts:** shift to fixed or passive gear versus overly efficient mobile gear using management measures gear restrictions in order reduce the sector's carbon footprint and to associate fishing effort and output more closely with the natural variation of the marine system.

- **Policy shifts**: shift fisheries and aquaculture effort to alternative species based on evidence from ongoing observations and based on preset targets for decision making.

- **Sector dependence analysis**: establish measures of local and regional dependence on fisheries and aquaculture through integrated social and financial information analysis with feedback to the access, allocation and governance processes.

- **Technological innovation**: improved science and engineering for advanced technology and innovation on materials and gear to decrease the carbon footprint, improve safety and reduce the risks of damage.

These responses are presented with respect to the potential impacts of climate changes and without critical analysis of their applicability or practicality in different contexts, regions, and scales of operation. Suffice it to say that technically, resource restrictions and practical issues of implementation notwithstanding, the current fisheries management toolbox can theoretically be responsive to the needs of the changing climate. However, it is noted that successful response requires a timely and practical application of the toolbox measures that arguably has not been attained to date.

The State of the Fisheries and Aquaculture report (FAO, 2009) points out that despite considerable scientific analyses, the future impacts of climate change on fisheries and aquaculture are nevertheless poorly understood. Further, FAO (2009) states clearly that the key issue lies less with our scientific knowledge than with our ability to respond practically and effectively:

> *The key to minimizing negative impacts and maximizing opportunities will be understanding and promoting of a wide range of creative adaptive strategies – implemented by public institutions or the private sector – and their interactions with existing policy, legal and management frameworks. Addressing the potential complexities of climate change interactions and their possible scales of impact requires the mainstreaming of cross-sectoral responses into governance frameworks. Responses are likely to be more timely, relevant and effective where they are brought into the normal processes of development and engage people and agencies at all levels. This requires not only the recognition of climate-related vectors and processes, and their interaction with others, but also the availability of sufficient information for effective decision-making and approaches that engage the public and private sectors. (FAO, 2009, p.90)*

The above statement underlies the real challenge for adapting the fisheries and aquaculture sector to the dynamics of our changing climate. The following section examines how an adaptive fisheries management toolbox can address effectively the complexity and uncertainty of climate change with a revised governance system.

Adaptive fisheries management

This section presents a blueprint for the evolution of a participative fisheries management system that is designed to adapt to sources of uncertainty including the pending impacts of climate change to coastal communities and our marine and freshwater resources. The characteristics of the governance system for an adaptive fisheries management program is described as the fundamental basis about which effective decision making can take place. Secondly, we describe the operationalisation of the precautionary approach as the means to managing uncertainty in the complex fisheries system. Finally, the ways and means and characterisations of moving toward an effective "best practices" adaptive fisheries management system is discussed.

Effective fisheries management systems are adaptive, flexible, and participatory. They embrace decision making under uncertainty based on precautionary and whole

ecosystem approaches to problem solving and taking into account the multiple criteria of ecosystem, social, economic and administrative consequences.

The following describes a renewed adaptive fisheries management system that seeks to redress these weaknesses identified above towards realising the required responses to climate change impacts through renewed governance arrangements and evolved decision-making structures.

Governance needs

Top-down command and control approaches do not offer the flexibility to ensure resilient fisheries systems and communities under climate change. Adaptive fisheries management is designed to address uncertainty and incorporate the knowledge and engagement of integrated resource users (Armitage *et al.*, 2008). Adaptive governance systems focus on continual learning from observations under ongoing experimentation and performance (FAO, 2007b). Thus, the most important adjustment of the current fisheries management toolbox is the shift from paternalistic government control of fisheries to a devolved process that embeds roles and responsibilities into all resource users.

Ostrom *et al.*, (2007) caution against the tendency, under uncertainty, to believe that linked social-ecological systems can provide general solutions to resource overuse. Rather, they note that since the preferences and perceptions of different resource users are not the same, then a diagnostic approach is required for initiating effective governance and monitoring. Thus, effective systems require the full engagement and participation of resource users and community members in this process, and a renewal of the heretofore prevalent roles of government in the fisheries management system.

The need for a governance shift and user engagement is acknowledged in the FAO's *State of the Fisheries and Aquaculture* report for 2008:

> *Policy-making and action planning in response to climate change will require cooperation and coordination across a range of government line agencies and departments as well as community or political representatives at subnational and national levels. It will also be necessary to build and strengthen partnerships among public, private, civil society and non-governmental sectors. In addition: Nationally, information gaps and capacity-building requirements need to be identified and addressed through networks of research, training and academic agencies. Internationally, networks should be created or developed that encourage and enable regional or global exchanges of information and experiences, linking fisheries issues with those of other sectors such as water management, community development, trade and food security. Existing management plans for the fisheries and aquaculture sector, coastal zones and watersheds need to be reviewed and, where appropriate, further developed to ensure they cover potential climate change impacts, mitigations and adaptation responses. (FAO 2009, p.90)*

Therefore, what is required is the establishment of real co-management regimes defined through the necessary policy, legal and implementation frameworks that recognise shared decision making authority and responsibility of resource users and all stakeholders. This also implies a renewal of the role of government as auditor and decision support to stakeholder decision makers in their delivery of access, allocation

rights, and operational regulations for the fisheries and aquaculture sector. This governance shift will require strengthening existing local and regional structures and processes with a focus on the changing environment, and explicit recognition of the multiple objectives and targets of the sector.

Further, the proposed co-management regime needs to be defined in an integrated fashion so that in the coastal zone, all agencies and stakeholders involved in ecosystem planning are contributors to policy that integrates the joint activities of commercial fisheries and aquaculture users, coastal zone managers, coastal developers, recreational users, other resource users (*e.g.* extractors of oil and gas), as well as non-governmental agencies. As noted in FAO (2009), this requires community capacity building and the realignment of scientific, management and technical services including links to "interior affairs, science, and education, but also those for national development planning and finance". The objective is to integrate fisheries and aquaculture management around integrated coastal zone management. This also requires an explicit identification of the coastal zone fishing areas and clarification of land-sea spatial planning and management jurisdictions. In marine areas, countries' spatial management can be encapsulated within coastal nation's exclusive economic zones as defined in the UNCLOS and UNFA limits, trans-boundary resources notwithstanding.

In Canada, for example, Fisheries Renewal includes improved governance mechanisms to support the participation of all relevant stakeholders in transparent, consistent, and inclusive decision-making processes that can bring about shared stewardship. The establishment of a National Advisory Body for short-term and more immediate consultation with stakeholders on developing policies including the consideration of climate change is proposed. However, a long-time barrier to this renewal in the Canadian system is the required devolution of the ultimate authority of the Minister of Fisheries and Oceans under the *Fisheries Act*, and the reluctance of the dominant players in the commercial fisheries to take on the responsibility now in the hands of the benevolent Minister of Fisheries and Oceans responsible for ecological sustainability, social stability and economic viability. This effectively implies the government's ongoing regional and public commitment to the sector to mitigate outcomes contrary to its mandated responsibilities.

Finally, associated with co-operative and devolved management is the need for enabling financial mechanisms currently under the auspices of governments to carry out their legally assigned command and control operations. The full potential of existing financial mechanisms, including insurance, will more than ever need to include the issue of climate change impacts and related food security concerns.

Accounting for risk and uncertainty in fisheries' adaptive decision making

The consideration of policy options and activities to minimise the negative impacts of climate change, to improve on mitigation and prevention strategies, and to maintain and build adaptive capacity in the face of an uncertain future was a topic of The High Level Conference on World Food Security: the Challenges of Climate Change and Bioenergy (FAO, 2008a). The list below identifies related approaches and decision support mechanisms with respect to the impacts of climate change (Table 6.7) and the toolbox response (Table 6.8) to account for risk and uncertainty in adaptive decision making in fisheries and aquaculture.

Enhanced ecosystem observation systems

The FAO Workshop noted the importance in planning for uncertainty of "developing the knowledge base" to take into account the greater possibility of unforeseen climate events. The knowledge base defines the enhanced systems required for ecosystem modelling, observation, and analysis. This includes ecosystem assessment of species' status (condition and abundance) including key supporting species in the food web, *e.g.* plankton production, prey species and predators, in a balanced perspective of ecosystem resources (FAO, 2008a).

This database is a collection of ecosystem data from all sources including scientists, fishermen, and occasional observers of the system. The knowledge base also includes a description of stock dynamics and species' life cycles (migration and timing and fish behaviour and ongoing predator-prey relationships and dynamics) and their interaction with the fisheries systems (the spatial and temporal analysis of the fishery and catches). The knowledge base provides key information for the planning and evaluation of future policy options for review by decision makers.

Issues of climate variability are well-known to the participants in the fisheries and aquaculture sector. They experience climate variability directly as part of their ongoing observations of the ecosystem. Consequently, the experience gained from observations by fishermen, processors, fish farmers and operational managers are extremely useful in documenting the changing climate and directing the simulated analyses, and trend models used for future planning. These parties need to be identified as data owners and important contributors to the overall knowledge base including the declared use and impact of their information.

Clarifying ecosystem objectives

Effective problem solving requires the clear, quantitative statement of the short-term targets and longer-term performance objectives associated with the delivery of the adaptive system. Moreover, these quantitative measures need to be subject to audit and accountability that is used as evidence for the performance of operational management decision making.

Further, the adaptive management approach recognises that different ecosystem objectives have different priorities for stakeholders in a responsible decision making framework. The multi-criteria objectives and the multi-participant context of fisheries management problem solving requires the application of group decision making methods for multicriteria decision making (Lane, 2007, 2008). The methods are well-known in the domain of decision theory and can be readily applied in fisheries and aquaculture settings to address risk and uncertainty. However, application of these approaches in support of fisheries management decisions is minimal.

Incorporating risk in precautionary measures

Adaptive fisheries management must embrace the inherent uncertainty of the ecological system. To do so, a description of the multi-faceted risk profile and trade-offs of the decision makers is required. This information is critical in evaluating and assessing alternative policy options. Risk profiles establish the perspective of the different decision makers with respect to the actual versus the target objectives of the policy evaluation

problem. These profiles are combined to establish policy priorities and ranked policy options in support of improved decision making (Lane and Stephenson, 1998b).

Building resilience in communities

Resilience refers to the coping ability or adaptation capacity of the fisheries and aquaculture sector to recover from negative external climate impacts. Mechanisms developed to assess community capacity to adapt to changing climate conditions are important for recognising and prioritising policy options (Sale *et al.*, 2008). Adaptation is constrained by the resilience of the natural systems in the evolution with human systems by their respective ability to cope with external climate shocks (Gunderson and Holling, 2002; Adger *et al.*, 2001). Adaptive fisheries systems build resilience in the coastal communities by advancing economic, environmental and social opportunities in the face of anticipated change.

Establishing flexible and timely seasonal management decision making

Adaptive decision making is applicable at the practical operating level and with minimal lag time for ongoing seasonal implementation. Specification of the well-defined problem situation, information sources, identification of the multiple objectives with targets, participants' risk profiles, and development of alternatives, permit the formulation of the in-season problem in a structured framework. This framework utilises spatial mapping and visualisation to simulate and animate hypothetical situations for participant analysis and discussion including exploring the impacts and response of adaptation and mitigation strategies to perceived and real threats.

Systems Dynamics (SD) techniques are useful for describing and linking environmental, economic and social baselines (Forrester, 1973). Spatial analyses are used to produce hypothetical cases of ecosystem shifts in local community ecosystems. SD projection models complement the delivery of participant-based discussion to identify areas of agreement in which to investigate future community environmental scenarios. Local adaptation planning and decision frameworks result from the group evaluation of the policy options leading to consensus on action planning for mitigation of fisheries and aquaculture problems.

Best practices and areas of further research

Building resilience to climate change and deriving sustainable benefits, requires that fisheries and aquaculture managers re-think the adoption and adherence of best practices in fisheries management response. Practical applications include those described in the FAO Code of Conduct for Responsible Fisheries (FAO, 1995) designed to reduce overfishing and rebuild fish stocks. These practices need to be integrated effectively with the management of the coastal zone, river basins, and watersheds. Applied policies for best practices are conceived from the indicated fisheries management toolbox responses (Table 6.8) and are provided below in this context.

Herbivore and multi-trophic aquaculture

Land-based aquaculture of herbivorous species provides nutritious food with a small relative carbon footprint in comparison with larger scale, international wild capture fisheries. Integrated multi-trophic aquaculture in marine sites involving finfish, filter

feeders, and seaweed production in close proximity offer mutually dependent systems that are self-regulating and mutually productive and provide an example of best practices in aquaculture. Farming of shellfish, such as oysters and mussels, helps clean coastal waters, while culturing aquatic plants and assisting waste removal from low water quality sites.

Shifts in fishing gear

Adaptive fisheries management seeks to reduce uncertainty and reduce GHG emissions. Mobile fishing gear obviates the inherent fluctuation of natural inter-seasonal variability by actively hunting migrating adult fish stocks while incurring significant GHG emissions. Alternative best practices point to shifts from mobile to passive or fixed gear approaches to wild capture fisheries. Mobile gear efficiencies reveal significant capability at hunting and capturing directed fish stocks to such an extent that species may be pushed to overexploitation. Passive gear configurations, by their nature, would reduce GHG emissions comparatively and could be configured to target capture of non-vulnerable stock components. Passive gear also encourages environmentally friendly and fuel-efficient fishing best practices attuned to natural fluctuations of species abundance.

Identification and protection of vulnerable species components

The historical mantra in fisheries science and management has been that of "spawn at least once" before recruitment to capture fisheries. The unfortunate consequence of this historical policy in efficient capture fisheries has been the systematic removal of the most productive spawners in the population and the eventual elimination of larger, older ages inevitably leading to stock decline and, in some case, collapse. The corollary of this mantra is the implicit protection of juvenile fish in the population. Alternatively, it may be more appropriate to designate productive spawners ("big fish") as worthy of protection as vulnerable population components, especially as regards reducing the risk of spawning event failures. Protection of spawners and the spawning event would appear to be a logical hedge against population decline and the negative impacts of reduced productivity from climate change impacts. Research into a switch using passive gear (see above) to exploit limits on more abundant juvenile stocks that are typically subject to high natural mortality may suggest significant returns to resource sustainability. The best practice example from the American lobster (*Homarus amercianus*) fishery in Atlantic Canada reveal that over 80% of juvenile lobsters have been regularly captured annually while spawning lobsters are protected. It is noted that this policy has resulted in burgeoning stocks and increasing landings.

Natural solutions

Mitigation solutions reducing the carbon footprint of fisheries and aquaculture require further innovative approaches found in nature itself. A natural example is inclusion of mangrove conservation as eligible for Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) funding, which demonstrates the potential for catchment forest protection (Pilkney and Young, 2009).

Technological innovation

Innovative technologies and more responsible practices can generate increased and sustainable benefits for fisheries and aquaculture. New technologies to encourage sustainable, environmentally friendly production, *e.g.* the use of biofuels produced from algae and seaweed are a promising and efficient innovation for fishing and aquaculture operations. Another promising innovation is new science used to identify options for carbon sequestration by aquatic ecosystems.

Climate change education

Climate change education in schools and in university cross-disciplinary programs in science, social science, and management create greater awareness within the community and among all stakeholders about the pending shifts in regional and local shifts in our environment. Enhanced education and public awareness sensitises the public to the need for change in adapting locally to climate impacts.

Examples of best practices provide the basis for future study and research. These items are therefore areas of recommended research into ways and means of responding to the impacts of climate change in fisheries and aquaculture and the development of adaptive policy setting.

Conclusions

This paper examines the strengths and weaknesses of modern fisheries management methods and its inability to deal with the risks and impacts presented by pending climate change. The paper also addresses management responses to climate change threats and impacts. Finally, the paper presents aspects of adaptive fisheries management methods as an effective means of re-alignment to adapt to climate change uncertainties. Adaptive fisheries management is characterised by a decentralised and devolved governance system with participation by responsible resource users working within an operational decision making framework that accounts for multicriteria trade-offs among multiple participants in the evaluation of fisheries and aquaculture policy options. Fisheries policy makers should develop strategies to adapt to climate change under uncertainty, taking into account ecological sustainability, social stability, economic viability, and administrative efficiency.

The conclusion to the rhetorical question of whether or not the fisheries management toolbox is sufficient to address climate change is answered by declaring that: (i) the toolbox is replete with historically developed measures that theoretically exert sufficient control of commercial fleets and operators for a myriad of situations including anticipated climate shifts; and (ii) in practice however, the toolbox has failed in delivering the declared objectives of fisheries management and is therefore not sufficient to address climate changes. Consequently, the findings of this paper with regard to the question are duly qualified.

The real question rests not so much with the toolbox and fisheries management measures, but who wields the tools. The evidence and criticism of the fisheries management toolbox indicate that government use of the tools in a command and control setting reduces the effectiveness and acceptance of the tools, and reduces the practicality of achieving stated objectives. An alternative role for governments would be to devolve management authority to users and act instead in an auditing and decision support role

rather than assuming the task of ensuring prosperity and sustainability. Local, spatial control on a scale compatible with local and regional climate observations, and associated property rights to communities and industry would enhance users' responsibilities and strategic perspective conducive to sustainability and viability.

In closing, policy makers need to address the following challenges in delivering adaptive fisheries management:

- Identify fishery and aquaculture sector partners

Adaptive fisheries management is focused on the inclusion of multiple groups including the government, the general public, as well as identified dependent subgroups (coastal communities, fishermen, aboriginal peoples), and amorphous "stakeholders" in the decision making framework. There is a clear need to identify partners as well as their respective roles and responsibilities in the management process, including observation and data collection, monitoring and enforcement, analysis and operational decision making in evidence-based decision-making.

- Renewed role of governments in adaptive fisheries management

Under adaptive management, government command and control in fisheries and aquaculture is devolved to sector partners. The idea is therefore that it is more effective for governments to "get out of the way" by adopting a more market-based orientation and assuming a supportive, public information, and fisheries and aquaculture auditing role. The difficulty with this change is that governments begin from a position of authority and are required to devolve this position. The challenge is to make governments see the net benefits of this response. The recent announcement by the New Zealand government has taken up this challenge by moving positively to provide the New Zealand Seafood Industry Council (SeaFIC) with increased authority to manage selected fisheries.

- Determining community dependence and adaptive capacity of fisheries and aquaculture

The evolution of adaptive management is dependent on the reliance, vulnerability, and adaptive capacity of the community. Better understanding is required about how the livelihood security of fishermen and farmers may be threatened by climate change combined with other social and environmental stressors. The challenge is to identify the potential and needs for livelihood transitions such as skills upgrading and education, and as well as individuals' future in fisheries and aquaculture faced with the uncertainty of the changing climate (Adger, 2006). It is likewise challenging to determine the mechanisms to strengthen fishermen's adaptive capacities pending climate change impacts including research on sustainable fisheries production systems, tenure security and equitable access.

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Chapter 7

The economics of climate adaptation and marine capture fisheries

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Climate change implies a certain degree of uncertainty in terms of temporal and spatial variations of fish populations, habitat viability and stability, and ecosystem interactions and feedbacks (Kirby et al., 2009). Since the ultimate effects of climate change are still unknown, one can only stress that fisheries policy makers and managers (should) be precautionary when assisting fishers, their communities and stakeholders to adapt to the bio-physical, social and economic consequences of climate change.

This paper provides a guide to policy makers and fisheries managers in terms of the economics of climate adaptation in marine capture fisheries, stressing the importance of designing and implementing flexible policies because of unexpected impacts and policy outcomes.

The "Promoting sustainable fisheries management" section provides an overview of the possible bio-physical effects of climate change on fisheries. "Resilience and adaptation ot climate change" describes how policy makers might promote resilience, invest in adaptation capacity and undertake adaptation to climate change. Then "Climate adaptation and fisheries management tools" itemises the possible fisheries management actions, tools and tactics to promote flexibility and resilience. It is followed by a section offering recommendations for further research and the final section concludes.

Introduction

In the coming decades climate change is expected to have substantial foreseen and also unexpected effects on the marine environment (Brander 2007, 2009). Not all of these impacts will be negative, but the changes will almost certainly increase the degree of uncertainty (Heal and Kristrom, 2002) in terms of temporal and spatial variations of fish populations, habitat viability and stability, and ecosystem interactions and feedbacks (Kirby *et al.,* 2009).

Policies that constrain and, ultimately, reduce emissions of anthropogenic greenhouse gases (GHGs) will mitigate the potential negative impacts of climate change on the marine environment. In the best case scenario, whereby world anthropogenic GHG emissions fall immediately and decline by 80 per cent within the next 20 years ─ a requirement to stabilise GHG concentrations in the atmosphere at levels that will make severe climate change extremely unlikely ─ there are still expected to be negative effects on the world's oceans from an elevated concentration of GHG and positive climate feedback effects. The more likely scenario is that the growth in anthropogenic GHG emissions slows and emissions peak sometime in the next two or three decades. In this case, climate change impacts will be magnified, especially by mid-century and beyond. Whether the ultimate effects of climate change are "mild" or "severe", prudent fisheries policy makers and managers should be precautionary and, at the very least, prepare a decision-making framework, strategies and tactics that, collectively, will assist fishers, their communities and stakeholders to adapt to the bio-physical, social and economic consequences of climate change.

This paper provides a guide to policy makers and fisheries managers in terms of the economics of climate adaptation in marine capture fisheries. It stresses that any policy should be flexible and be able to adjust to unexpected impacts and policy outcomes and, whenever possible, encourage and assist fishers and their communities to autonomously adapt to climate change. Further, it emphasises that there are "win-win" approaches in terms of best practice management that will be beneficial to fisheries in both the present and the future and that should be implemented regardless of possible climate change impacts.

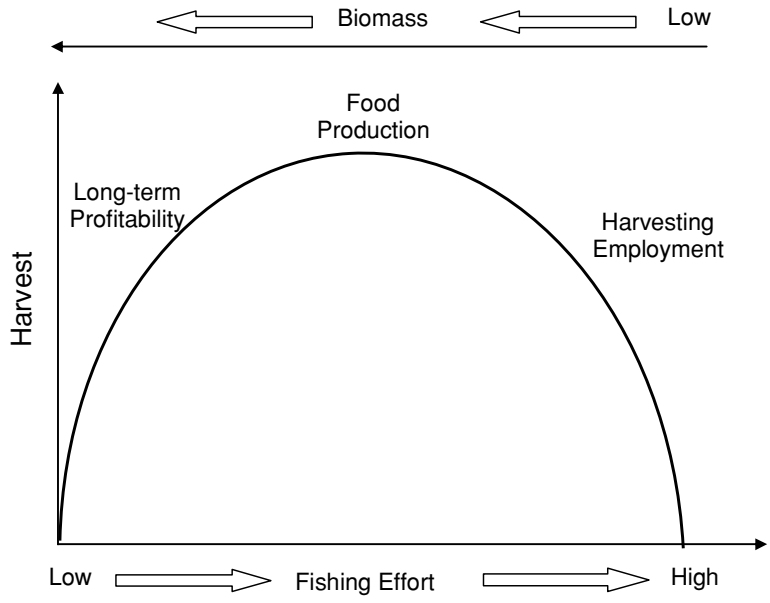
The following section reviews how the goals of policy makers and management instruments influence adaptation to climate change. The next, "Promoting sustainable fisheries management" provides an overview of the possible bio-physical effects of climate change on fisheries. "Resilience and adaptation of climate change" describes how policy makers might promote resilience, invest in adaptation capacity and undertake adaptation to climate change. The following section provides: (1) a framework to assess inter-temporal trade-offs and when to undertake adaptation; (2) a risk-based decision-making process; (3) a risk and simulation approach to guide policy makers when assessing vulnerabilities and choosing between alternative adaptation strategies; and (4) best practice fisheries governance to improve the effectiveness of adaptation. Then "Climate adaptation and fisheries management tools" itemises the possible fisheries management actions, tools and tactics to promote flexibility and resilience. It is followed by a section offering recommendations for further research and the final section concludes.

Promoting sustainable fisheries management

To effectively adapt to climate change policy makers, fisheries managers, fishers and their communities must have clearly defined and quantifiable objectives of what they wish to achieve. Managers typically have a number of goals that include maintaining employment, maximising the long-term profitability of the harvesting sector, promoting viable fishing communities and sustaining fish stocks and marine ecosystems. The FAO Code of Conduct for Responsible Fisheries, adopted by almost all coastal states, requires signatories to prevent overfishing and excess capacity, conserve non-target species and protect critical fisheries habitats, as far as possible (FAO, 1995).

Different management goals generate different fisheries outcomes. If managers wish to maximise the sum of the discounted economic returns from fishing then low—levels of fishing effort and, ultimately, higher fish stocks are preferred (Grafton *et al.*, 2007a). If employment maximisation is the goal then higher levels of fishing effort and lower fish stocks may be preferred. The implications of different goals for fishing effort are presented in Figure 7.1. The relevance in terms of adaptation to climate change is that goals that promote higher levels of fishing effort and lower stocks in the current state of the world may be less desirable in an environment subject to greater uncertainty due to climate change if it increases the risk of unsustainable harvesting. Conflicting goals are also problematic because if fish populations decline, possibly due to climate change, managers may seek to maintain current rates of employment even if it jeopardises long-term sustainability (Cochrane *et al.*, 1998).

Figure 7.1. Objectives of fisheries management, fishing effort and biomass

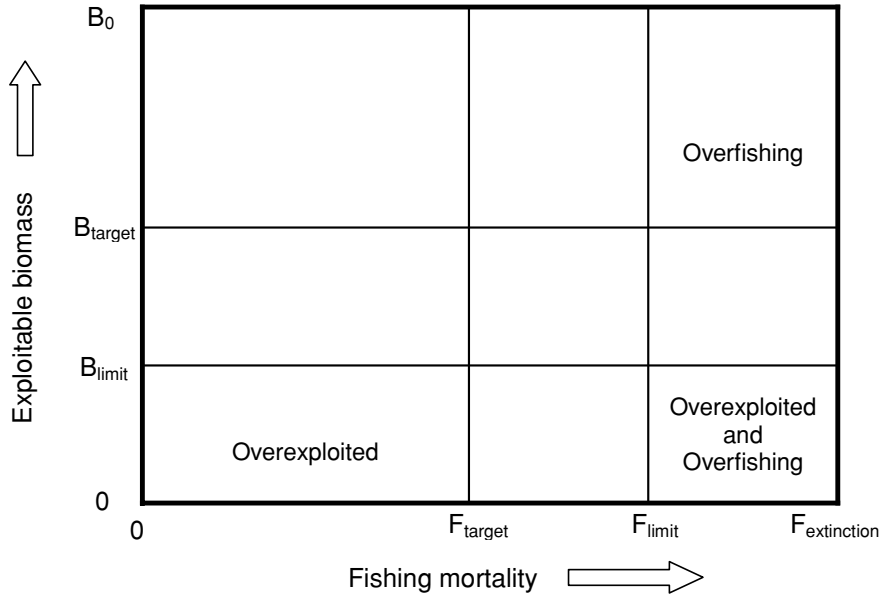


Management targets

In Organisation for Economic Co-operation and Development (OECD) countries, sustainability is often implemented through the use of target and limit-reference points, usually defined in weight of fish (biomass) in the ocean, and implemented through a

combination of effort restrictions and harvest strategies. For instance, in the United States 1996 *Sustainable Fisheries Act*, target species are designated overfished if current biomass is less than the biomass which maximises the sustained yield (B_{MSY}), a target reference point. In theory a fishery below its target biomass, but above its limit reference point, would have strategies to rebuild the stock while still allowing some harvest. The strategies, however, to achieve the defined management objectives can vary substantially across fisheries and between jurisdictions. Figure 7.2 shows a typical "strategy box" that relates biomass reference points to fishing mortality and whether the fishery has been overexploited and if there is overfishing. Should climate change result in a more uncertain biomass subject to greater shocks then these targets and limits should also adapt to manage these risks.

Figure 7.2. Limit and reference points in fisheries management



In recent years, a broader and more integrated management in the form of an ecosystem-based approach to fisheries has been enacted in many OECD fisheries to ensure that interactions across species, including by-catch species, and habitat impacts are accounted for in decision making and to promote ecosystem health. The ecosystem approach encourages managers to employ spatial controls on fishing and restrictions on fishing gear and practices to reduce by-catch. Thus, it goes beyond the management of target species to include the marine ecosystem (Pikitch *et al.*, 2004). The broader and the more comprehensive are the management targets associated, however, the more likely it is that at least one of these targets will be affected by climate change. Thus, how fisheries are able to adapt to climate change, and the resources that will be required for this purpose, is intimately related to management goals or target.

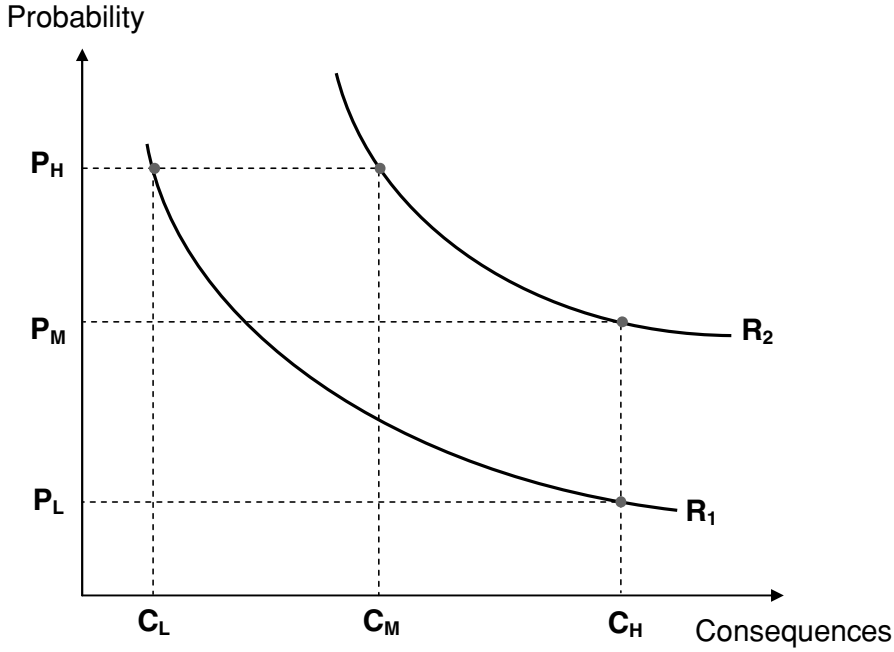
Management instruments and risk

Although target reference points do vary across countries with some specifying bio-economic targets (Smith *et al.,* 2009), the principal difference across management regimes is the choice of instruments used to achieve the targets. Incentive-based approaches (Grafton *et al.*, 2006), such as dedicated catch shares, encourage fishers to autonomously adapt to change in a "bottom-up" way while command-and-control methods foster change via "top-down" structures. Incentive-based fisheries management stresses the importance of fisher behaviour, their incentives and motivations to indirectly generate desired outcomes (Hilborn *et al.*, 2005) while command-control management involve constraints and regulations designed to directly achieve desired goals.

Both incentive and command-and-control approaches can be used simultaneously and each has its merits. For instance, dedicated catch shares provide incentives to avoid the "race to fish", but cannot be successfully implemented unless a total allowable catch (TAC) is set and enforced by a regulator that ensures the long-term sustainability of the fishery.

The existing set of management instruments will almost certainly need to be expanded to help fisheries adapt to climate change. For instance, management that tries to sustain target species will not be successful without ensuring habitat or marine ecosystems are sustainable given climate-induced changes in the marine environment. The preferred instruments or tools will depend on the nature of the problem posed by climate change, the magnitude of the change, and the degree of uncertainty about the change. In a risk assessment-based approach to climate change adaptation, the likelihood of a given change and its expected consequence or effect together helps to determine the preferred instrument(s). This is illustrated in Figure 7.3 with a probability-consequence risk trade-off in two states of the world. In the current state of the world without climate change, given by risk trade-off curve R_1, low probability events but with a high consequence or negative impact may be viewed as equivalent to high probability events with a low consequence. The risk trade-off curve R_2 shows what might arise with climate change when the consequences of an event increase even if the probability of the event remains unchanged while the probability of an event can increase even if the consequence does not. Every point along a curve generates an equivalent level of risk, but all points on R_2 represent a higher level of risk than R_1.

Figure 7.3. Managing risk with climate change



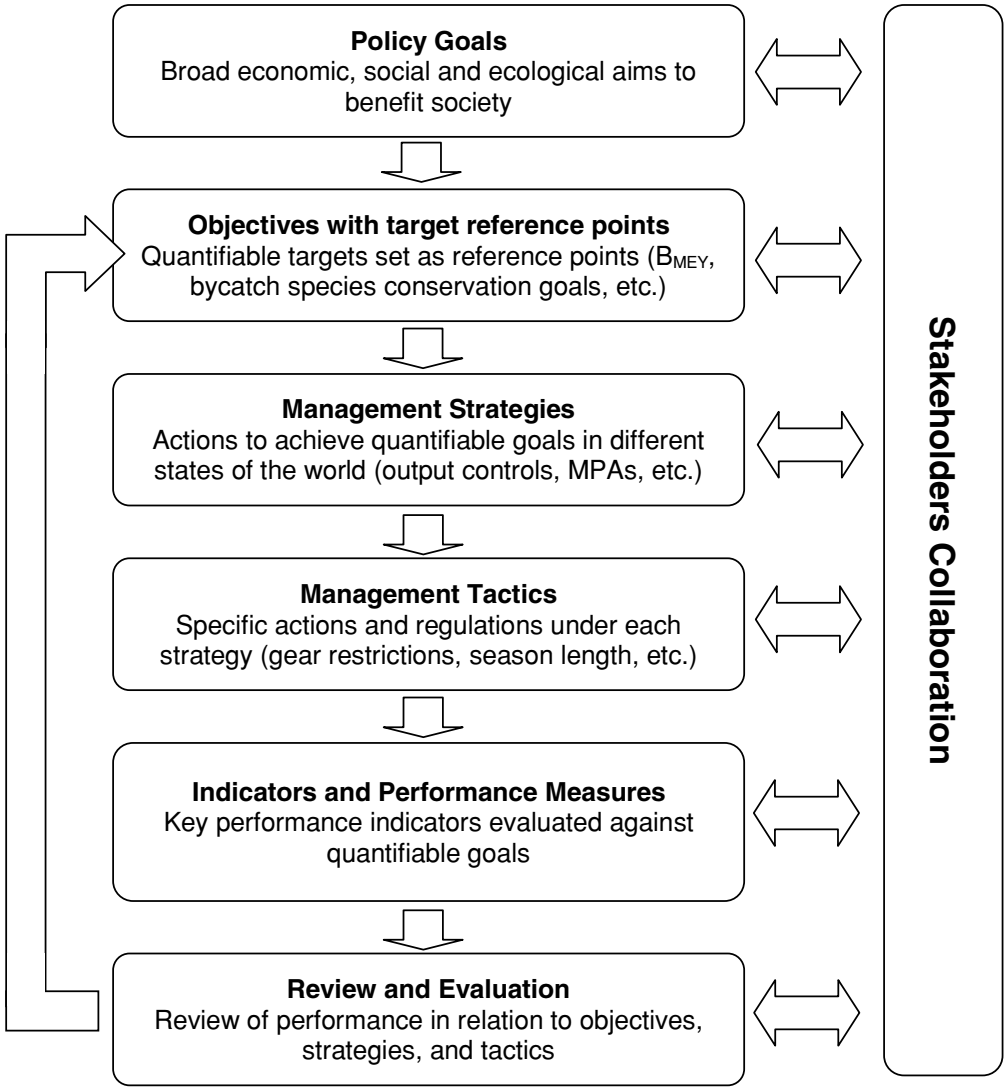
A high probability event, but with a low consequence (P_H, C_L) under current management, such as "high grading" of fish at sea, may be effectively managed in the current state of the world (R_1) by incorporating the estimated this extra mortality in stock assessment models. However, with climate change the risk of high grading may be greater (R_2) even if the probability of high grading remains unchanged, as represented by (P_H, C_M), because of greater uncertainty in terms of the stock size. In this more risky state of the world with climate change, additional management measures, such as improved monitoring at sea, may be required to reduce the consequences of high grading. Similarly, in the current state of the world a low probability event with a high consequence (P_L, C_H), such as a recruitment failure due to higher ocean temperatures, may not be even be planned for because the probability of the event is currently too small. However, with climate change and an increase in the probability of the event, the risk becomes (P_M, C_H) with existing management measures. As a result, fisheries regulators may wish to establish additional management measures in response to a higher probability of recruitment failure. The key point is that instruments developed in the current state of the world to manage a given set of risks will need to be adapted to a riskier world associated with climate change.

Adaptive management and resilience

Adaptive management is a process whereby goals are quantified and the strategies and tactics developed to achieve these aims, but are flexibly adjusted to new information and circumstances (Walters and Hilborn, 1976). Its importance to fisheries is that it provides a method to flexibly manage and change actions as new information is provided to decision makers. The greater the uncertainty about the future the less able managers are to predict the consequences of their actions and the more valuable is an adaptive approach to decision making. This adaptive cycle is illustrated in Figure 7.4. Its importance in

terms of climate change adaptation is that not all impacts will be foreseen and fisheries managers will likely need to flexibly respond to large and unexpected shocks by changing existing management strategies and tactics. It is a "robust" management approach as it confronts uncertainty by evaluating and updating actions in response to change so as to achieve desired objectives under various states of the world.

Figure 7.4. The fisheries adaptive management cycle



While adaptive management allows decision makers to be more effective *ex-post* in an uncertain world, the concepts of resilience provide guidance about how to assist fish populations, ecosystems and people to *ex-ante* adapt to undesirable shocks. Resilience can be defined in various ways but it is essentially about how systems (bio-physical and socio-economic) are able to respond to change or shocks while maintaining their key characteristics or "identity". Two widely used resilience definitions are: (1) Holling-resilience that refers to how capable is a population or system to stay within a set of boundaries and maintain its "identity" following a shock (Holling, 1973) and (2) Pimm-

resilience which refers to how quickly a system returns to within some neighbourhood of its previous state following a shock (Pimm, 1984).

The relevance of resilience in terms of climate change is that if a current state of the world is desirable, actions that allow systems to stay within a boundary of their desired state, or to return to it quickly if perturbed, are valuable. Consequently, management instruments that promote resilience, all else equal, are desirable. For example, it has been shown that even with optimal TAC, setting appropriately designed marine reserves increase both Holling and Pimm-resilience (Grafton *et al.*, 2009). Thus, the establishment of appropriately sized and located marine reserves is a precautionary response that can promote resilience of marine ecosystems that may, in turn, assist in the adaptation to climate change.

Socio-economic resilience in terms of fishers and their communities refers to how they are able to maintain their livelihoods and desired ways of living, without outside assistance, following undesirable shocks. For instance, it would include their flexibility to substitute to more abundant fishery resources or to alternative economic activities to help offset declines in harvests from targeted fisheries. The greater proportion of a fishing community employed in a particular capture fishery, the fewer alternative employment activities available within the community, the greater the distance to other communities, and the more specialised the job skill set within fishing the less resilient will communities likely be to shocks associated with climate change.

Fisheries effects of climate change

The specific effects of climate change on particular marine ecosystems and fish populations are difficult to predict and quantify. However, on a global and regional basis there is sufficient research to indicate that many, but not all, of these impacts will be negative. The consequences of climate change include primary or direct effects due to sea-level rise, sea temperature change, lower ocean pH levels, changes in rainfall that will affect estuarine fisheries, and changes in ocean circulation. These primary effects will, in turn, alter habitats and change the distribution and mix of species that will have a profound impact on fisheries and marine ecosystems (Brander, 2007).

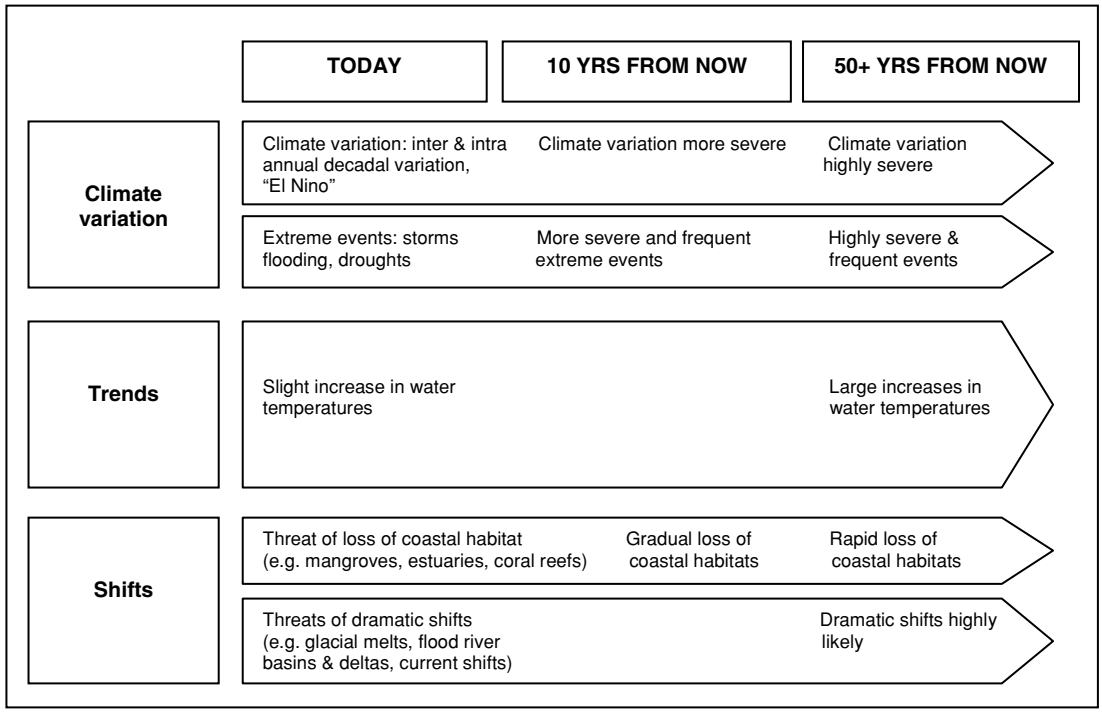
The impacts of climate change, at least in the short run, may only affect a relatively small proportion of fishes, but longer-run indirect effects are likely to have major implications on all marine ecosystems (Cinner *et al.*, 2009). Not all of these impacts will be predictable or proportional to the bio-physical change. For instance, unexpected and non-linear effects of climate change (Brander, 2009), possibly exacerbated by fishing pressure, could result in shifts that favour lower-trophic species, such as jellyfish, at the expense of high-valued species, such as cod (Kirby *et al.*, 2009). The fish populations and ecosystems most at risk with climate change will be those that are already: (1) near their physiological limits in terms of temperature, salinity and pH; (2) severely compromised in terms of their resilience due to existing anthropogenic factors, such as overfishing; and (3) are in locations most likely to suffer climate change impacts.

Some of the direct effects of climate change are predictable although many are not. For example, higher concentrations of CO_2 in the atmosphere will lower the pH level of the sea as it changes the carbonate-bicarbonate ion balance. This, in turn, is expected to have a negative impact on corals and calcifying invertebrates and some vertebrate species whose larvae are relatively sensitive to increased acidity (Moy *et al.*, 2009). Higher ocean temperatures are expected to generate shifts of existing fish populations to higher

latitudes to cope with the change. Shifts in the geographical location of fishes will not only occur in terms of target species, but also for pathogens and parasites that will migrate and may generate population declines, especially for sedentary species that may have had no prior exposure (Rahel and Olden, 2008). Sea-level rise coupled with a higher incidence of intense storm activity is expected to have negative impact on coastal breeding grounds of some key species, such as prawns. Changes in ocean circulation are also expected to reduce new primary productivity in key fishing areas (Behrenfeld *et al.*, 2006) although some locations may benefit from these changes, such as the Arabian Sea (Goes *et al.*, 2005).

A synthesis of the expected effects of oceanic climate change is provided in Figure 7.5 in terms of climate variations, trends and shifts. Many of the severe impacts are projected to occur several decades hence, but less pronounced effects are expected within 10-20 years, and some impacts are already occurring as the location of fish populations shift in response to temperature change. The consequences on fishing and coastal communities will be determined by: (1) their climate change exposure, as some locations will be more affected more than others; (2) the sensitivity of climate change in terms of targeted species and the ecosystem on which fishers and communities depend; and (3) on the fishers and their communities' ability to adapt to change. Artisanal fishers who are confined to harvesting in a very limited geographical area and who have few, if any, alternative sources of income are likely be the most vulnerable to climate change as they will have least ability to adapt. By contrast, more mobile fishers with an ability to catch different species using alternative gears over a wide geographical area, and with the capacity to borrow and access credit so as to manage climate variability, will be more able to adapt to climate change.

Figure 7.5. Synthesis of the dimensions of climate variation, trends, and shifts in marine ecosystems

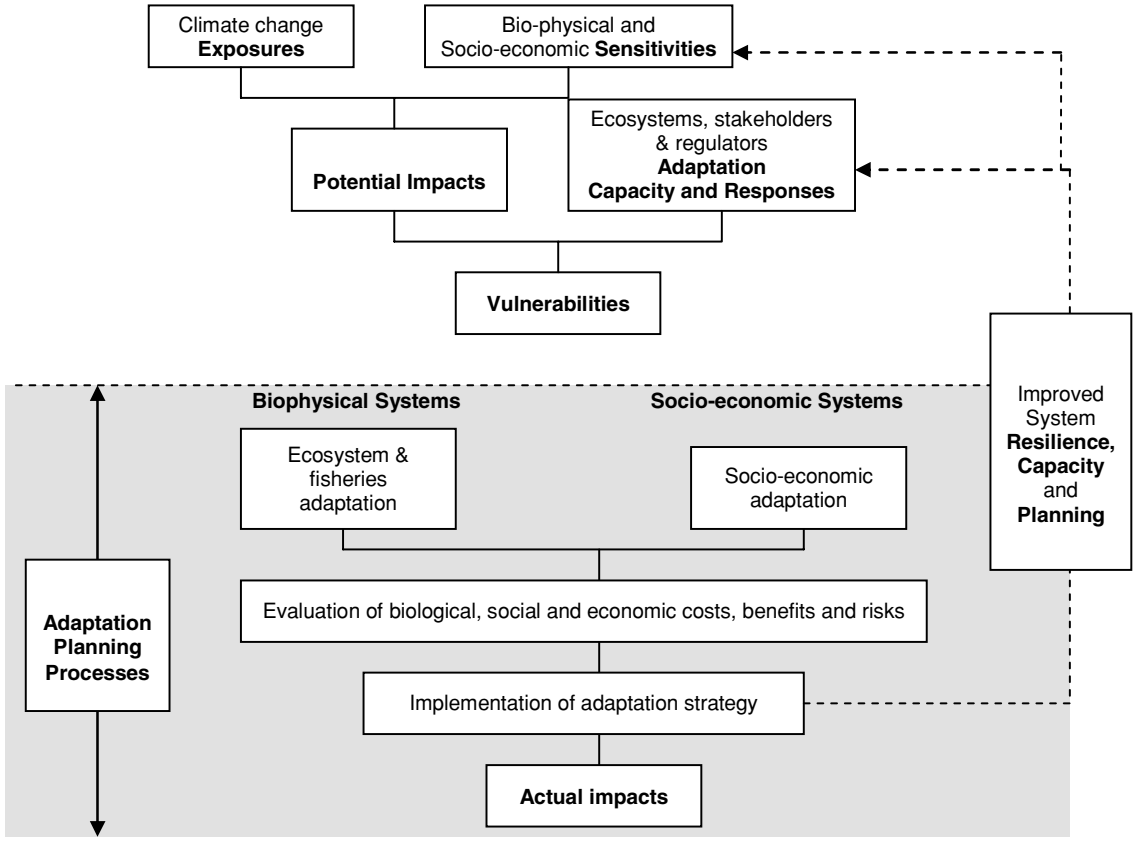


Source: FAO (2007, p.4

Resilience and adaptation to climate change

A heuristic for assessing the potential impacts of climate change that combines both bio-physical and social vulnerability measures is illustrated in Figure 7.6. At the top of the figure are the exposures to the bio-physical drivers of climate change and the sensitivities (bio-physical and socio-economic) that describe the degree to which the systems respond to climate change. The potential impacts are determined by the amount of exposure and the sensitivities that together determine the vulnerabilities or the potential for harm from climate change. The actual impacts, however, are determined by the capacity of bio-physical and socio-economic systems to adapt and the actual adaptive responses that are influenced by the adaptation planning processes described at the bottom of Figure 7.6. Thus, actual impacts of climate change can be reduced by: (1) promoting resilience so as to reduce system sensitivities; (2) increasing adaptation capacity and effectiveness of adaptation responses and (3) improving the adaptation-planning processes.

Figure 7.6. Adaptation capacity, planning and vulnerabilities to climate change



Source : Adapted from Pecl *et al.* (2009)

Promoting resilience

Reducing bio-physical sensitivities of climate change is essentially about promoting the resilience of marine ecosystems and fish populations. Promoting resilience is analogous to building walls or shelter before a storm. It does not prevent the storm from occurring but reduces its impact. Desirable strategies to promote resilience must be developed at a fishery level because marine ecosystems, fish populations and communities are likely to have different structures and feedbacks. In all cases, however, the strategies should allow the bio-physical and socio-economic systems to "bounce back" and help maintain their "identity" following undesirable shocks.

A useful way to develop strategies for resilience is to map the network structures within the bio-physical and socio-economic systems and the connections between them. Some "linkages" may need to be strengthened to help fish populations respond to shocks such as changing gear selectivity to ensure a population with a wider distribution of aged cohorts. By contrast, undesirable linkages such as subsidies and other payments that keep fishers in particular locations and enterprises may need to be diminished or removed to respond to allow them to effectively respond to environmental signals and avoid "lock in" of undesirable and inflexible fishing behaviour.

Strategies that could be helpful in promoting resilience in a bio-physical sense include: lower rates of fishing mortality; larger exploitable biomass of targeted species and increased "no take" areas that may provide a buffer stock in the face of unexpected shocks (Grafton and Kompas, 2005; Grafton *et al.*, 2009). A lowering of socio-economic sensitivities and increased socio-economic resilience could arise from economic and regional development and improved infrastructure (human and physical) that create opportunities to a wider set of opportunities to residents of fishing communities.

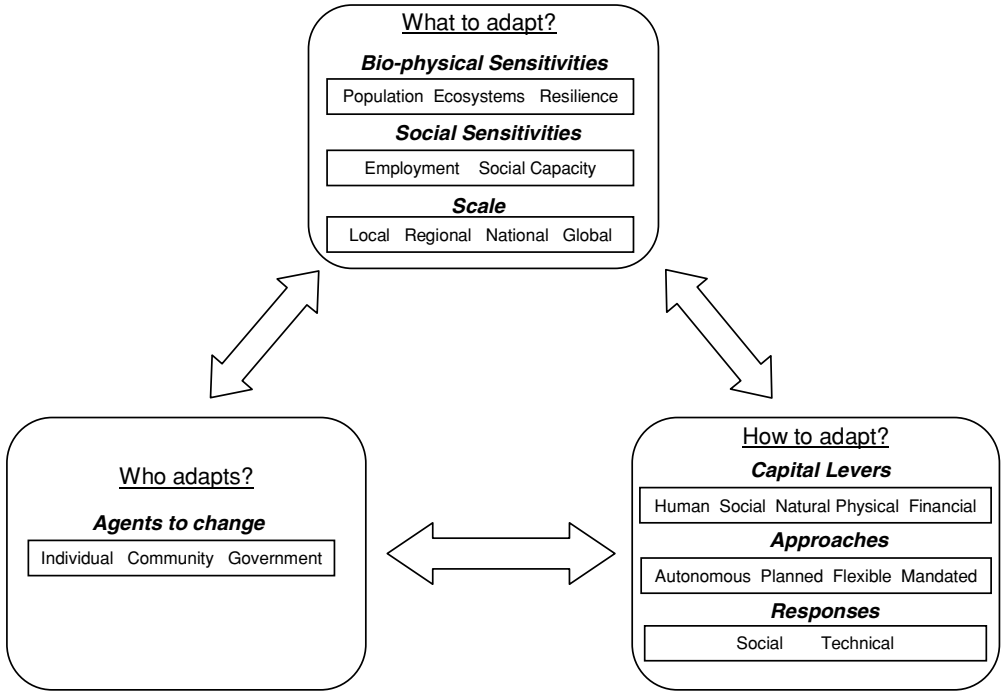
Adaptation capacity

The key to confronting climate change impacts is ensuring adequate adaptation capacity and effective adaptation responses that exist at: (1) an ecosystem and fish population level; (2) an individual, community and stake-holder level; and (3) at a decision-maker, regulator or planning level. Adaptation capacity is about empowering socio-economic systems to respond to climate change. It is different to the actual adaptation response. For instance, poor countries are likely to have much lower adaptation capacity than rich countries. This is shown by Allison *et al.* (2005) who use measures of exposure, sensitivity and adaptation capacity and find that fishers and their communities in semi-arid countries with substantial coastal and/or inland fisheries, many of them in Africa, are the most vulnerable. The greater adaptation capacity of rich countries, however, does not necessarily mean that their adaptation responses will be more effective. For example, rich countries could use their greater financial resources to provide subsidies to assist fishers stay fishing if incomes decline due to climate change, but such actions are maladaptive and will likely increase vulnerabilities.

Many strategies are available to augment adaptation capacity. Building this capacity can help overcome present and future constraints that may arise from inadequate financial resources, inappropriate governance structures (Grafton *et al.*, 2007b) and lack of information or knowledge. A useful way to evaluate these constraints or barriers is to pose the following questions: (1) Who should adapt? (2) What should be adapted? (3)

How to adapt? These queries, collectively, form a ”triangular” adaptation process, as illustrated in Figure 7.7.

Figure 7.7. Triangular adaptation process



Source : Adapted from Preston and Stafford-Smith (2009)

The “who” refers to those that undertake adaptation and includes: individuals; communities; and governments. Communities and governments have a comparative advantage in large-scale adaptation planning processes that require substantial resources over longer time periods. By contrast, individuals are better suited to adjusting to immediate short-run changes or shocks that are within their historical experience. The “what” addresses the scale of adaptation (local, regional and national), and also the possible extent of adaptation in terms of bio-physical sensitivities and socio-economic sensitivities. The “how” examines the resource or capital that is available (financial, human, natural) for adaptation and the approaches (bottom-up or top-down) that can be used to respond to climate change.

Adaptation processes

Multiple approaches are available to facilitate adaptation to climate change. A useful way to classify these processes is whether they are autonomous or planned; flexible or mandated; and social or technical. In practice, these approaches are not dichotomous and policy makers will likely wish to draw upon a range and mix of responses to help adapt to climate change.

Autonomous versus planned adaptation

Climate adaptation is about responding to the direct and indirect effects of climate change. Typically this is viewed as a planned response, but many forms of adaptation will occur informally. For example, if climate change reduces the availability of the current target species then fishers may end up catching a greater proportion of alternative species without changing their current fishing behaviour. By contrast, planned adaptation to this impact would involve a conscious decision to switch fishing grounds, use different gear or to deliberately target other species.

A key to improving adaptation capacity is about assisting stakeholders in their planning processes. This is because although fishers may have a great deal of tacit knowledge they may lack the data, models and methods to assess the possible long-term effects of change. Such knowledge would typically reside with regulators and marine fisheries research agencies. Planned adaptation should, therefore, involve collaboration that mutually transfers knowledge to help fishers, communities and policy makers to improve the quality and scale of their own adaptation responses.

Flexible versus mandated adaptation

Climate adaptation can be both a "top-down" and a "bottom-up" process. Typically "top-down" management is about mandating certain actions imposed by regulation so as to manage environmental and climatic variability. For example, restrictions on what fishing gear can be used, when and where provide limits on the effects of fishing mortality, especially at periods of vulnerability such as spawning times. These approaches work best when there is a firm understanding of causes and effects developed from research, the tacit knowledge of fishers and stakeholders, and trial and error. Under rapid climate change, with unexpected effects, mandated approaches may not be adequate in promoting effective adaptation, and may not respond quickly enough to negative shocks. For example, mandated vessel licensing provisions that prevent fishers from participating in a variety of fisheries make it difficult for fishers to adjust to variations in fish populations. By contrast, allowing fishers the flexibility to participate in many different fisheries, while maintaining desired levels of fishing mortality for each species, could reduce the socio-economic sensitivities of climate change.

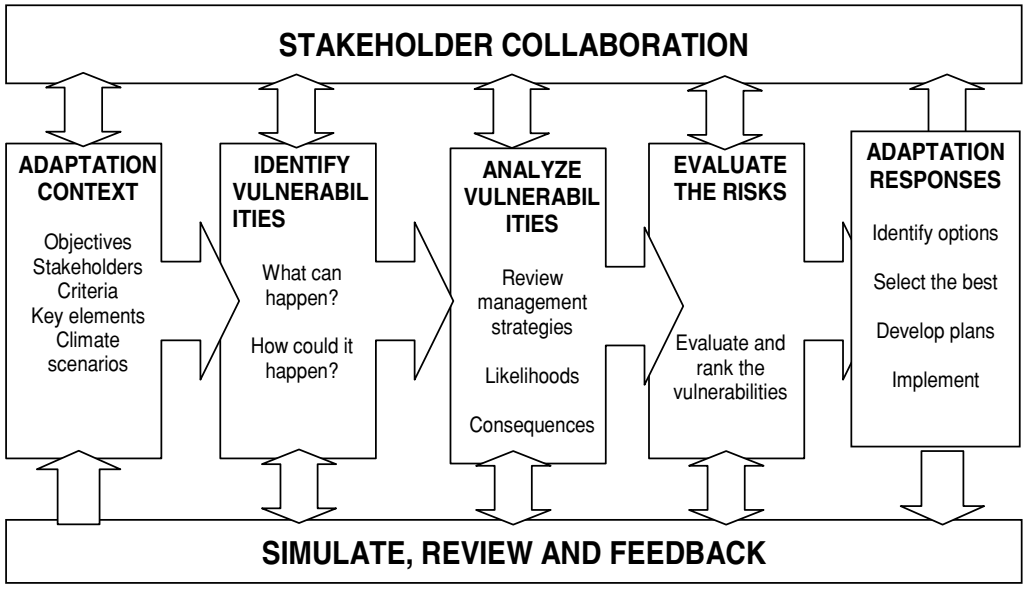
Social versus technical adaptation

Social adaptation is how communities and networks of fishers and stakeholders collaborate to respond to change. Such adaptation is important because it: (1) brings together and integrates different knowledge sets and experiences; (2) promotes sharing of risk across stakeholders; (3) assists in collective decision making about the delivery of common services and public goods enjoyed by them. Promotion of social adaptation may also contribute to socio-economic resilience as it provides additional governance arrangements to "back stop" more formal management structures. Technical adaptation focuses on technological advances and innovations that will assist in reducing the consequences of climate change (Tomkins and Adger, 2004). For instance, technical innovations that reduce by-catch and support biodiversity may increase the resilience of marine ecosystems. Both forms of adaption (social and technical) are important to effectively respond to climate change.

Risk assessment and management for adaptation decision making

A risk framework to assist with climate adaptation decision making is provided in Figure 7.8. It consists of five inter-connected steps: (1) delineation of the adaptation context that includes management goals, description of the stakeholders and agents of change and the relevant climate change scenario; (2) a description of the exposures, impacts and vulnerabilities being evaluated; (3) a review and assessment of the current fisheries management strategies and tactics, and an assessment of current adaptation strategies in place to manage climate change variability and risks from climate change; (4) ranking of the possible exposures, impacts and vulnerabilities in terms of their significance; and (5) consideration of the adaptation options to manage the vulnerabilities and risks from climate change. Throughout these five steps there should be effective communication and consultation with stakeholders and explicit monitoring and review of actions that feeds back into the decision-making process.

Figure 7.8. Vulnerability assessment and the adaptation decision-making process

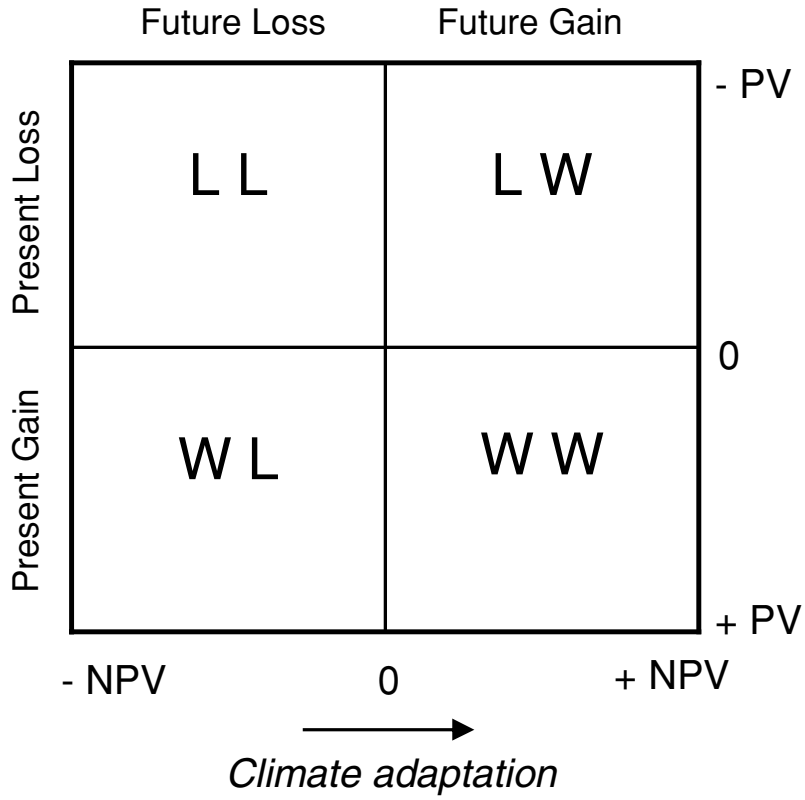


Inter-temporal adaptation

A critical part of the adaptation decision-making process is when to adapt, before the effects are evident, or subsequent to their impacts. In many cases, adaptation involves a mix of *ex-ante* and *ex-post* responses. However, adaptation is not costless and deciding when to adapt involves trade-offs between the present and the future and consideration of the risk and returns of adaptation investments. A framework to help understand these trade-offs is presented in Figure 7.9 using a common metric that monetises costs, benefits and also risks. On the horizontal axis is the monetary loss or gain in terms of the net present value from adaptation over the long-run that may involve a planning period of several decades. The vertical axis represents the monetary loss or gain in net present value terms from adaptation in the short-run, typically no more than three to five years. The four parts to the decision box represents the inter-temporal payoffs. The two squares to the left of the line that bisects the box vertically represent actions that, over time, will

generate a negative net present value while to the right are actions that will generate a positive net present value. The two squares below the line that bisects the box horizontally are actions that generate a positive net present value in the short run while the two quadrants above this line generate a negative present value. In terms of the inter-temporal trade-offs, climate adaptation can be visualised as a process that tries to increase the payoffs in the future, possibly at the expense of increased costs and lower returns in the short run.

Figure 7.9. Inter-temporal climate adaptation framework



The four quadrants in Figure 7.9 represent the present and future payoffs of climate adaptation. The "lose-lose" (L L) quadrant represents adaptation actions that generate losses both in the short and long run while the "win-win" (W W) quadrant represent actions that generate positive net returns today and also into the future. The other two quadrants represent action space that may, or may not be, desirable depending on the non-economic benefits and costs that may be used in the adaptation planning process. The larger the discount rate is the greater will be the set of "win-lose" (W L) actions that generate positive payoffs in the short run, but net economic losses overall. Conversely, the smaller the discount rate is the larger is the set of "lose-win" (L W) actions that generate transitional costs or losses in the short run, but positive net returns when evaluated over all time periods.

The inter-temporal trade-offs show that win-win actions should be implemented immediately while lose-lose actions should never be undertaken. Examples of win-win strategies are those that increase the net returns today and also into the future and would

include appropriately designed dedicated catch shares that can reduce harvesting costs and increase revenues (Grafton *et al*., 2000) or gear restrictions that increase yield per recruit. Lose-win actions such as stock rebuilding may initially generate short-run transitional costs, but result in an overall positive net present value that may be very large (World Bank, 2008). Examples of such actions would be harvest controls that reduce the current harvest to rebuild the overall biomass and that are likely to promote bio-physical and socio-economic resilience. Such controls can increase the net present value of returns from fishing (Grafton *et al.*, 2007), but typically with short-run transitional costs. Win-lose actions provide positive short-run gains, but possibly at the cost of maintaining unsustainable or high risk levels of exploitation of targeted populations that result in an overall negative net present value. Examples of such actions would be deliberate recruitment overfishing to maintain higher levels of short-run employment in a fishery.

Climate change could promote either lose-win or win-lose strategies depending on the potential impacts and characteristics of fisheries. For instance, the rebuilding of fish stocks is likely to become more favoured if the expectation is that increasing the resilience of a fish population will enable it to be sustained with climate change. Such an approach is consistent with the FAO Code of Conduct and is precautionary. By contrast, if there is no expectation that a fish stock can be sustainably exploited because of climate change, regardless of any conservation action, then harvesting at unsustainable levels in the present may be considered appropriate by some fishers (Johnston and Sutinen, 1996) although it would be contrary to the stated sustainability objectives in many jurisdictions. Understanding which strategies or actions are desirable and their net benefits (costs, benefits and risks) requires an evaluation of the vulnerabilities of climate change and a risk and simulation approach to evaluate different vulnerabilities and adaptation responses.

Vulnerability assessment

To decide when and also how to adapt to climate change, decision makers need to undertake a vulnerability assessment. If there are limited financial resources, personnel and also information available as to the exposure and sensitivities to climate change, the decision making process outlined in Figure 7.8 may be abbreviated to an initial assessment that reviews the possible vulnerabilities in terms of failing to achieve key management objectives. A possible scale-based approach to the prioritisation of vulnerabilities in an initial assessment would include: (1) catastrophic vulnerabilities (key management objectives would not be achievable and there is little or no expectation of them being realised under current or alternative strategies); (2) major vulnerabilities (key management objectives would not be achievable with existing strategies but alternative strategies offer potential pathways to realise these goals); (3) moderate vulnerabilities (key management objectives would be placed at considerable risk without a change in strategies and/or tactics); (4) Minor vulnerabilities (key management objectives are achievable with existing strategies and only minor change in tactics is required); and (5) Insignificant vulnerabilities (key management objectives are achievable and no immediate action is required). The assessment of these scales would be reviewed periodically and could be undertaken using a risk and simulation approach to assess climate change vulnerabilities and reviewed through collaborative stakeholder workshops.

An integral component of the initial adaptation assessment is to describe in detail the policy context and have this reviewed by key stakeholders. Following this feedback, and

either as part of existing management planning processes with stakeholders or as an additional activity, fisheries managers and stakeholders would work together in collaborative "vulnerability and adaptation" workshops. These workshops would be an important step in building and supporting adaptation capacity and would seek to: (1) identify key vulnerabilities; (2) analyse existing strategies and tactics to respond to potential climate change impacts; and (3) prioritise actions to help bio-physical and socio-economic systems respond to the most significant impacts, as identified in the planning process.

Adaptation of fisheries that cross multiple jurisdictions and institutional boundaries will, in general, be more difficult than in a single state or country. This is because stakeholders and decision makers will likely have more disparate objectives and methods of management. For instance, coastal states may be more concerned about sustainability of their own fisheries than stakeholders who harvest the same stocks in the high seas. Where agreement on what adaptation measures are required, co-ordination across stakeholders in terms of who does what and who pays will also likely be more difficult as they will be greater incentives to "free ride" on the efforts of others. Rather than developing new institutional structures, existing institutions for co-operation such as regional fisheries management organisations (RFMOs), and bilateral arrangements, should be used to facilitate the dialogue necessary to develop adaptation decision-making processes for high seas fisheries and straddling stocks.

Risk and simulation

As much as possible, the categorisation of vulnerabilities should use a common and quantitative metric to allow comparison across vulnerabilities. A risk-adjusted monetary metric is one alternative that explicitly accounts for the probability or likelihood of a climate change occurrence and the consequences or the costs of such an event, as illustrated in Figure 7.3. This can be implemented using a "risk and simulation" approach that has been used in cost-benefit and risk-benefit analysis (Campbell and Brown 2003). Its implementation requires the use of Monte Carlo simulations to construct a probability density function for: (1) the expected losses associated with specific climate change impacts and (2) the expected net benefits of given adaptation responses or investments in adaptation capacity.

In almost all cases, decision makers will not know the underlying distribution of potential costs associated with different climate change impacts, but may have some idea about the upper and lower bound of these costs. To account for this uncertainty, alternative distributions (uniform, triangular, normal, gamma, etc.) can be used to assess the payoffs of investments in adaptation capacity or in particular adaptation responses. For example, a decision maker may expect the costs of an increase in sea temperature on a given fishery to range from \$0 to \$10 million. If the decision maker assumes a triangular distribution for these costs then a "most likely" value must also be estimated or determined by subjective judgment. If the most likely value is \$2 million then the resulting probability density function is given in Figure 7.10. Assuming a different "most likely" value or a different distribution would generate a different probability density function. For instance, if a histogram probability distribution were assumed, but with the same lower and upper bounds on the costs and specific probabilities (0.1, 0.4, 0.3 and 0.2) assigned to each quartile, then the probability density function would be as presented in Figure 7.11.

Figure 7.10. Probability density function of a hypothetical vulnerability (triangular distribution)

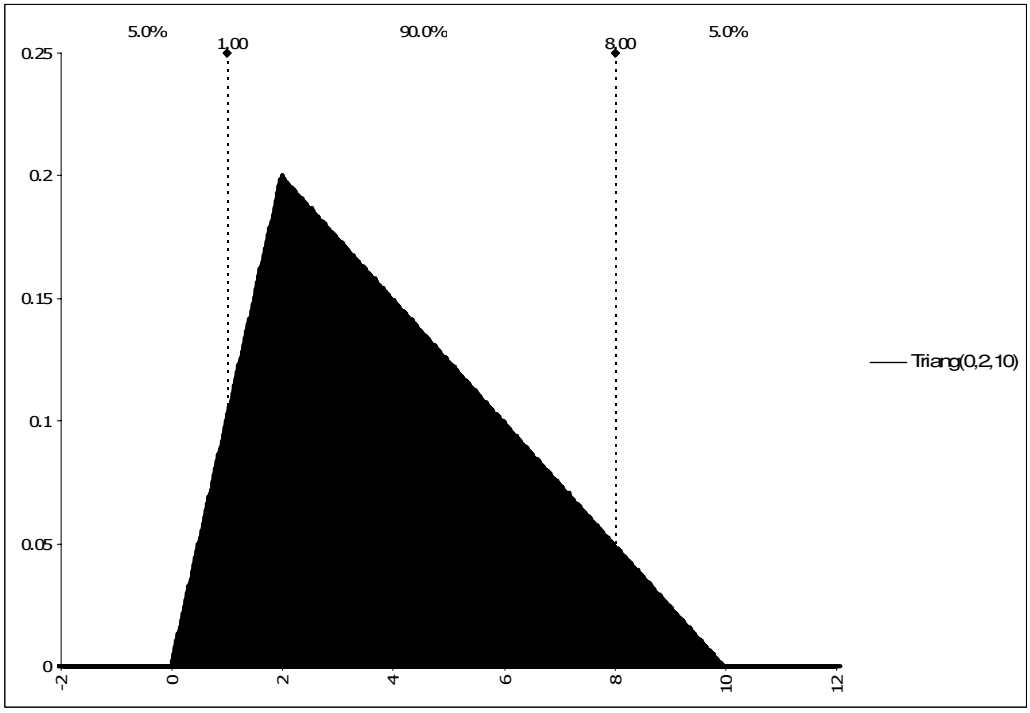
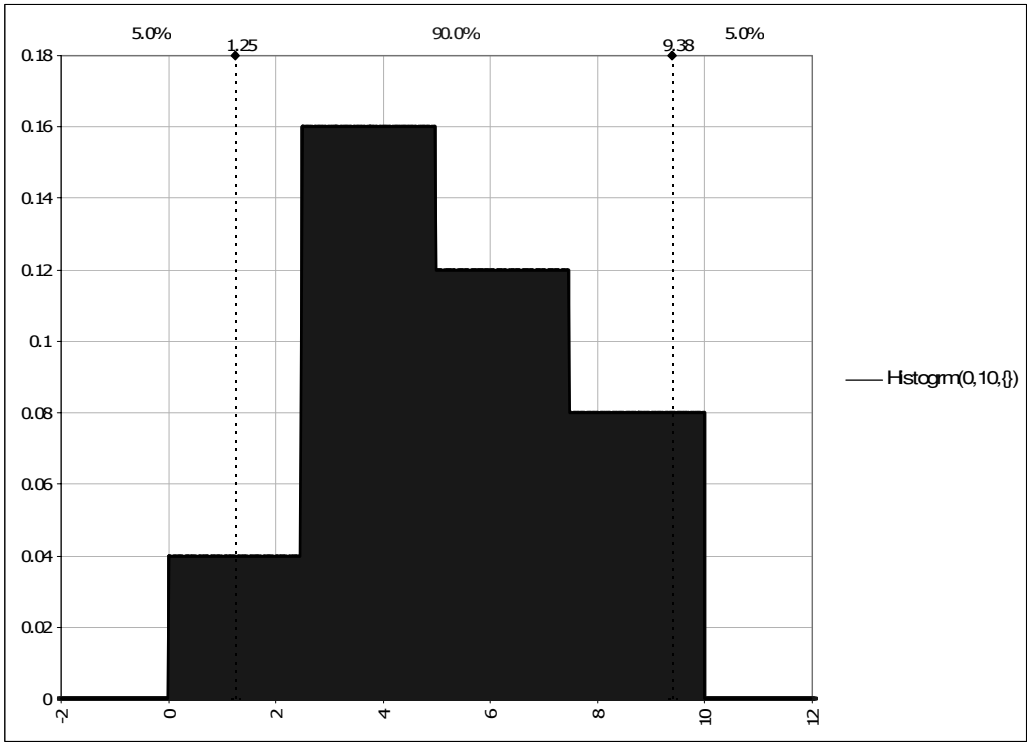


Figure 7.11. Probability density function of a hypothetical vulnerability (histogram distribution)



The value of the risk and simulation approach is not in generating a mean, mode or median value estimate of vulnerabilities, but in the hypothetical probability density function and confidence intervals it provides to decision makers. For instance, Figure 7.10 shows that there is 90% probability that the estimated costs lie within the range of $1 and $8 million. Different parameter values and bounds of the potential climate change impacts would, ideally, be presented and refined with stakeholders in collaborative workshops.

The risk and simulation approach can also be used to assess the net benefits of adaptation strategies to mitigate vulnerabilities. In this case, decision makers need to also calculate the costs of adaptation and the expected benefits of adaptation. This approach should complement or be integrated with existing procedures to manage risk and uncertainty in fisheries that have been developed in the context of stock assessments and harvest control rules (Hilborn *et al.*, 1993; Punt and Hilborn, 1997). Ideally, risk and simulation of climate adaptation responses should be part of a management strategy evaluation (MSE) that uses simulation-tests feedback-control management procedures (Punt, 2006) to adjust harvests and other management controls in response to shocks. To account for climate change, the operating models within MSE would need to account for the possible effects of climate change and also assess whether the management procedures are robust to climate change uncertainties. As the climate drivers will likely have system-wide impacts such an approach would also need to consider "whole of system" effects perhaps using ecosystem models (Pauly *et al.*, 2000), rather than evaluating vulnerabilities independent of each other.

At present, few OECD fisheries management authorities/regulators employ MSE and none incorporate fully developed ecosystem models that also account for climate change. Until such procedures are developed, it would be advisable to undertake initial assessments of climate change that utilise vulnerability assessments and a risk and simulation approach to identify robust adaptation responses. Subsequently, the adaptation procedures could become part of a comprehensive and integrated approach to simulation-tested and feedback control management systems.

Adaptive management and adaptation

Decision-making under uncertainty is an adaptive process whereby new information and circumstances feedback into goals, strategies and tactics that determine the adaptive responses. These responses can cover a wide variety of alternatives including: (1) risk sharing, whereby fishers mitigate shocks via co-operation and possibly revenue sharing; (2) avoidance, whereby fishers and their communities are provided with better forecasts to avoid negative impacts; (3) development of planning approaches that account for climate change and extend planning horizons that go beyond day-to-day operational management; and (4) bridging knowledge gaps in terms of forecast and predictions as well as sharing of information across stakeholders.

Stakeholder collaboration should not only be about knowledge sharing, but should also consider which actors (fishers, communities, non-governmental organisations, fisheries regulators, etc.) are best suited to what adaptation action. Polycentric or nested governance structures that involve multiple decision centers allows for greater flexibility and opportunity to experiment with alternative responses, and may also create "redundancy" that promotes resilience in socio-economic systems (Dietz *et al.*, 2003; Mahon *et al.*, 2008). Different layers of management and complementary rules in fisheries governance also increase management options across scales: local; regional and

national (Grafton, 2005). Such governance systems promote adaptation capacity and become increasingly important the greater is the uncertainty and the scale and scope of fisheries (species, geographic, stakeholders) to be managed. An adaptive co-management approach (Olsson *et al.*, 2004) also encourages autonomous adjustment by fishers and their communities, values different knowledge sets (tacit, traditional and scientific) and collaborative decision-making across key stakeholders.

The decision to respond and the choice of the response to climate change should, ultimately, be based on the risk that decision makers and stakeholders are prepared to accept and the expected net benefits. Monitoring and evaluation of actions should feed back to re-assess the value of the response as additional information becomes available. Thus, when to adapt, what and how to adapt should be the outcomes of a decision-making process that uses a risk and simulation approach to (1) assess climate change impacts and (2) evaluate adaptive responses. The success of adaptation should be judged in terms of whether the planned strategies and adaptation actions ensure the identified vulnerabilities are limited to the levels projected in the planning processes. Failure to constrain the vulnerabilities does not necessarily indicate a failure in the planning process, but would require an evaluation, as with all strategies, to determine and understand what actions were, or were not, successful.

Overview of the adaptation decision-making framework

The vulnerability assessment and decision-making framework presented in Figure 7.8 shows the key steps that policy makers and fisheries managers should follow to develop effective adaptation responses. It can, and should, be applied in existing capture fisheries and, if at all possible, the processes integrated with existing management processes. For instance, the objectives of adaptation should be consistent with current management goals while the analysis of vulnerabilities should, ideally, be part of existing management strategies. Such integration will help decision makers assess the trade-offs of supporting strategies that might promote socio-economic resilience, such as allowing fishers to participate in multiple fisheries, against the increased management costs that this may entail. In sum, the key to effective adaptation is to link vulnerability assessments, where feasible, to existing processes such as stock assessment and active adaptive management procedures.

A useful way to integrate current fisheries management processes to vulnerability assessments is to apply the inter-temporal framework in Figure 7.9. This framework links current and future actions in terms of their fisheries outcomes. Thus, it allows policy makers to identify actions that should be implemented in the present under existing management frameworks and those that might need to be developed over time in response to longer terms impacts of climate change. For instance, a "lose-win" strategy that involves stock rebuilding and imposes substantial transitional costs may never be justified using existing decision-making frameworks and processes. However, an explicit inter-temporal framework that also accounts for the long-run benefits of say, increased bio-physical resilience, would connect to actions in steps three and four of a vulnerability assessment to existing management strategies and processes. The key point is that such integration that: (1) connects current management processes to the future decisions; and (2) incorporates vulnerability assessment within existing decision-making processes, will much be more effective at delivering desired outcomes in the present and future.

Climate adaptation and fisheries management tools

Regulators have a wide range of strategies and tactics to manage fisheries that are summarised in Table 8.1. Output controls restrict the total harvest and can involve either a competitive TAC or the partitioning of the TAC into dedicated catch shares assigned to individuals or communities. Input controls restrict the fishing effort in particular ways, typically through licensing restrictions that limit the total number of vessels permitted in a fishery. In many fisheries, additional effort controls are also applied that try to constrain the amount of fish caught for a given level of effort. Technical and temporal measures control the type of catch for a given level of effort such as ensuring that only fish of a certain size are caught, or that the gear used avoids by-catch of protected or endangered species. Spatial controls constrain fishing and other use activities to particular locations and may also specify restrictions on where particular types of fishing or gear can be used.

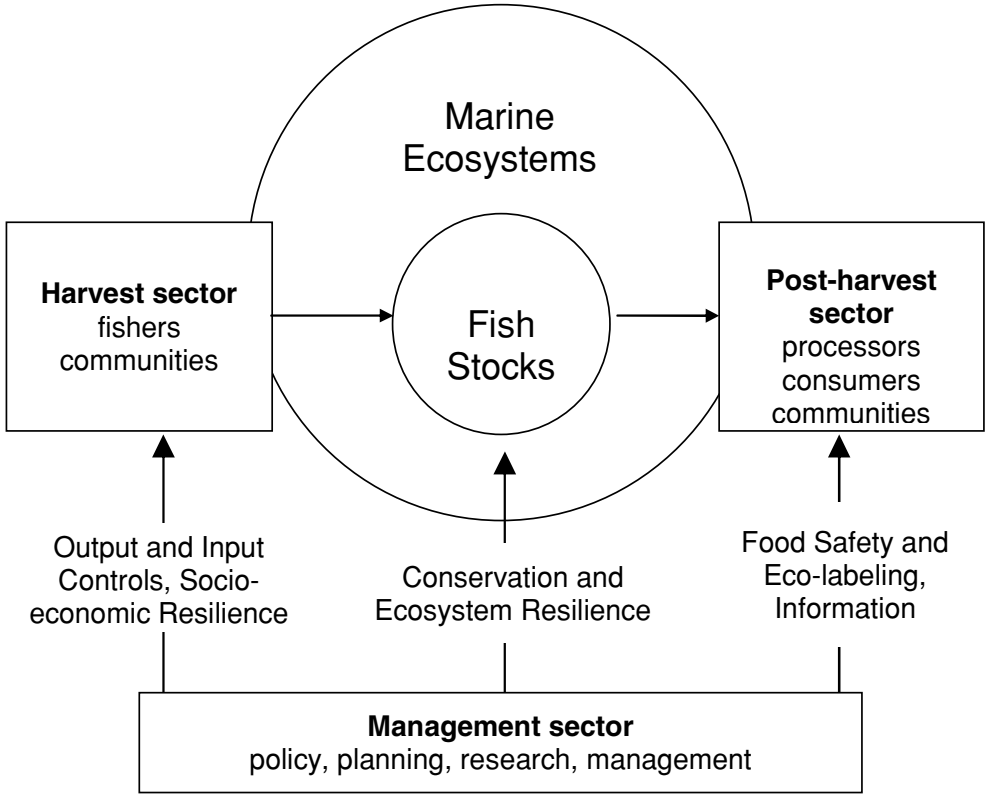
Table 7.1 Management controls in fisheries

Catch controls	Input controls	Technical & temporal controls	Spatial controls
Total allowable catch (TAC)	Vessel licence controls	Season length	"No take" areas
Dedicated catch shares	Effort quotas	Fishing gear specifications	Territorial user rights in fisheries
Trip catch limits	Gear and vessel restrictions	Size and gender selectivity restrictions	Individual vessel spatial licensing

Source : Adapted from OECD (1997)

A combination of all four types of control may be applied to influence the harvest sector, the marine ecosystem and post-harvest, processing and consumption, as shown in Figure 7.12. Possible adaptation to climate change using these controls is represented by the arrows from the management sector in the figure.

Figure 7.12. Fisheries management tools and adaptation to climate change



Source : Adapted from King (2007)

The availability of a suite of management tools is necessary but not sufficient to develop effective adaptation responses to climate change. The tools must be combined with processes that (1) promote resilient marine ecosystems and (2) model and confront uncertainty about the state of the world and the effect of adaptation actions. Using the criteria of accountability (with seven indicators), transparency (with three indicators), incentives (with four indicators), risk assessment and management (with four indicators) and adaptability (with four indicators) a method of benchmarking has been developed to evaluate fisheries governance using a five-point performance scale (Grafton *et al.*, 2007). Table 7.2 summarises these indicators and also provides a five-point scale that may be used when comparing fisheries in terms of their governance structures. This approach can, and should, be extended to identify weaknesses in current governance, such as management controls that fail to prevent the "race to fish" that result in overcapacity and other actions that detract from socio-economic/ecological resilience (Folke, 2006).

Table 7.2 Benchmarking for fisheries governance

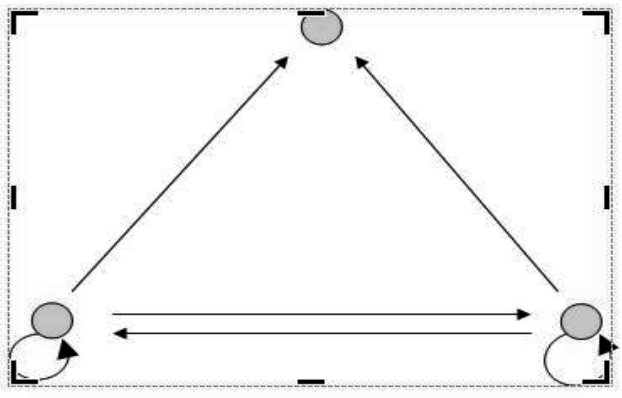
Governance criteria	Score
(1) Accountability	
Explicit "rules of the game"	
Independent report cards	
Full operational accountability	
Stakeholder involvement in decision making	
Fishery performance indicators	
Economic performance indicators	
Ecosystem performance indicators	
(2) Transparency	
Non-confidential data easily accessible	
Open and publicly recorded decision-making process	
Open and systematic process for evaluation and feedback of past decisions	
(3) Incentives	
Secure and durable individual or community harvesting or area fishing rights	
Effective monitoring and enforcement	
Competitive and well-developed market for fishing rights	
Incentives to avoid by-catch and habitat damage	
(4) Risk assessment and management	
Use of management strategy evaluation	
Effective use of limit reference points	
Effective spatial and harvest management controls	
Well-defined and agreed to risk boundaries	
(5) Adaptability	
Adaptive and responsive decision-making	
In-season adjustment to management	
Nested decision-making structures	
Systematic use of localised fisher and community knowledge	

✓ = governance component fully in place in the fishery;
P+ = governance component mostly satisfied, but not yet fully operationalised;
P = governance component partially satisfied, but further development is required;
P- = governance component is not satisfied, but steps towards its development are in place;
X = governance component missing in the fishery;
Source : Adapted from Grafton *et al.* (2007)

Many management tools currently in use were designed to ensure a given level of recruitment or fishing mortality, but not necessarily to promote resilience, or to provide robust management approaches to climate change. At best, they provide a degree of control over "persistent vulnerabilities" or environmental shocks that are known and occur periodically, such as *El Niño* events. While ensuring populations remain above a minimum viable size is a useful strategy given a variable environment (Shaffer, 1981), this may not be sufficient with climate change, especially if measurement of fish populations and harvests is problematic. Moreover, even in the current state of the world management controls have frequently been applied ineffectively (Beddington *et al.*, 2007) because almost two-thirds of assessed fish stocks require rebuilding (Worm *et al.,* 2009). Many governments have also failed to fully deliver on their commitments to implement precautionary management (Pitcher *et al.*, 2009). Thus, confronting climate change in fisheries requires much more than "conservative" or precautionary TACs. It demands that fishers, stakeholders and managers develop mixed controls that provide a degree of leverage to known environmental surprises (Grafton and Silva-Echenique, 1997; Ludwig *et al.*, 1993) and also "emergent risks" that are unexpected.

Management actions developed to confront uncertainty and promote resilience are likely to become more favoured with climate change. For instance, appropriately designed "no take" areas generate Pimm-resilience. This enables targeted fish populations to recover faster subsequent to a negative environmental shock (Grafton *et al.*, 2005) without necessarily requiring an adaptive management response subsequent to the shock. Importantly, this resilience effect generates positive payoffs that cannot be achieved with input or output controls alone, and in many cases there is no trade-off between the economic payoff of fishers and ecological benefits if no take areas are established at equal to or less than their optimal size. Critical to generating "win-win" outcomes is establishing "no take" zones in locations that are population sources, populations A and B in Figure 7.13, rather than population sinks, population C in Figure 7.13. For instance, establishing a no take area in location C will not provide any spillover benefits to other populations following a negative shock as fish only migrate to and never migrate from a population sink. Consequently, even if the population density in C were greater than in A or B following a shock there would be no outward migration of fish and, thus, no harvesting benefits from a establishing a reserve at C.

Figure 7.13. Connectivity between spatially dispersed populations



Source : Adapted from Jennings *et al.* (2001)

Some types of fishing gear, such as line fishing, also help to maintain resilience better than other forms of harvesting, such as traps, because they help to reduce the catch of susceptible and recovering species in coral reef ecosystems (Cinner *et al.*, 2009). Other types of gear reduce by-catch, such as turtle excluder devices on trawls, bird-scaring lines on longlines and the Medina Panel on purse seines that reduce dolphin mortality (Hall *et al.*, 2000). By reducing by-catch mortality and morbidity, these technical measures help to maintain marine biodiversity, and also promote resilience.

Experiences with existing management actions provide guidance about management controls that undermine resilience. For instance, the use of standalone input controls or competitive TACs fail to resolve the "race to fish" inherent in the exploitation of common-pool resources like fisheries. Consequently, fisheries managed by these approaches are frequently characterised by overcapacity that makes fishing a marginal activity for many harvesters. This, in turn, reduces the resilience of the socio-economic systems around fishing and their communities as even small shocks may generate large negative effects. By contrast, approaches that encourage to fishers to minimise costs for a given level of harvest and reduce the race to fish, such as incentive-based approaches to management (Grafton *et al.*, 2006), promote a resilient fishing sector.

Further research

Many knowledge gaps exist in terms of who, how, what and when to adapt to climate change. These research needs encompass a lack of understanding of bio-physical and socio-economic systems, especially in terms of how to promote resilience, and also ways to adapt to climate change that are flexible, cost-effective and resilience-effective.

Bio-physical research needs

From the bio-physical perspective, key knowledge gaps include exposure or the direct consequences of climate change such as sea temperature, pH and salinity change at scales sufficiently precise for regional fisheries and ocean planning. In particular, decision makers need guidance as to the effects of climate change on the distribution, diversity and productivity of targeted populations. Such information is a requirement for undertaking vulnerability assessments that underpin the adaptation decision-making processes. Beyond the direct climate drivers, there is also uncertainty about the effects of climate change on marine ecosystems and fish populations, and what factors might assist in improving ecosystem resilience. The understanding of species interactions is also an important information gap because without such knowledge it is difficult to provide realistic assessments of the indirect effects of fishing, and how climate change may exacerbate these impacts. Many of these uncertainties cannot be resolved by field work or experimentation alone, and will require modeling of different scenarios to evaluate possible vulnerabilities at the appropriate scales and with ecosystem-based models.

Socio-economic research needs

A key knowledge gap is the scale and scope of the socio-economic sensitivities that, together with climate change exposures, determine potential impacts. Measures of overall sensitivities have been developed on a national level data (Allison *et al.*, 2005), but require a finer scale and better quality data for effective adaptation at an individual fishery level. Fishery-scale sensitivity assessments will provide guidance as to whether

autonomous adjustment may be sufficient, or whether additional adaptation capacity needs to be developed, and if so, what should be the priorities. Another key area of research is governance. For instance, active research is required to develop "rules of thumb" and fishery-specific operational strategies and tactics to implement the five foundations of good governance: accountability, transparency, incentives, risk assessment and management, and adaptability. Active research and experimentation to develop appropriate nested governance structures is also an important knowledge gap in many fisheries, and is crucial to promoting adaptation capacity.

Adaptation research needs

A major disconnect exists between the adaptation planning process and the effective implementation of adaptation responses. Current thinking would suggest the need for *ex-ante* measures that would promote ecosystem and socio-economic resilience, but it is not clear what approaches are the most cost-effective or resilience-effective. Nor is the possible trade-offs between cost effectiveness and resilience effectiveness properly understood. The recommended *ex-post* approach to responding to climate change, or any uncertainty, is active adaptive management. While adaptive management principles are well developed, the effects of existing tactics or actions under climate change are not. For example, while theory suggests that mixed management controls, especially types of spatial management that enhance the connectivity of geographically dispersed populations (Botsford *et al.*, 2009) promote resilience, there is little research as to the actual effects of "no take" areas, and even less attention to the possible trade-offs that may exist between resilience other management goals.

Concluding remarks

Fisheries are inherently variable and subject to unexpected shocks. In response to such uncertainty fishers, their communities and regulators have developed ways to respond to change, but not always successfully. Climate change will increase uncertainty and accentuate the magnitude or incidence of shocks. Some changes may be positive for some areas and targeted populations, but the current state of knowledge suggests that for many fisheries the effects will be undesirable.

The dilemma for all fisheries stakeholders is when and how to adapt when confronted with the inherent uncertainties of marine ecosystems and the effects of climate change. Risk management that: (1) incorporates an assessment of current and future vulnerabilities; (2) engages stakeholders; and (3) models and simulates different states of the world and strategies, should be used to guide decision makers when responding to climate change. Precautionary fisheries management demands that a risk management planning framework be used today even if the actual planned adaptation from this process may not occur for several years to come. Without a precautionary decision-making process, current actions may increase vulnerabilities (maladaptation) or be inadequate (under-adaptation) to manage either the increased probability or greater magnitude of environmental shocks attributable to climate change.

The strategies and tactics to adapt to climate change will vary by fishery because exposures, sensitivities, vulnerabilities and adaptation capacity differ. Nevertheless, two broad approaches that are universally valuable are: (1) *ex-ante* measures that promote resilience in bio-physical and socio-economic systems where the current state is desirable; and (2) *ex-post* management that is actively adaptive and that ensures a speedy

response to shocks. Strategies that are "win-win" in that they generate increased net benefits in both the short run and long run, after accounting for all direct cost and risks, should be implemented immediately. For example, actions that rebuild depleted fisheries and increase the net present value of fishing promote bio-physical and socio-economic resilience. Similarly, appropriately designed and sized "no take" areas can promote resilience and increase the discounted net returns from fishing. Barriers to implementation of "win-win" actions can be mitigated if "losers" such as fishers, who may no longer have access to traditional fishing grounds, are compensated from the increased benefits that accrue to others. "Lose-win" actions that generate an overall positive net benefit, but incur short-run negative net benefits because of transitional costs, can also become feasible with appropriate inter-temporal transfers facilitated by regulators or via autonomous adjustment whereby future beneficiaries compensate current losers.

The many uncertainties associated with climate change will require research in terms of bio-physical and socio-economic systems, and also adaptation needs. The present lack of knowledge, however, does not prevent fishers, their communities and managers from risk management and adaptation planning today, or from implementing "win-win", or even "lose-win" actions. The payoffs to adaptation can be very large, especially in overexploited and unprofitable fisheries plagued by overcapacity, managed with top-down input controls and procedures that fail to consider ecosystem effects or to include key stakeholders within management processes.

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Chapter 8

Climate change, adaptation and the fisheries sector

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The fishing industry is a primary example for an industry subject to nature's variability, including climate change. Climate change affects fisheries along two main axes, changes in productivity in a given location and changes in fish migrations or the location of their habitats. Based on IPPC reports and other sources the paper summarizes expected changes in the marine environment. It then looks into potential fisheries productivity implications by drawing on examples from changes that occurred in the past. The paper also outlines the impacts of changing fish migration patterns of shared stocks, again illustrated by examples from the past. Those changes can influence the behaviour of the partners exploiting a shared stock, with critical consequences for the status of the stock and/or the relationships between the partners of an agreement. The paper further illustrates that if those changes affect stocks located entirely or partially in the high seas, shared management through RFMOs becomes even more challenging.

The paper concludes that the policy implications of climate change for fisheries will depend on the speed with which those changes occur. If change occurs gradually, management can be adjusted accordingly. If change occurs unpredictably, management adaptation requires better marine and climate change science to be able to react. Secondly, management systems need to be flexible as in the case of unpredictability they can only adapt once change has occurred.

The paper concludes that climatic changes have caused adjustment in the marine environment already in the past and will continue to do so, be in a predictable or rather unpredictable manner, causing reversible or irreversible changes. In any case, the climate change discussion provides momentum for refocusing on good fisheries management as the key issues are unlikely to change considerably with global warming. The challenge is to understand what adaptation to a fluctuating environment means for good governance.

Introduction: the issues

What are the key issues for fisheries arising from climate change? Most people probably associate climate change with global warming; that certainly is one of hottest issues of our times (no pun intended). Global warming will affect not just the atmosphere but the oceans as well, but how much, how rapidly, and even, for some areas, in what direction is unclear. In fact, even if global average temperature is rising, it will not necessarily rise uniformly in every location, and what evidence there is indicates that some areas, such as the Arctic and sub-Arctic, are warming more rapidly than others. Some areas might even become cooler. This is likely also to be the case in the world's oceans; climate change will manifest itself in changing ocean currents, and some areas might even get colder because of diversion or changing intensity of currents.

But climate change need not be due to global warming. In fact, the climate has always varied on long and short time scales and will undoubtedly continue to do so whether or not man-made global warming is occurring. Since global warming will occur as a trend around which there will be variations, perhaps substantial, many of the issues associated with it are much the same as the issues raised by climate variability in the past. Conversely, whatever lessons we can learn from climate variability in the past should definitely be of interest for the issues raised by global warming. Hence we shall devote considerable attention to some climate variations that have happened in the not too distant past (within a time horizon of a hundred years or so). How did they affect fisheries? How did the industry and society in which it was embedded respond?

So what are the issues? The fishing industry is a bit special, being essentially an advanced form of hunting.[1] It does not attempt to control nature, except indirectly through how it exploits the fish stocks. There are, with few exceptions (salmon hatcheries), no measures applied to enhance the productivity of the oceans, analogous to seeding, fertilisation, or ploughing and harrowing; the fisheries take what nature gives them, and nature responds in a niggardly way if the fisheries take too much. The productivity of the oceans depends on ocean climate; the upwelling of nutritional materials from the deep sea that occurs in certain areas depends on currents, which in turn depend on winds, and currents carry plankton to certain areas so the fish can thrive. The strength and even location of ocean currents can vary substantially over time, which in turn gives rise to fluctuations in the productivity of fish stocks, as well as in their migrations and location. This variability is further affected by predator-prey dynamics; a dearth of suitable prey fish due to changes in productivity lower down in the food chain will affect the growth of their predators, and abundance and migration of predators will affect the abundance of their prey.

Hence the fishing industry is a primary example of an industry that is subject to the vagaries of nature and so must adjust to nature and her variability; there is little or nothing that the industry can do to affect the natural processes. The first issue to arise, then, is can we predict changes in ocean climate? Unfortunately it is unclear whether we can, at least in a sufficiently precise and timely fashion to be of much help for the industry in the short term. The synthesis overviews of climate change predictions, such as those produced by the Intergovernmental Panel on Climate Change (IPCC), make few predictions on a spatial or temporal scale that would be useful for fisheries management. Other work on regional scales has the potential to produce more useful predictions, and these predictions are likely to improve as the methods are developed further. The fact remains, however, that there is substantial uncertainty in these models and their

predictions, and their ability to predict non-linear or threshold responses might be particularly limited.

Whether or not we can predict in a sufficiently precise and timely fashion to meaningfully affect management raises the question of whether we really need predictions. If changes occur gradually it may be true that all we need is to adjust gradually; the necessary information will be revealed as it is required. This is not true if changes in fish migrations or productivity occur suddenly and on a major scale as certain "threshold values" of environmental variables are exceeded (Arnason, 2006). Such changes may be difficult to predict, and all the more so since they might occur even if the underlying change in ocean circulation and temperature is gradual; ocean conditions might suddenly reach a point where certain fish stocks can no longer survive, or radically change their migratory habits. We would only know what to expect if: (1) similar things had occurred in the past; and/or (2) if we had a strong understanding of the mechanisms and interactions underlying climate change and its impacts on oceans and ecosystems.

Then, being able to predict changes or not, what changes could we expect? It is useful to distinguish between two main types of changes that could occur: (i) changes in the productivity of the ocean in a given location and (ii) changes in fish migrations or the location of their habitats. Changes in productivity could go both ways; less intensive upwelling in the areas where this occurs would adversely affect the productivity in these areas. This is what occurs during the famous *El Niño* events when warm waters are carried towards the west coast of South America and the upwelling diminishes, adversely affecting the anchovy stocks in the area and the fisheries of Peru and Chile (see Annex 9.A1). Conversely, the blooming of plankton could increase and so could the intensity of currents carrying plankton to certain areas; this is what happened in the warm period in the 1920s and 30s in the north-east Atlantic, to be further discussed below. How fish stocks will be affected is a more complicated issue, depending on predator-prey interactions. As to the industry and society, changes in productivity of fish stocks may necessitate investment in new equipment or finding new markets, or cause obsolescence of real and human capital and loss of markets.

Changes in fish stock productivity, if they occur uniformly in a given area, would affect all countries sharing the stocks involved in a similar way. Changes that affect fish stock migrations or displace their habitat may on the other hand affect different countries differently. Some might be disadvantaged while others might gain. This could cause problems when fish stocks migrate between the exclusive economic zones (EEZs) of different countries. The countries involved might be affected differently, and so they would be if the habitat of a given fish stock is largely or wholly displaced from one country's EEZ to another's. This could upset existing agreements on sharing fish stocks.

These are the key issues to be further discussed below. We begin with what we might expect, drawing on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the Arctic Climate Impact Assessment (ACIA), and past experience ("What can we expect?"). We then move on to consider implications of changes in fish stock productivity, such as would not involve changes in migration and stock habitat ("Changes in fish stock productivity"). Thereafter we consider the consequences of changed stock migration or habitat location and what this means for stocks shared between two or more countries ("Changed fish migrations and shared stock") and those partly or wholly found on the high seas ("High seas fisheries"). After a concluding section on policy implications ("Conclusions and policy implications") there is an annex where there is a brief discussion of climate changes that have occurred in the

north Atlantic and the eastern Pacific and their implications for the fisheries in these areas. These experiences are useful to keep in mind when we are dealing with the consequences of future climate change, and we have also drawn on them in various parts of this paper.

What can we expect?

Climate change has been a high profile international issue for about twenty years. For some time the average global temperature has been increasing, and most climate scientists have concluded that this is mainly due to emissions of greenhouse gases, particularly carbon dioxide. Since there is no way emissions of these gases could, in the medium term, be reduced to a level that would stabilise their concentrations in the atmosphere the global temperature is likely to rise further, although by how much is highly uncertain.

Global warming will affect not just the atmosphere but also the oceans. Emissions of greenhouse gases, in particular carbon dioxide, will affect the oceans in at least three ways: (i) warmer atmosphere will warm up the oceans; (ii) some of the carbon dioxide will be absorbed by the ocean (but some might in fact be released from the ocean to the atmosphere), which could affect ecosystems through acidification; (iii) increased melting of glaciers in the Arctic will release fresh water to the ocean, affecting its salinity, level and possibly its circulation. In addition, if global warming affects wind patterns and strength, this in turn will affect ocean currents. This could have two effects. First, changes in ocean currents would affect the distribution of plankton and hence migrations of fish stocks and location of their habitats. Second, changes in the winds that cause upwelling of nutritional material from the deep sea could affect the upwelling and hence the growth of fish stocks that depend on it. Some of the richest fisheries in the world exploit species that depend on upwelling (sardines and anchovy off southern Africa, California, Morocco and Peru and Chile).

These are complex effects and their magnitude and time profile highly uncertain. It is no wonder, therefore, that the voluminous Fourth Assessment Report of the IPCC has very little to say, at least very little that is definitive, about how world fisheries will be affected. It notes that changes in salinity, circulation and ice coverage that already have happened and may be expected to continue will affect primary production, fish growth and fish migration. In some cases the effects have been positive, but in others negative (IPCC, 2007b, pp. 234-236 and p. 333). The most definitive conclusions concern coral reefs and coastal areas, both of which are likely to be negatively affected (IPCC, 2007b, Chapter 6). Bleaching of coral reefs is likely to increase, both because of rising temperature and because of acidification of the ocean due to absorption of carbon dioxide. Acidification has wider implications, as it adversely affects animals with a hard shell, which would threaten ecosystems where such organisms play a pivotal role (IPCC, 2007b, p. 236).

More definitive predictions, but still fairly vague, were made in the Arctic Climate Impact Assessment (ACIA, 2005).[2] This was the result of work done by a group of scientists asked to assess the effects of global warming on the Arctic and sub-Arctic region. This assessment was based on a number of climate scenarios and models used in the Third Impact Assessment Report of the IPCC, but ACIA went into much greater detail about how the said region and its various parts might be affected. Fish stocks were predicted to move further north because of rising ocean temperature and melting of Arctic ice. These movements would not necessarily be displacements but also expansions, with

new areas colonised by certain stocks, which thus would increase in abundance. The most northerly species (capelin and Greenland halibut, for example) would probably decline in abundance, while more southerly ones (cod, pollock, herring, and some flatfish) would probably increase. The melting of sea ice was expected to increase primary production by opening up new areas for the inflow of sunlight. This was expected to increase fish production, but it was pointed out that the latter would depend critically on fish larvae being carried by currents to the blooming of zooplankton at the right time (ACIA, 2005, Chapter 9). Overall, predictions were positive rather than negative, which agrees with the experience from the warm period in the north-east Atlantic in the 1920s and 30s. The ACIA report also dealt with possible economic effects of this, a subject we shall return to in the following section (ACIA, 2005, Chapter 13).

Given the rather uncertain predictions of the consequences of climate change for fisheries, we shall deal with changes in fish stock growth and migration in quite general terms. While in a number of cases it seems reasonably clear in what direction the growth and migrations of certain stocks will be affected, the speed and magnitude of these changes are much less clear. It is also unclear if these changes will be gradual, in response to a gradual increase in global average temperature, or whether they will be released when certain threshold values of environmental variables such as temperature and salinity will be hit, displacing stocks from their previous habitats or inciting them to change their migrations.

What we seem to be seeing is global warming occurring as a trend, but with swings, perhaps substantial ones, around the trend. Even if some of the warmest years ever recorded have occurred fairly recently, the warming seems to have come to a halt lately. On a longer time scale, the 1960s and 70s were a cool period in north-west Europe, compared to the 1920s and 30s and the last two decades. Even with global warming, all areas will not warm to the same extent; it appears that the Arctic and sub-Arctic are warming much more rapidly than the rest of the world.

As regards ocean climate, this is an even more appropriate description. The temperature in a specific area is highly dependent on ocean currents and can vary substantially from year to year or decade to decade, depending on the strength and direction of these currents (examples of this are discussed in the annex). This means that any trend towards warming will be overlaid with substantial variations around that trend. Some areas might even be going against the trend for a long and possibly indefinite period, due to a change that might permanently strengthen or switch on a cold current. As an example, substantial weakening of the Gulf Stream and the thermohaline circulation is a scenario that cannot be totally dismissed, even if it is considered unlikely (IPCC, 2007b, p. 797 and 802).

This has some important implications for the adjustment towards a changed climate in the ocean. First, how can we tell a permanent change from a temporary one? In the past we have had so-called regime shifts in various parts of the world which have been fairly long-lasting, such as the warm period in the north-east Atlantic in the 1920s and 30s (Vilhjálmsson, 1997; Drinkwater, 2006), the cooling off in the 1960s and 70s, and the shift to a warmer regime in the north Pacific in the late 1970s (Miller and Munro, 2004). It is not easy to distinguish such regime shifts from a more permanent change. On the other hand it can be argued that this does not much matter for practical purposes; from the point of view of investing in production equipment or finding new markets, a regime lasting 10-20 years is a regime lasting forever.

As a result of such regime shifts, partly at least, we have in the past seen fish stocks disappear and migrations being changed for long periods, and some have not returned to their previous state or patterns. The West Greenland cod stock was severely depleted in the 1960s and has been virtually non-existent since 1990, while the shrimp stock increased (ACIA, 2005, Chapter 13). The northern cod of Newfoundland disappeared in the early 1990s. Also here shrimp, as well as crab stocks, increased. Migrations of Norwegian spring-spawning herring to Iceland stopped when the waters north and east of Iceland became colder in the 1960s and have not fully resumed their previous pattern despite a warmer ocean and stock recovery after the mid-1980s. The Pacific sardine disappeared from the coast of California in the 1950s and was absent for decades (some of these changes are further discussed in the annex).

As was noted in the introduction, if the changes in ocean climate are incremental, they might not pose much of a problem. Adjustment could occur gradually, and sound expectations could be formed on the basis of past experience. But the changes just discussed seem to be due to the passing of certain environmental thresholds rather than dramatic, underlying climate changes. As the temperature rose, or cooled, nothing much happened until suddenly a certain fish species was seemingly unable to reproduce or find enough food to survive, or predators invaded and decimated a fish stock that earlier was thriving. Such changes are impossible or at least very difficult to predict. In order to know the threshold values involved they must have been passed at some time in the past, but then the fish would not be around anymore unless the change was reversible. Many such changes are in fact reversible; both the Norwegian spring-spawning herring and the Pacific sardine were almost wiped out at one point, but once the environmental conditions were appropriate they came back, although much later than the environmental conditions would seem to warrant (see annex).

As has been argued, global warming is certain to be a trend with inter-annual and perhaps even decadal variability, not least in the oceanic environment. This may mean that critical thresholds could be crossed in opposite directions from time to time. Does this mean that the ecosystem will return to its previous state? How quickly? These temporary setbacks are particularly likely to cause problems with shared fish stocks whose migrations might switch between different states' EEZs. We shall return to this problem later in this chapter.

Changes in fish stock productivity

As discussed in the previous section, climate change is likely to cause changes in fish stock abundance, albeit of uncertain magnitude and direction. Here we ignore international repercussions and assume that changes in fish stock abundance are confined to one nation's exclusive economic zone (EEZ) or, for stocks that move between the EEZs of different nations, affect them all in equal measure. This also covers the case where new stocks expand to new areas without declining in their traditional areas. Previous climatic variations provide examples of this latter effect. Cod and even herring began to spawn at Greenland during the warm period in the 1920s and 1930s. The area must have been seeded from somewhere, but not necessarily at the expense of those areas; adult fish probably migrated in search of food or larvae drifted with the currents and then settled at Greenland. Migrations or larval drift from other areas to which the adult fish return, like the cod at Iceland that drifts over to Greenland and then returns, is a different issue which would get us into the subject of shared stocks and how sharing agreements are affected by climate change, the subject of the following section.

Climate change, whether it is warming or cooling, will affect different fish species differently. Each fish species is found only within a certain temperature range, which may have as much to do with the availability of prey as with temperature as such. Any change in temperature is therefore likely to be beneficial for certain stocks and harmful to others. Disappearance of cod and booming shrimp and crab stocks at Newfoundland and Greenland as a result of climate change has already been noted. Change in ocean currents, which manifests itself as a change in temperature, may also affect upwelling of nutrients from the deep sea. Even small changes can apparently cause major disruptions, such as the switch from anchovy to sardine and *vice versa* which occurs in various upwelling areas around the world (Benguela, Humboldt, the California current) from time to time, for reasons that are not well understood.

Whether or not global warming will affect the productivity of the oceans negatively or positively depends on two things: how it will affect (i) primary production and (ii) upwelling (or runoff) of nutritional material. The Fourth Assessment Report of the IPCC leans towards thinking that primary production will be negatively affected (IPCC, 2007b, pp.234-5). Nutritional upwelling from the deep sea depends critically on the strength of winds and the currents they generate, and it seems difficult or impossible to make any definite forecasts about that. A given primary production will end up producing a different species mix at each trophic level, according to how changes in ocean currents affect the survival of different species. Whether we will end up with more or less valuable species mix as a result of global warming is very difficult to say.

How each particular country will be affected will depend on the composition of species within its EEZ (abstracting from any fishing the country could be involved in outside its own zone). It is unlikely that all its fisheries would be adversely affected; if, say, fish *X* that preys on fish *Y* will be adversely affected, fish *Y* is likely to survive better, and provided that there is enough food around for fish *Y*, the country in question could increase its catches of this fish. Whether the country in question gains or loses from the change will depend on, among other things, the value (monetary or otherwise) of fish *Y* relative to the value of fish *X* and the costs associated with taking them. As a case in point, consider what happened to the fisheries in Newfoundland after the collapse of the Northern cod in the early 1990s. A contributing factor to the collapse of this fishery was the cooling off of the waters around Newfoundland at the time. This fishery was both large and valuable, and its disappearance caused a major disruption to the economy and culture of Newfoundland. However, the abundance of crabs and shrimps increased in the wake of the collapse of the cod, probably due to less predation from cod on these species or their larvae. After a few years the value of fish catches (including crabs and shrimps) was higher than ever before.[3] However, the impacts on Newfoundland were serious: the benefits of the shrimp and crab fisheries were distributed among a much smaller segment of the population than were those of the cod fishery; the cod fishery was fundamental to the culture of Newfoundland; and there were substantial costs in helping thousands of fishers and processing workers make the transition to other industries.

Regardless of whether in the end a country would gain or lose from a climate change in the waters around its coasts, all changes, even those for the better, necessitate adjustments. Boats may need to be adapted to catch new species and new ones might need to be built. This, needless to say, is likely to be most demanding when new and very different species replace old ones. It was not too much of a problem in the herring fisheries of Norway and Iceland to switch to capelin when the herring stocks collapsed (these fisheries are discussed at a greater length in the annex), but switching from cod to crabs or shrimp is likely to be more problematic, as the fishing gear is quite different. On

the processing and marketing side the problem of switching will depend on how similar the species are with respect to the processing equipment required and the markets they supply. The aforementioned switch from herring to capelin as raw material for the fish meal industry was unproblematic, both with respect to processing and marketing; the meal from both is very similar and the same processing equipment can be used for both. The situation would be different if, say, a herring fishery providing raw material for cured products collapses. Cured products of herring do not have perfect or maybe not even close substitutes and appeal to a specific and acquired taste among consumers. If a switch from Species *X* to Species *Y* is required and Species *Y* serves a totally different market, it will be necessary to find and make inroads on such markets and probably to invest in new processing equipment as well. In the end the country might end up with more valuable fish catches, but at a certain cost.

It is difficult to generalise about these points, other than to say that flexibility on all fronts will be helpful. Regulatory regimes should be such that the industry can switch its boats and processing equipment from the retreating species to the expanding one as needed. In regimes that rely on fish quotas or licenses there should be flexibility as required to switch from a quota or a license for species *X* to species *Y*, needless to say without unduly raising the exploitation pressure on species *Y*. This could be achieved with markets for licenses or quotas where the total amount for each type of fish is decided on sound biological and economic principles, allowing the industry to achieve maximum efficiency within those limits.

Likewise, easy market access would be helpful to cope with switches to new species and markets. Traditional supplies to a given market could dry up if the fish species involved can no longer be caught by the traditional suppliers, be they domestic fishermen or some specific exporting country. It would be in the interest both of the consumers in those markets and of the new potential suppliers emerging if imports of fish are unimpeded by tariffs and other trade restrictions, except those necessary for health and safety purposes.

In general, one would be tempted to conclude that the richer a country is, the better it will be able to cope with structural changes made necessary by climate change, in fisheries as in other industries. Rich countries certainly are in a better position to pay monetary compensation to those whose skill and capital equipment might be made obsolete by disappearing fish stocks. On the other hand, rich economies are often more demanding in terms of specific skills than poor ones; specialisation is indeed one of the factors behind economic growth. The skills acquired in an industry like fishing could, in a rich country, be less easily transferable to other industries relying on a different set of skills. Hence, reintegrating redundant fishermen into the labour market could be more difficult and expensive in rich countries than in poor countries.

The ACIA report mentioned earlier went into considerable detail about the possible economic effects of changes in fish abundance in the Arctic and sub-Arctic region (ACIA, 2005, Chapter 13). Of particular interest is the analysis of what might happen to the economies of Iceland and Greenland. This is so because in most countries fisheries are a very small part of the overall economy, but often important locally and possibly pivotal in certain regions. The impact of changes in fish stocks would therefore hardly be noticed in statistics at the national level, while regional statistics are often too rudimentary to evaluate such regional effects and may not exist at all. For the Icelandic economy a gradual change in fish stocks spread over 50 years would hardly have a discernable impact on the economy. However, a more sudden change for the worse – a

decline of 25% over five years – would produce serious effects, producing a dip in GDP to 90% of a reference level, attained over a few years, and then a recovery.[4] The Greenland economy, being more fish-dependent, seems still more sensitive to changes in fish abundance, so even a moderate increase in fish abundance would have a significant impact on the economy. From this it appears clear that such gradual and moderate effects as foreseen by the ACIA scenarios would have a relatively minor impact, except in extremely fish-dependent communities with few opportunities, such as Greenland.[5]

Changed fish migrations and shared stocks

Some fish stocks traverse the great oceans; tuna is a primary example. This is most likely driven by a search for food. Some stocks migrate recurrently to certain locations to spawn; north-east Arctic cod and Norwegian spring-spawning herring are two examples, discussed at some length in the annex. Whatever the reason, the extensive migrations of some fish stocks take them across national boundaries at sea, and sometimes into what is left of the high seas.

The fact that one country cannot effectively control a stock that periodically migrates out of its EEZ and into that of another or into the high seas, has prompted some of the countries sharing a stock to agree on its management and control. All countries involved have an interest in avoiding overexploitation, but apart from that their interests and incentives may be different. Their goals might possibly differ, and even if they are only concerned with economic gain, the relevant parameters such as costs, prices, or discount rates might differ among them. But even if the said parameters were the same the incentives for avoiding overfishing could vary in strength.

Fish stock management involves the resolution of two questions: (i) how much fish should be caught from each stock at each point in time, and (ii) how that amount should be divided among the parties. Several principles have been invoked in the resolution of the latter question; some at least are based on what may loosely be called zonal attachment, *i.e.*, how much of the stock is within the EEZ of one particular country, or how much time the stock spends there (Engesæter, 1993). Both are essentially variations on the same principle.

But things could be less straightforward. If sovereign states are to agree to anything, they must fare better under the agreement than without it. This means that a state will only agree to limiting its fishing effort if this results in greater gain than it would get otherwise. This is only loosely related or not at all to zonal attachment. In Box 9.1 this is illustrated with a simple, numerical example. It is also illustrated how a sudden, unexpected and perhaps imperfectly understood change in the distribution of the stock might upset an existing agreement.

One example of how a scenario of the kind illustrated by the example in Box 9.1 can play out is the warming of the north-east Pacific after the late 1970s and its consequences for the salmon runs to the rivers of Canada and the United States. The runs to the rivers of Oregon and Washington were adversely affected, and so were the runs to the Fraser River in Canada, but the latter increasingly took a northerly route north and east of Vancouver Island instead of rounding its southern tip where they would have been temporarily available in US waters. The agreement between the US and Canada had sought an acceptable interference by Americans with the runs to the Fraser River and by Canadians with runs to Washington and Oregon. The warm regime kept the Fraser River salmon mostly in Canadian waters, while the runs to Washington and Oregon were severely

down. Further north, salmon runs to Alaska increased greatly, and Alaskans were increasingly able to catch fish heading for rivers in Canada. This essentially led to the emergence of three players; Oregon and Washington together, Canada, and Alaska, all with different interests and differently affected by the climate change. The sharing agreement broke down in 1993, but was eventually renegotiated, with allowances for differential changes in salmon abundance and inclusion of side payments (Miller and Munro, 2004; Miller, 2007).

Box 8.1: Zonal attachment and the sharing of a fish stock

Suppose we have a stock 20% of which annually spills over from Country A's EEZ to Country B's EEZ. The reproduction of the stock from one year to the next depends on how much of the stock is left after fishing in both countries' zones, the stock remaining in Country B's zone after fishing returning to Country A's zone. Suppose the stock reproduces according to the relationship $R = Sa$ where $0 < a < 1$, so that the size of the stock in the absence of fishing would be $R = S = 1$, and the sustained catch would be $Sa – S$ in case we always leave S behind after fishing. Suppose, for simplicity, that both countries have the same economic parameters such that if one of them controlled the stock it would be interested in maximising the sustainable yield. That would in this simple example mean that it would maximise $Sa – S$, which would imply □S□ - 1 = 1. With □ = 0.5, we would get S = 0.25, so 25%of the stock would be left for breeding and growth, giving a total catch of □0.25 – 0.25 = 0.25. Would Country B be happy with getting 20% of this? This is, arguably, its zonal attachment of the stock. This would amount to 0.05. But what would country B do on its own? It knows that A would try to maximise its catch, given whatever amount of fish is left to migrate from B's to A's zone. Country A would maximise 0.8(SA + SB)□ - SA, that is, the share of the stock in its zone less what it leaves behind to breed and grow, the subscripts A and B denoting the stock levels left behind in the two countries' respective zones. Country A can only determine what it leaves behind, and for any given stock that country B leaves behind, the solution to country A's maximisation problem implies 0.8□(SA + SB)□ - 1 = 1, which gives us a solution for SA for any given SB. We get a similar result for Country B, 0.2□(SA + SB)□ - 1 =1, from which we can find a solution for SB for any given SA. The problem is, however, that for most stock levels that country A might leave behind, Country B would not want to leave behind anything at all, knowing that it would always get some fish to its zone due to A's incentives to preserve the stock. The mutually consistent solution to both problems would be SA = 0.16 and SB = 0, resulting in a catch of 0.16 for A and 0.08 for B.a Country B would therefore not be satisfied with its zonal attachment share of the maximum sustainable yield, which we have seen is equal to 0.05; it could get 0.08 on its own, and this much it will demand as a minimum if it is to go along with an agreement about managing the stock. Suppose, then, that A and B have reached an agreement in their best mutual interest, so that the sum of what they leave behind is 0.25, producing a stock of 0.5 at the beginning of each season, of which 0.1 spills over into B's zone. B takes 0.08, the minimum acceptable to it, leaving behind 0.02, with A leaving behind 0.23 and taking 0.17. Suddenly the tables are turned, with Country B now getting 80% of the stock and Country A only 20%. This may take some time to discover, at any rate with a sufficient degree of certainty. Country B would most likely consider itself entitled to a greater catch of fish, and A might be reluctant to recognise its present eroded position. A used to have a stock of 0.4 within its zone at the beginning of each season, but now it has only 0.1. There is no way Country A can catch 0.17 and leave behind 0.23 as it used to do. Suppose that, partly in ignorance and partly in frustration, A takes all the fish in its zone, and that Country B feasts on the bonanza and only leaves behind 0.02 as it used to do. In the next period a stock of only □0.02 = 0.1414 appears, instead of 0.5. A vicious downward spiral has begun. How quickly would the parties recognise and adjust to the new situation? Would the authorities in the two countries believe this is just a freak event or permanent? How long would it have to prevail before they accept it as permanent? How large losses would occur in meantime? Could the stock be fished to extinction? a With SA = 0.16 and SB = 0, the emerging stock is □0.16 = 0.4. Of this 80 percent, or 0.32, is in Country A's zone, and Country A catches 0.16 if it leaves behind 0.16. Twenty percent of the stock, or 0.08, migrates to Country B's zone, and Country B can take it all, knowing that Country A has an incentive to leave 0.16 behind in its zone. If we check the maximum condition for Country B, we find that 0.2x0.5/□0.16 = 0.25 instead of 1, which means that Country B would want to leave a negative amount of fish behind (- 0.15), which is not possible.

Changes in fish migrations due to climate change could thus put the existing agreements on sharing fish stocks under strain, or make it more difficult to reach agreement where none is in place. Some sinister outcomes are possible. Suppose, for example, that a stock has been confined to Country *A*'s EEZ. Climate change increasingly diverts the stock into Country *B*'s EEZ, while the growth and reproduction of the stock still depend on how much of the stock is left after fishing in the EEZs of both countries. Country *A*'s command over the stock will be steadily eroded and so will its previously strong incentives to protect it, while Country *B* will acquire an interest in the stock, at first fleeting but then a more substantial one. If things continue in this direction, *B* will ultimately acquire a stronger incentive than *A* to preserve the stock for reproduction and future growth, while *A* will become a player which only has a minor fraction of the stock and which in fact will be able to demand a disproportionate share of the stock, since it will in any case benefit from *B*'s conservation efforts without making much of a contribution itself. But how quickly will the players realise this reversal of roles and how timely will their adjustment to it be? This is likely to be a difficult issue, because global warming and the changes it leads to in ocean climate will be a trend around which will see substantial variations, similar to the climatic variability in the past. Changes in fish migrations are thus likely not to be smooth trends but trends with temporary reversals. How is Country *B* to know that the fish are shifting over to its zone on a long-term basis? With expectations formed on the basis of recent experience, Country *B* may see fluctuations without much of a long-term trend and may thus come to realise its pivotal role for the stock much too late. And when will Country *A* realise that the stock will leave its EEZ for good and that its days with a major interest in the stock are numbered? It is possible to think of a "twilight" period in which Country *B* has not yet realised that it has acquired a permanent, major interest in the stock while Country *A* will realise that it has no long-term interest in the stock any more. Country *A* may therefore decide that it serves no purpose to preserve the stock for future use and so neglect to leave any of it behind, while Country *B* has not yet realised that it would be in its interest to do so. As a result, the stock would be depleted, possibly once and for all.[6]

Are there examples of stocks which could be shifted permanently out of one country's zone into another? No stock seems to have undergone such radical permanent shifts, but there are stocks which have experienced major shifts as a result of depletion or climate change and possibly a combination of both. As the stock of the Pacific sardine collapsed, what remained of it was mainly within what is now the EEZ of Mexico, while in its heyday sardines were caught as far north as British Columbia. As the stock has grown in recent years it has again been found as far north as British Columbia. Prior to its collapse in the late 1960s, the Norwegian spring-spawning herring migrated towards Iceland during the summer and was caught in what is now the Icelandic EEZ in substantial quantities. After the collapse it became confined to what is now the Norwegian EEZ, although its changing habits were at least in part caused by a temporary cooling of the waters north and east of Iceland (Malmberg, 1969; Hamilton *et al.*, 2006). This was well before the EEZs became established, but in any case one may surmise that a sharing agreement based on the catch shares or "zonal attachment" back in the 1950s and early 1960s would hardly have survived these changes. A sharing agreement for the stock in fact broke down for a few years early this century because expectations about the stock migrations did not materialise.

Another example along similar lines is the North Sea herring. As the stock was decimated in the 1970s it became more and more concentrated in the EU-part of the North Sea. When the fishery was resumed in the 1980s Norway and the EU, within whose

EEZs the stock was located, negotiated a total quota and how it should be shared. The EU wanted to base the sharing on the zonal attachment of the stock, which had been found to be 4% in the Norwegian zone. The Norwegians argued that this low attachment was due to the concentration of a small stock in the EU-area and refused to accept the offer. They allowed their fishing fleet to fish at will within the Norwegian zone, resulting in a much greater Norwegian share of the catch than the 4% offered by the EU. The following year a sliding scale for sharing the total catch was agreed, with the Norwegian share being greater the larger the stock.

A warming of the Barents Sea could change the habitat of the north-east Arctic cod, which inhabits the EEZs of Norway and Russia. Its spawning grounds are off the coast of Norway, while the larvae drift towards Spitzbergen and into the Barents Sea. A warming of the ocean in this area is expected to shift the stock further east and north, into the Russian EEZ. Ever since the EEZs were established and a total quota imposed for the stock, the two countries have shared it evenly, apart from a minor allocation to third countries. A major relocation of the stock might undermine this sharing agreement for the reasons discussed above.[7]

It is possible that the picture being painted above is too gloomy. There are factors mitigating against dramatic fish stock depletion and breakdown of agreements as a result of climate change. One such is that fishing costs are sensitive to stock size. If the cost per unit of landed fish goes up as the stock is depleted, this provides some protection against a serious stock depletion resulting from a breakdown of sharing agreements. And the sharing agreements themselves could be resilient against variations in fish migrations. Oceanographic conditions vary a great deal from year to year, due to factors that are unlikely to be related to global warming, and so do fish migrations. Many of the existing sharing agreements seem to be quite resilient to these variations, even if no formal allowance is made for this. The sharing of the North Sea stocks between Norway and the EU is based on an investigation carried out in the early 1980s and has withstood the test of time, with the exception of the North Sea herring already discussed. But both the North Sea herring example and the north Pacific salmon runs indicate that if changes in fish migrations are too dramatic and long lasting, agreements on stock sharing will indeed come under pressure.

High seas fisheries

Changed fish migrations need not only affect the EEZs of individual countries, migrations between one or more EEZs and the high seas could become established or existing ones be affected, positively or negatively. Some stocks (straddling stocks) are mainly contained within the EEZ of one or more countries while others are predominantly or even exclusively in the high seas area. The example in the previous section about a stock migrating out of Country *A*'s area into Country *B*'s area is perhaps particularly pertinent to stocks straddling into the high seas, with the latter replacing Country *B*'s EEZ in this context. Not only would the conservation incentives for Country *A* be seriously eroded by the weak incentives the high seas players have to leave anything behind, the high seas players also face considerable difficulties in coordinating their actions and in finding a common interest.

There is no doubt that management of fish stocks that are partly or wholly within the high seas is a great deal more difficult than it is for stocks confined within the EEZs, even

those that migrate between the EEZs of two or more countries. The reason is the absence of national jurisdiction on the high seas; boats fishing in this area are under the jurisdiction of their home countries. The UN fish stock agreement has given the role of fish stock management on the high seas to regional fisheries management organisations (RFMOs), and some experts are of the opinion that fishing in contravention of regulations by these organisations is in contravention of international law, even if the offending country is not a member of or does not accept the authority of the RFMO in question (*e.g.* Serdy, 2008). The enforcement of these regulations is still up to the individual countries whose boats fish in this area, an arrangement that is much less effective than if one single state had jurisdiction, as the case is within the EEZs. The attempts to deal with enforcement have therefore concentrated on access to markets or port services, denying access to markets for fish taken in contravention of RFMO regulations and services to boats engaged in such fishing. How successful this is depends on market concentration and how vigorously these measures are pursued by the countries where the major markets are.

It is very difficult to say anything in general about how global warming might affect fish migrations into the high seas versus containment within one or more countries' EEZ. To the extent that fish migrations into the high seas increase, fish stock management is bound to become more difficult. That difficulty is due to the fact that it is more difficult to reach agreement the more parties that must agree, and on the high seas there are more parties to be reckoned with than there are for stocks that stay within the EEZs. This problem is aggravated to the extent that the number of parties with an interest in a high seas stock is indeterminate, while the number of countries with an interest in stocks that stay within EEZs is either just one or at any rate defined by the migratory habits of the stock in question (and which may change as already argued). Traditionally, fishing on the high seas used to be open to any country, and it is still unclear to what extent the RFMOs can limit that number or whether, and in that case how, they must accommodate new, untraditional members.

Among the high seas stocks that could be affected by climate change the tuna stocks are the most important, partly because of their extensive migrations and partly because of their high value. Miller (2007) has discussed the effects of climate change on the tuna stocks and pointed out the need for flexible arrangements that could adjust automatically to the challenges of climate change. She mentions transferable catch or effort quotas that could be utilised irrespective of where the fish are taken. Such measures would require that the RFMOs involved have reached an agreement on allocation of quotas or fishing licenses among the parties involved and solved the new member problem so that an existing agreement could not be undermined by countries that suddenly might want to engage in the fishery. This is a taller order than it might seem; it is possible to imagine that those who now are engaged in these fisheries deliberately abstain from ambitious agreements that might appreciably improve the profitability of the fishery, as this might attract entrants that would not find it worthwhile to participate in the fisheries as they are at present.

It is possible that the strains climate change might put on the tuna fisheries, and other high seas fisheries for that matter, will depend on the shape and size of the EEZs involved versus the high seas. Both the Indian Ocean and the eastern Pacific have vast spaces of high seas in which much of the tuna fishing takes place, and there are relatively few national EEZs involved. The western Pacific is different in that it is interspersed with EEZs of many independent island countries, with high seas "holes" in between. The *El Niño* events are known to displace tuna migrations by hundreds or even thousands of

miles (Miller, 2007). This has led to major shifts in catches taken by some of the Pacific island nations in the area. Migrations between the EEZs and the high seas are also affected. Such international agreements on tuna fishing as there are or might be attained in the Indian Ocean and the Eastern Pacific are therefore less likely to be upset by climate change, as the distribution of fish between the high seas and the EEZs will not change much, while in the western Pacific climate change might cause major shifts in the bargaining strength of the different nations involved.

Conclusions and policy implications

One thing is certain: there will be changes in the ocean climate, as there have been in the past, irrespective of whether global warming is happening or not. Global warming will add two complications. First, it will add a trend, around which ocean climate will fluctuate. Second, because of that trend, it is more likely than it used to be that changes in ecosystems will be irreversible. It is uncertain how great the associated changes in fish stocks will be, in what direction, and how quickly they will happen. They are also likely to differ from place to place, not only in magnitude but also in direction. Certain stocks may fade in certain areas, or may disappear altogether and in some cases be replaced by other stocks. Whether on balance this is for the better or for the worse will vary from place to place. Suffice it to say that all changes, be they for the better or for the worse, call for adjustments, and adjustments are always costly.

What are the implications for fisheries management? This depends on whether the effects of climate change occur gradually or not, and whether they can be predicted or not. If these effects take place in small, incremental steps they would not seem to be very problematic; adjustment could be made in similarly small, incremental steps. That climate change will occur as variations around a trend might seem to support the notion that its effect will also be gradual and at times even reversing direction, but this would be too hasty a conclusion. It is quite possible, and indeed likely, that there are certain threshold levels in terms of water temperature, salinity or flow of currents that make certain fish stocks unviable in their previous environment, or at least substantially affect their abundance. These effects could manifest themselves suddenly as the critical threshold levels are surpassed, even if the underlying climate change itself is incremental. Furthermore, it is highly uncertain whether fish stocks would bounce back from their depleted levels, even if the climate change that led to their demise was reversed.

Could sudden and possibly dramatic effects of climate change on fish stocks be predicted? If they could, management authorities could develop responses to cope with them. Unfortunately, it is uncertain whether or not these effects can be predicted sufficiently far in advance. To make such predictions, one would need either to have experienced similar changes in the past or to have a firm understanding of the mechanisms of climate change and its impacts on ocean ecosystems. It is worrying that none of the fisheries collapses that occurred in the past, some of which are discussed in the annex, were predicted; on the contrary they came as surprises. However, these collapses occurred before significant attention was focused on climate effects on fisheries. More recent developments and ongoing work suggest that there is hope to have fewer such surprises in the future, although the issue of possibly increasing climate variation will complicate the picture.

That the effects of climate change on fisheries cannot be predicted with much confidence and will sometimes occur suddenly has two implications for how to respond

to them. First, a strengthening of marine science and its interface with climate science is needed. It is of obvious value to know what might happen, even if one cannot predict precisely when it will happen and on what scale. Such understanding can only come from a general advance in marine science; from oceanography, which tells us how ocean currents, salinity, temperature, upwelling and uptake of carbon dioxide in the ocean is likely to be affected, to fish ecology, which tells us how plankton, fish stocks and marine mammals interact, and how a change in one will affect the abundance of another.

The second implication is, in broad terms, the need for flexibility in response. If changes cannot be reliably predicted the only option we have is to respond to them after they have occurred. To do so in the fisheries context, flexibility is needed both in terms of market access and for adjustment in the use of labour and capital. Unnecessary barriers between different types of fisheries, some of which could expand while others must contract, should be avoided; this could be accomplished by transferable fishing licenses or quotas where the total number of licenses or quotas is based on sound biological principles applied to changing stocks. It is particularly important to avoid "preserving" work opportunities if this is achieved by maintaining a large and unsustainable catch from a dwindling stock. Instead, mobility out of a fishery that must rely on smaller catches because of worsening environmental conditions should be encouraged. In an economy with far-reaching specialisation and few opportunities for unskilled labour this would often necessitate support for retraining and perhaps geographic mobility as well. For capital equipment there may be second hand markets, especially once the world gets a grip on the global overcapacity problem. For markets, unimpeded access would facilitate switching to new sources for supplies when needed.

The changes that we have seen in world fisheries in the past and that appear related to climate change are suggestive of what might happen as a result of climate change and how we could or should respond. These changes have sometimes been of a magnitude to call forth adjectives such as "spectacular" and nouns such as "collapse". Over just a few years fisheries have collapsed, from hundreds of thousands of tonnes to nearly nil. These collapses are unlikely to have been caused solely by climate change; the primary reason is likely to have been in large part mismanagement, due to insufficient information, inappropriate interpretation of the information at hand, lack of appropriate institutions or measures, or short sighted lobbyism by industry. However, climate change may have added to the evils of bad management and helped bring about a collapse.

Several conclusions follow from this. The outcomes of future climate changes may in some ways be quite similar to those we have experienced in the past – there are some similarities between changes in ocean climate in the last century and what we expect to happen in the coming decades. The global temperature has in recent years reached a higher level than we have seen since the beginning of reliable measurements. Further increase could take us into an unchartered territory and, together with other stressors on marine eco-systems, cause unprecedented impacts. Second, what is critical is good management of stocks. The management of many of the stocks that have collapsed was either absent (Atlanto-Scandian herring, North Sea herring) or deficient (northern cod). Therefore, management, or the lack of it, is likely to have been the major cause of the collapse. How these stocks would have fared under better management we do not know, but it is not unlikely that the protracted absence of the herring could have been avoided, and the cod fishery of Newfoundland might have been saved.

Hence, climate change serves to strengthen further the arguments for good management, in particular avoiding such overfishing as typically results from open

access. Global warming is unlikely to pose fundamentally new problems for fisheries management, but the present focus on it serves the good purpose of emphasising how dependent fisheries are and have always been on the variability in ocean climate. This has important, but unfortunately unclear implications for the sustainability of fisheries. The deterministic fisheries models, despite their usefulness as pedagogical devices, may have led some people to believe that sustainability of fisheries revolves around maintaining steady stock levels and steady catches over time. This is unlikely to be desirable for stocks the growth and reproduction of which depend critically on a fluctuating environment, and it may even be impossible to attain. Hence, if sustainability means anything, it means adaptation to a fluctuating environment. Unfortunately, it is not clear what that adaptation means. Does it mean preserving depleted fish stocks in the expectation that they will bounce back once the environmental conditions have returned to an advantageous state, or are some stocks doomed in certain areas because of irreversible changes in the ocean climate, so that we had better take them while they are still around? It is not easy to answer these questions, because of the difficulty to know whether climate changes are permanent and irreversible or part of a repetitive pattern.

Notes

1. This is not, of course, true for aquaculture, but it is capture fisheries that are the subject of this paper.

2. This report has been well summarised by Schrank (2007).

3. The value of total fish landings in Newfoundland in 1989-90, while the cod was still around, was about CAD 275 million per year (*Historical Statistics of Newfoundland and Labrador*, Vol. II (VII), 1994) published by the Government of Newfoundland and Labrador, Executive Council). In 2004-09 it was about CAD 470 million per year (Internet website of the Government of Newfoundland and Labrador: *http://www.fishaq.gov.nl.ca/stats/landings/index.html*). According to the consumer price index for Canada (*http://www40.statcan.gc.ca/l01/cst01/econ46a-eng.htm*), prices rose by 42% from 1990 to 2007, so allowing for inflation the value of fish landings was about 20% higher in 2005-2009 than in 1989-90. In the first years of this century the value of fish landings in Newfoundland was even higher (*http://www.dfo-mpo.gc.ca/stats/commercial/land-debarq/sea-maritimes/s2000av-eng.htm*).

4. This is about the same as the dip in GDP expected to occur in 2009 as a result of the collapse of the Icelandic banks.

5. The analysis of Iceland and Greenland is discussed from a more technical point of view in Arnason (2007).

6. This problem, with adaptive expectation, is considered formally in Hannesson (2007).

7. This problem is considered in a bioeconomic model in Hannesson (2006). This exercise illustrates the point made above that a decline in zonal attachment may up to a point strengthen the bargaining position of the country so affected.

Annex 8.A1

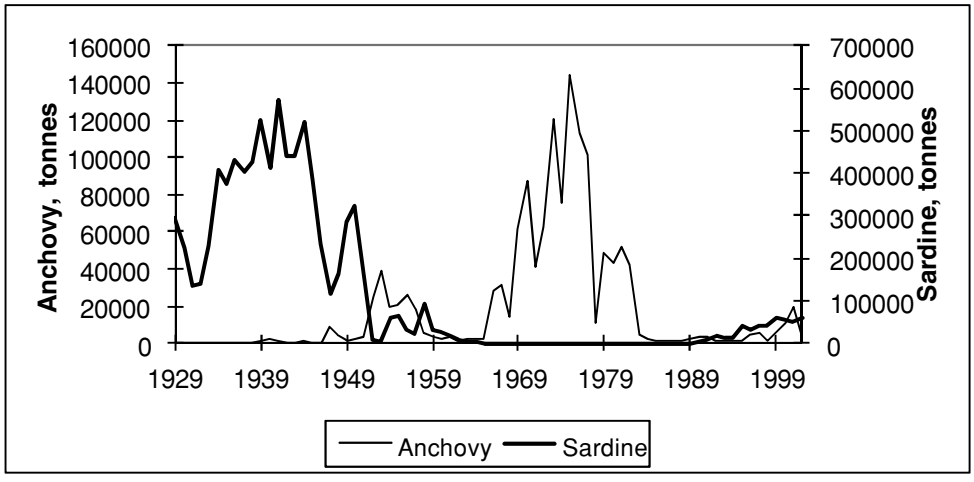
Examples of past climate changes and their consequences

In this annex we discuss several well known cases of fishery collapses and changes in the oceanic environment. It is recognised that the global temperature has in recent years reached a higher level than we have seen since the beginning of reliable measurements and that further increase could take us into an uncharted territory and, together with other stressors on marine eco-systems, cause unprecedented impacts.. However, it is valuable to review past experiences to identify potential lessons for the future. The environmental indicator used is ocean temperature, but the temperature is unlikely to have been the causal factor behind the collapses, even if any given fish species thrives within certain temperature limits and so could have been rendered unviable by passing critical thresholds. Rather the temperature is associated with other attributes of the water masses involved; such as salinity, higher concentrations of nutrients (upwellings), or transport of plankton and prey fish necessary for fish higher up in the food chain. Yet temperature is a convenient and widely used indicator for environmental changes in the ocean.

Another point to note is that the association between changes in ocean temperature and the collapse of fisheries is suggestive rather than a clearly established quantitative, causal relationship. Yet these associations appear to be widely accepted among fisheries biologists and oceanographers. The picture is further complicated by the fact that misinformed and inflexible fish stock management has also been involved in the fisheries collapses to be discussed.

Pacific sardine

Figure 8.A1.1. California landings of anchovy and sardine (1920-2002)



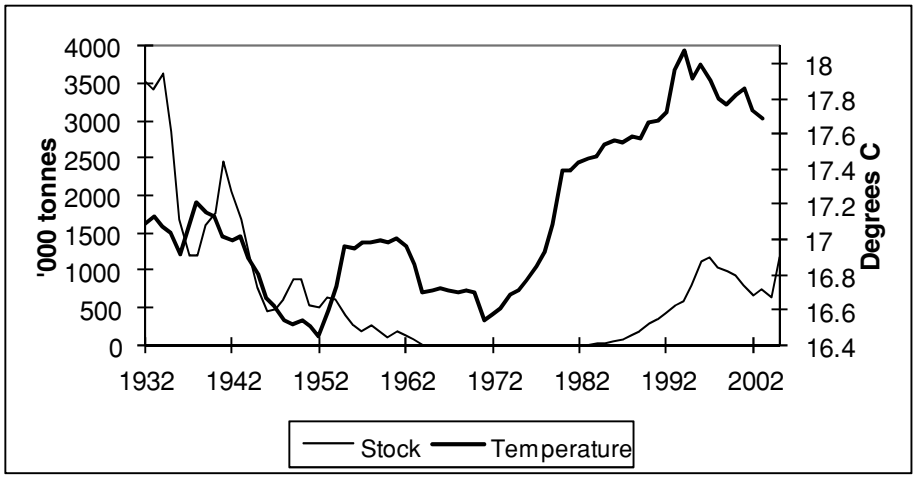
In the 1930s and 1940s, the Pacific sardine supported one of the largest fisheries in the world (*cf.* Figure 8.A1.1). Some fish was used for reduction to meal and oil and some

by a large canning industry in California, made famous by John Steinbeck's novel "Cannery Row." In the 1950s the sardine fishery collapsed. The collapse was initially attributed to overfishing (Herrick *et al.*, 2006). Later, when marine biologists began analysing cores from sediments in the Santa Barbara channel, they found that sardine and anchovy appeared to have alternated in this area long before European colonisation and attributed this to climate changes (Baumgartner *et al.*, 1992). The collapse of the sardine fishery may thus have been partly due to a climate change. In the 1950s the North Pacific became cooler and entered a climate regime disadvantageous to the sardine, with anchovy taking its place in the ecosystem. As Figure 8.A1.1 shows, the anchovy fishery flourished in the period when the sardine was down (note that the scales for the two fisheries are different).

Figure 8.A1.2 shows the sardine stock and the nine-year moving average of the average annual temperature at the Scripps Pier in La Jolla, California. The figure suggests a positive correlation between temperature and the abundance of the sardine, although it is by no means perfect. The decline in the stock in the early 1940s coincided with a declining temperature, and the upswing in the 1990s coincided with a substantial rise in temperature. Due to a bulge of high temperatures in the late 1950s the temperature during the virtual absence of the sardine was not much lower than during the sardine heydays in the 1930s and early 40s, but certainly well below what it has been from the mid-1980s onwards.

As a result of the collapse of the sardine, people were thrown out of work, fishing boats became obsolete, and so did processing capital onshore such as fish meal factories and canneries. Some of the fishing and processing equipment was exported to countries where new and similar fisheries emerged, partly as a result of the collapse of the sardine fishery in California (Glanz, 1992). In the 1950s both the anchovy fishery in Peru and Chile and the sardine fishery in South and south-west Africa developed. Over a few years these became major suppliers of fish meal on the world market. Some of the cavernous sardine canneries in Monterey are now used by the Monterey aquarium.

Figure 8.A1.2. Spawning stock of Pacific sardine and temperature at Scripps Pier, La Jolla, California
(nine-year moving average)

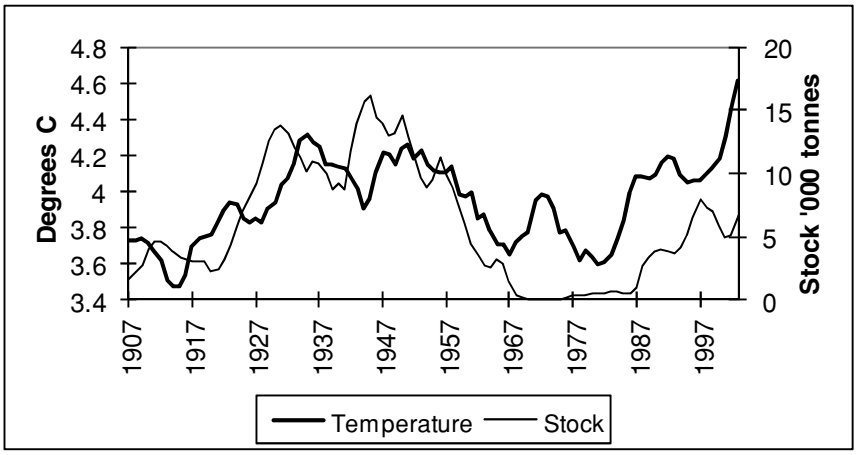


The Atlanto-Scandian herring

The collapse of the Atlanto-Scandian herring was no less spectacular than the collapse of the California sardine. The collapse has usually been attributed to overfishing, brought on by a major technological change that occurred in the fishery over just a few years (the introduction of a mechanical winch to haul in purse seines). At the time (late 1960s) the fishery was largely conducted in international waters, and an effective control of the fishery would have involved an international effort by Norway, Iceland and the Soviet Union and possibly others. This was not attempted. Apart from the difficulties in getting several parties to agree, it is doubtful if the problem was recognised in a timely enough fashion to do anything about it.

Lately attention has been drawn to the fact that there probably is a correlation between ocean temperature and the abundance of the herring stock (Toresen and Østvedt, 2000). Figure 8.A1.3 shows the size of the spawning stock of Norwegian spring-spawning herring and average annual temperature at the Kola section (nine-year moving average). The figure indicates a positive correlation between herring abundance and temperature; the period while the herring stock was down (1967-87) coincides with a period of lower temperature than before or after, and the recovery of the herring stock occurred after the temperature began to rise. While few would go as far as attributing the collapse of the stock to climate change only, it is certainly likely that some decline in the stock would have occurred as a result of cooling temperatures if the fishery had continued in the same fashion as it did before the technical change.

Figure 8.A1.3. Spawning stock of Norwegian spring-spawning herring and average annual temperature at the Kola Section
(nine-year moving average)

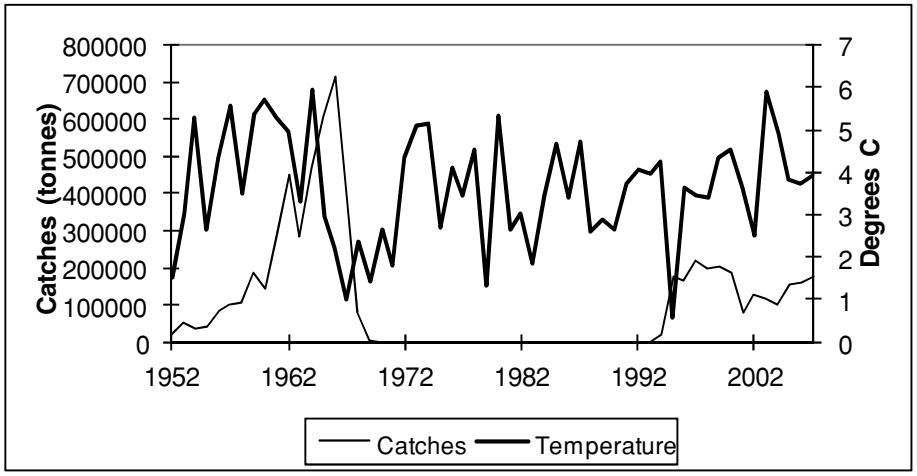


The decline in the herring fishery caused major disruption in the fishing industries of Norway and Iceland (Hamilton *et al.*, 2006; Lorentzen and Hannesson, 2006). In Iceland the gross domestic product fell, unemployment became a major problem, and many people emigrated in search of work. At the aggregate level these effects are much less visible in Norway, the Norwegian economy being much bigger and more diversified. In both countries the collapse of the herring fishery led to the development of new fisheries, especially the capelin fishery, which for a while was the major supplier of raw material for the fish meal factories in Norway and still is in Iceland. It is indeed possible that the

capelin stock in the Barents Sea, exploited by Norway and Russia, came to occupy a part of the ecological niche left vacant by the herring.

What probably aggravated the herring collapse in the Icelandic fishery was a temporary cooling of the waters north of Iceland in the late 1960s (Figure 8.A1.4) (Malmberg, 1969; Hamilton *et al.*, 2006). This adversely affected primary production in the area and disrupted the traditional feeding migration of the herring to this area. In fact, a separate stock of spring-spawning herring that spawned at Iceland disappeared at this time, either due to overfishing or adverse climatic conditions. The same thing happened to the spring-spawning herring at the Faeroe Islands, so the Norwegian component is the only one remaining of what used to be called Atlanto-Scandian herring (an autumn-spawning herring stock still remains at Iceland). The importance of the temperature regime for the collapse in the catches of herring is masked by the fact that after the migrations to the traditional area north of Iceland stopped in 1963, the boats chased it further east and north towards Spitzbergen. The migrations did not resume after the temperature recovered in the mid-1970s, the reason probably being that there was very little left of the stock (*cf.* Figure 8.A1.3). These migrations still have not been fully re-established, but since the mid-1990s the Icelandic catches have been resumed, even if the Icelandic stock of spring spawners appears to have vanished.

Figure 8.A1.4. Icelandic catches of spring-spawning herring and spring ocean temperature at Siglunes



The north-east Arctic cod

Figure 8.A1.5. Stock of north-east Arctic cod and average annual temperature at the Kola Section (seven-year moving average)

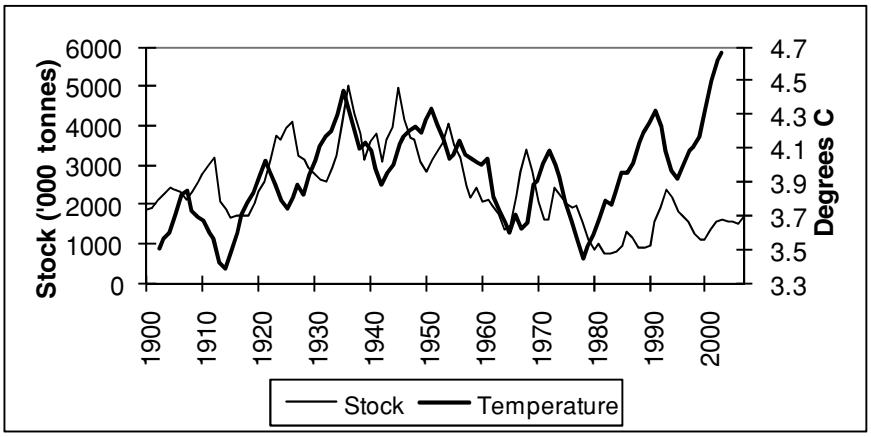


Figure 8.A1.5 shows the abundance of north-east Arctic cod and the average annual temperature in the Kola section (seven-year moving average). There figure suggests a positive correlation between stock abundance and temperature. The correlation is least convincing for the years after 1980. Since then the temperature has been on the rise, reaching in 2007 its highest level since 1900, but the stock abundance has been relatively low during that entire period, even if it did reach a local peak in 1994, about three years after a local peak in temperature. This is a long-lived stock; maturing at an age of six-seven years (later in earlier years) and recruited to the fishery at an age of three. If temperature primarily affects recruitment, a time lag of five years or more between temperature and the stock should be expected, and there is some indication of that. Unlike the herring and the sardine stocks, this stock has not collapsed, but the rate of exploitation increased very substantially in the 1960s and 70s, which could be the reason why the correlation between temperature and stock size is less convincing for the years after 1970.

Figure 8.A1.6. Recruitment of three-year olds to the north-east Arctic cod stock and temperature at the Kola Section three years earlier

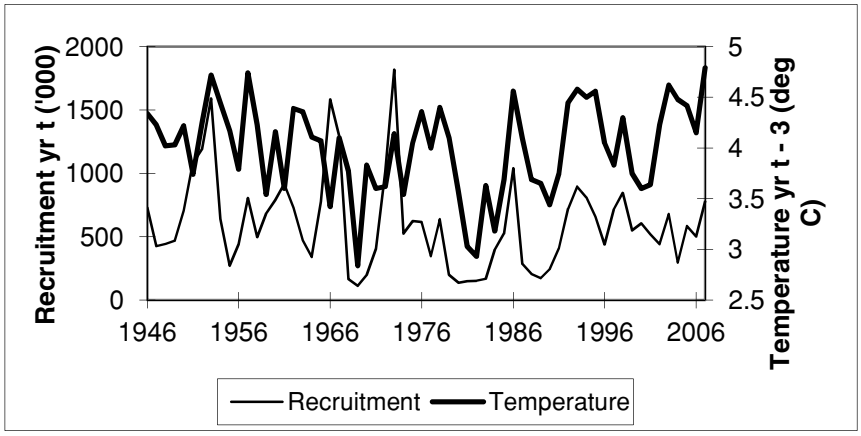
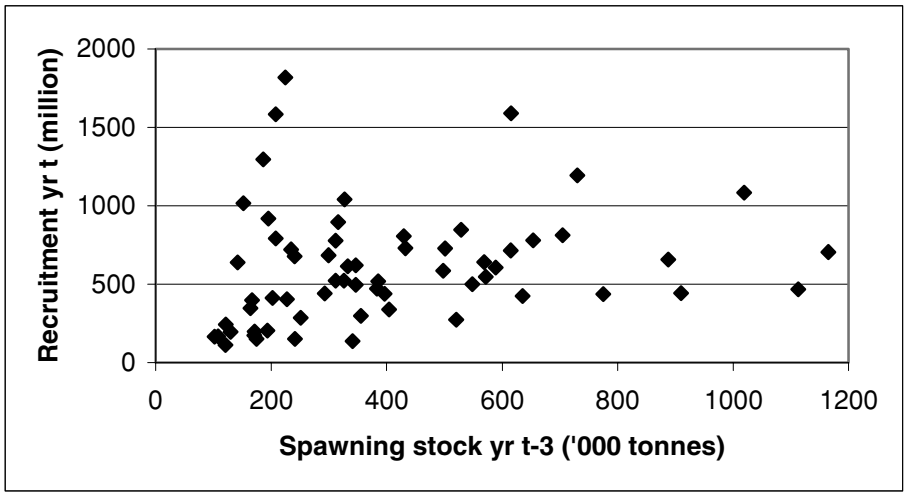


Figure 8.A1.7. Recruitment of three-year olds to the north-east Arctic cod stock and the spawning stock three years earlier



The ocean climate is probably particularly important for recruitment to the stock. Figure 8.A1.6 shows recruitment to the stock and the temperature at the Kola section three years earlier. The correlation between the two is not particularly high (0.27), but it is significant at the 5% level. Figure 8.A1.7 shows a scatter plot of recruitment and the spawning stock three years earlier. It is difficult to see any relationship between those two, except perhaps that a large spawning stock would not bring a large recruitment.

The northern cod of Newfoundland

The northern cod of Newfoundland is probably the only one among major commercial fish stocks that has been fished to extinction in an economic sense. The fishery was closed in 1992 and has not been reopened since, except on an experimental basis to help assessing the stock. This happened despite a management policy that was explicitly cautious (the $F_{0.1}$ criterion was used as a guideline). In hindsight the stock turned out to have been overexploited, due to erroneous stock assessment. Investigations have not uncovered serious methodological faults, but belatedly it was realised that the catch per unit of effort did not fall as much with the stock as expected, due in all probability to a herding behaviour of the stock in warm-water pockets on the Grand Banks during a cold ocean climate regime. The colder ocean climate may also have played a further role by retarding the growth and reproduction of the stock. The story illustrates well how difficult it can be to account for environmental variability despite well developed fisheries science and good intentions.

Figure 8.A1.8. Catches of northern cod (1850-1992)

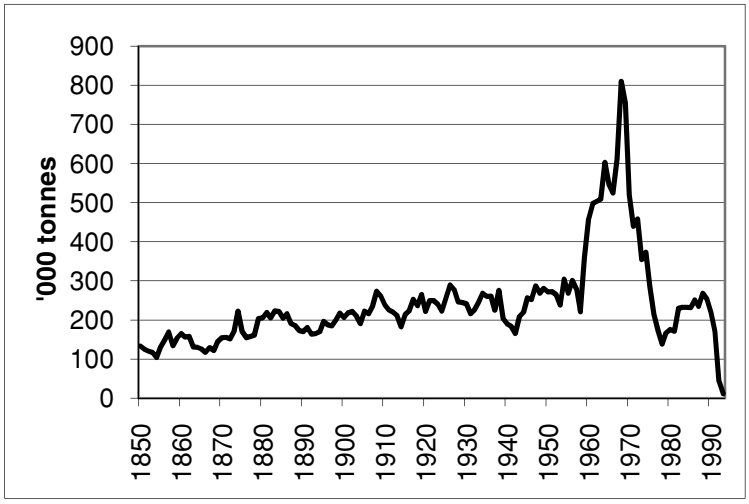
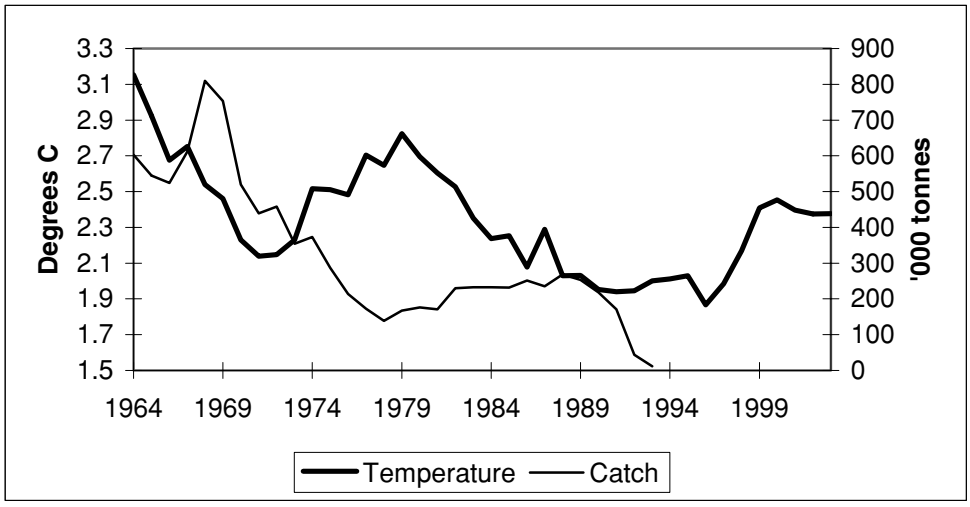


Figure 8.A1.8 shows the catches of northern cod from 1850; the high peak reached in the 1960s was due to the advent of large trawler fleets from various nations, which raised the rate of exploitation to an unsustainable level. After Canada established its exclusive economic zone in the late 1970s the catches fell to a level similar to what had prevailed before the international trawler fleets came along and continued in that fashion for about ten years, until the collapse in 1992. Figure 8.A1.9 shows that the collapse coincided with a cold ocean climate regime in the area.

Figure 8.A1.9. Catches of northern cod and summer sea surface temperature at Newfoundland
(nine-year moving average)

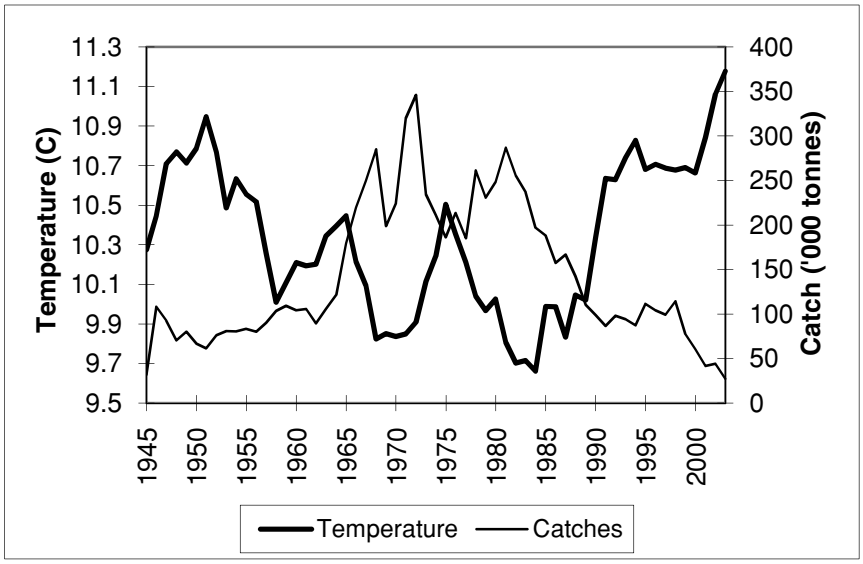


The North Sea cod

It is generally acknowledged that the North Sea cod stock is not in good shape. This is typically attributed to overexploitation. This may indeed be true, but it is also true that the catches of North Sea cod are inversely related to ocean temperature, indicating that there

may be more to the story than just overexploitation. Figure 8.A1.10 illustrates this, using temperatures from the northern fringe of the North Sea.

Figure 8.A1.10. Catches of North Sea cod and ocean temperature off the Sognefjord
(seven-year moving average)



If ocean climate plays such as large role as Figure 8.A1.10 indicates it raises some challenging questions. Is it possible to save the North Sea cod, or is it doomed to disappear because of adverse environmental changes? If so, it would not help much to cut back on fishing, and it might make most sense to catch it while it is still around. Similar questions can be asked about the Baltic cod. Both the Baltic and the North Sea are marginal areas for the cod, so that relatively small environmental changes threaten their survival.

The Peruvian anchovy

The fishery for anchovy in Peru developed in the late 1950s, partly as a response to the collapse of the Pacific sardine. A new fish meal industry was built on the basis of the Peruvian anchovy, and some of the equipment made redundant by the collapse of the California sardine was sold to the new Peruvian industry. Before the late 1950s hardly any anchovy was caught in Peru, and the anchovy was "harvested" indirectly by guano deposited on islands off Peru and Chile. The guano industry opposed the development of the anchovy fishery, fearing that its raw material base would disappear.

Figure 8.A1.11. Catches of anchovy and pilchard (sardine) in Chile and Peru

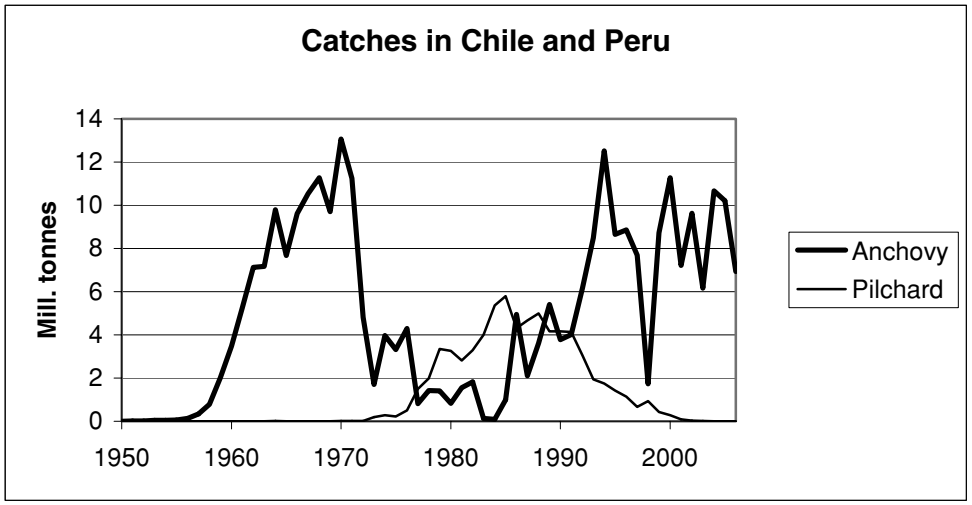


Figure 8.A1.11 shows the development of the anchovy and sardine (pilchard) fisheries in Peru and Chile. In 1972 there was a strong *El Niño* event, adversely affecting the catches of anchovy. Measures for cutting back the anchovy fishery were not taken in time, the stock collapsed, and the fishery did not regain its previous peak until 1994.

In 1997 there also was a strong *El Niño* event. This time measures were taken to reign in the fishery. The catches dropped precipitously in 1998, but recovered already next year. It appears that the lessons of the early 1970s had been learned, but prior to that time there was no experience of how the *El Niño* event might affect the anchovy fishery.

A noteworthy thing in Figure 8.A1.11 is the rise of the sardine fishery after the collapse of the anchovy, as well as its decline after the anchovy recovered. Sardine and anchovy occupy the same niche in the ecosystem and typically alternate in abundance, a phenomenon known to occur in several upwelling systems such as the California current, discussed above, the Benguela current, and the Canary current. So even if one species virtually disappears for a time, it is not necessarily the case that the primary production (plankton) goes unutilised.

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Chapter 9

Climate change and the management of high seas, straddling and migratory fish stocks

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In this chapter, impacts of climate change on high seas, straddling and highly migratory stock fisheries are discussed in the context of capture fisheries trends and socio-economic implications. Factors considered include impact pathways, impact effects, future impacts and relationships to other trends. The exposure and sensitivity of fisheries to climate change are considered in terms of "vulnerability" and "resilience". Climate change "adaptation" and "mitigation" are highlighted, noting a need to explicitly account for uncertainty in available climate impact information and potential fisheries responses. Gaps in current knowledge of climate change impacts are identified for high seas, straddling and highly migratory fish stocks. A need for relevant institutions to provide anticipatory adaptation measures to minimise impact(s) is recognised. Consequently, increased environmental and fisheries uncertainty have serious implications for the management of climate-impacted fisheries.

A generalised management approach is outlined and possible models identified to describe the variables, constraints, driving forces, temporal considerations and data needs necessary for an anticipatory management approach. Practical implementation of management action is dependent on predicting the effects of climate change impacts on the fisheries being considered. Research initiatives are explored to promote institutional awareness/capacity globally, provide relevant information and improve policy development aimed at boosting ocean governance of high sea fisheries.

Introduction

The complex debate on global climate change has raised awareness that marine living resources are particularly vulnerable to a combination of effects, ranging from overexploitation to climatic shifts (Pauly and Palomares, 2005; Pauly *et al*., 2002; Hofmann *et al.,* 2010). Notably, the United Nations (UN) Food and Agriculture Organization (FAO) has stated:

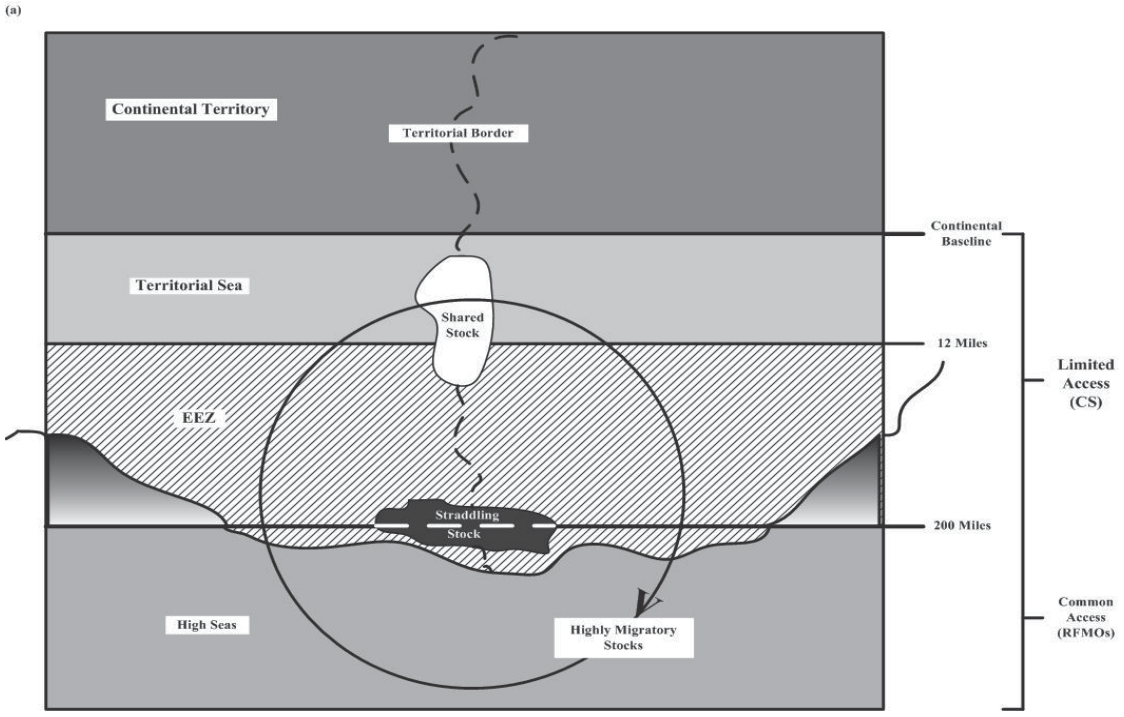
> *Climate change is a compounding threat to the sustainability of capture fisheries and aquaculture development. Impacts occur as a result of gradual warming at the global scale and associated physical changes, as well as the consequence of extreme weather events. These take place in the context of other global social and economic pressures on natural resources and ecosystems. In addition to action to mitigate the factors driving climate change, urgent adaptation measures are required in response to opportunities for, and threats to, food and livelihood provision arising from climate variation. (FAO, 2009)*

To assess the potential consequences of such statements, consideration must first be given to the drivers, trends and status of marine capture fisheries globally. Equally, the direct and indirect impact of climate change on harvested stocks should be explored. The latter includes a need to evaluate the consequent vulnerability and sensitivity of harvested stocks to such change. Socio-economic and food security concerns are then the yardstick for strategies aimed at addressing climate change-fisheries effects.

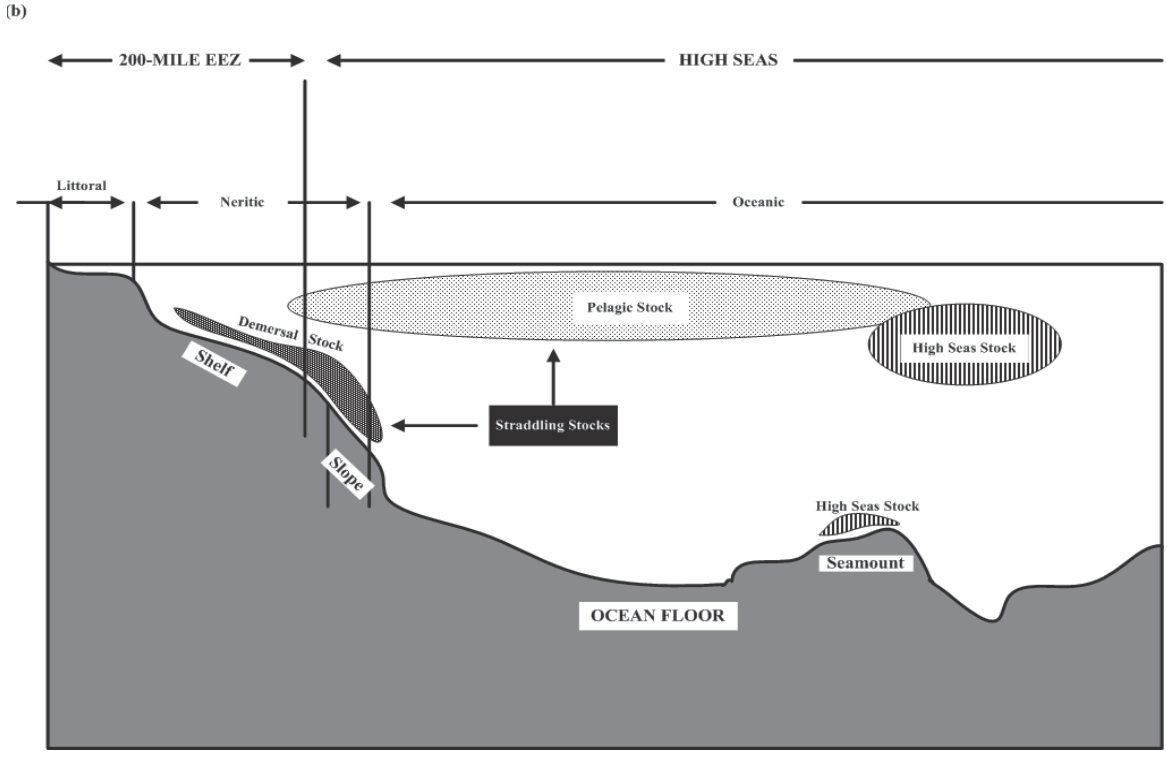
Initially, it is necessary to identify the actual fish stocks being considered. The general terminology outlined by the FAO (1994) is applied to define "high seas" [1] resources as those existing beyond national jurisdiction (Figure 9.1a). These resources comprise species that are predominantly encountered beyond the 200 mile Exclusive Economic Zone (EEZ), although they may spend part of their life cycles closer to shore during reproduction or feeding. EEZ stocks that extend into and beyond, or between, EEZs are referred to as "straddling stocks" (Table 9.1). Species that move ("migrate") between EEZs and the high seas, across the high seas and across many EEZs are known as "highly migratory stocks". They are identified in Annex I of the 1982 *United Nations Convention on the Law of the Sea* (UNCLOS) while straddling stocks are defined in Article 63 of the Convention.

Biologically, high seas resources may be "neritic" or "oceanic" depending on their proximity to the sea floor (Figure 9.1b). Neritic resources are largely confined to the continental shelf and upper shelf slope, even though their distribution may extend onto the high seas where they may be caught. They are also encountered where no EEZs have been proclaimed (*e.g.* in the Antarctic or in parts of the North Atlantic) (FAO, 1994). Neritic high seas resources are "demersal", with a strong affiliation to the sea floor, or "pelagic", being encountered in the oceans' upper reaches with little association to the sea floor.

Figure 9.1: Maritime zones and fish stock types (a)



and fishery terminology to define "deep seas" (b)



RFMO – Regional Fisheries Management Organisation, DWFFs – Distant Water Fishing Fleets

Source: FAO (1994); Japp and Wilkinson (2006)

Table 9.1. Fishery types, locations and targeted stocks

Fishery	Location	Stocks Targeted	Definition
High seas	High seas	Discrete	UNCLOS[1] does not address the term "discrete high seas fish stocks" or the concept behind it. However, Part VII of the Convention addresses living resources of the high seas in general. The term or concept does not appear in the FSA[2] either. The term "high seas stocks" thus refers to stocks that are purely or entirely encountered on the high seas, that is stocks that are neither "highly migratory" or "straddling".
Straddling	High seas and EEZ	Trans-boundary	UNCLOS Article 63.2 refers to: "*the same stock or stocks of associated species [which] occur both within the exclusive economic zone and in an area beyond and adjacent to the zone*". This is taken as a working definition for the concept of a "straddling stock" in this paper.
Migratory	High seas and EEZ	Migratory trans-boundary	"Highly migratory species" are listed in Annex 1 of UNCLOS. This is a legal definition rather than a scientific definition based on the actual migratory behaviour of the species. Nevertheless, the species listed in Annex 1 are generally capable of migrating relatively long distances, and stocks of such species are likely to occur within EEZs and on high seas.

EEZ – Exclusive Economic Zone

1. 1982 United Nations Convention on the Law of the Sea.
2. 1995 Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks.

As a group, high seas resources are predominantly caught beyond the outer shelf and/or migrate extensively across the open ocean. Their life history stages may be confined within continental EEZs where large catches may also be taken (FAO, 1994). Important pelagic high seas resources include high value fisheries for species such as migratory billfish, tunas and swordfish (FAO, 1994; FAO, 2009; *www.fao.org/fishery/topic/16917/156463/en*), while equally commercially-valuable demersal species may be encountered on seamounts, or in other areas, of the deep ocean (FAO, 2005; Japp and Wilkinson, 2006).

Most oceanic high seas stocks are dispersed and difficult to harvest commercially while information on their catches is patchy and usually incomplete (see "Fisheries status and trends", below). They are often exploited by distant-water fishing fleets (DWFFs) at crucial times during the life cycle of targeted stocks; for example when they aggregate to spawn or feed. (FAO, 1994).

It is generally acknowledged that improved fishing technology, and the increasing scarcity of near-shore ("coastal") resources caused by heavy EEZ fishing pressure, have contributed to the expansion of high seas fishing; a situation that has been clearly evident over the past two to three decades (Pauly *et al.,* 2005). Fishing pressure on high seas species also does not appear to be subsiding (Baker *et al.,* 2001) with, most notably, the relatively recent discovery of high value deepwater species, such as toothfish and orange

roughy, and the demands for species such as tuna (Japp and Wilkinson, 2006; Sissenwine and Mace, 2007). So serious are such pressures that the term "global fisheries crisis" was initially used almost a decade and half ago to emphasise general concerns for global food security in the future, and more noticeably as a particular concern for the OECD over the past decade (Nixon, 1997; Schmidt, 2002).

While high seas stocks (Figure 9.1 and Table 9.1) are targeted here, the underlying principles discussed are also relevant to the harvesting of wild aquatic resources generally. In this context, a "stock" is considered as a population, or biomass, of a fishery resource separated by geographic location and/or genetic differences. A stock itself may comprise one or more species. In turn, Gulland (1969; 1983) has proposed that a group of fish may be treated as a "stock" and managed as an independent unit. The strategic basis for management is then used to clearly identify operational criteria and practical constraints (Butterworth, 1986). Conversely, management action is predicated by assessment, whereafter the impact of management measures should not differ significantly from those for a truly independent stock (Gulland, 1983).

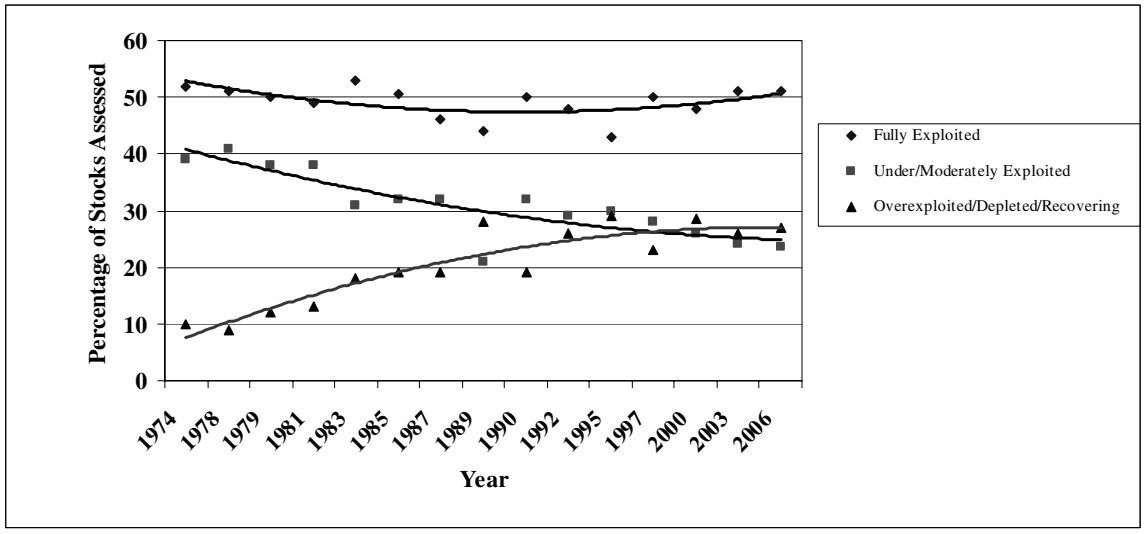
Exposure, sensitivity, vulnerability and resiliance to climate change

Fishery status and trends

Daw *et al.* (2009) indicate that global food security is profoundly affected by prevailing fisheries status and trends. However, the impact of the latter is largely unclear due to a lack of precision in the fisheries data reported for high seas areas to the FAO (Box 1 in FAO, 2009). For historical reasons, the boundaries of national EEZs and FAO Fishing Areas do not coincide, and data on high sea catches *per se* cannot be easily, or unequivocally, estimated from data submitted to the FAO alone. This requires the FAO to co-operate with regional fisheries management organisations (RFMOs), and regional fisheries arrangements (RFAs), to align the FAO's statistical reporting boundaries with those of relevant RFMO/RFAs to improve separation of catches taken on the high seas from those in national EEZs. Nevertheless, some general statements can be made, even though exact catch figures are not specifically available for the three stock categories being considered.

Based on FAO analyses to date (FAO, 2009), it is generally accepted that the global, and overall, proportion of underexploited, or moderately exploited, stocks has declined from about 40% in the mid-1970s to 20% in 2007. The proportion of fully exploited stocks has remained steady at about 50%. The proportion of overexploited, depleted or recovering stocks appears to have stabilised at between 25% and 30% since the mid-1990s (Figure 9.2). Where data are available, examining the status of groups of stocks indicates that the proportions of overexploited, depleted and recovering stocks remained relatively stable between 2003 and the end of 2008. This followed an increasing trend in the 1970s and 1980s.

Figure 9.2. Global trends in the state of world marine stocks for the period 1974 to 2006



Source: Redrawn from Figure 21 in FAO (2009).

A primary complication in all of the above is that many fish stocks worldwide were negatively impacted by notable increases in fishing effort during the 1950s and 1960s. Such increases were accompanied by large catches, improved fishing technology and expansion of fishing onto the high seas (Koslow *et al.,* 2000; Pauly *et al.,* 2002). They also resulted in the decline and collapse[2] of many fish stocks to the extent that Mullon *et al.* (2005) indicate that between 1950 and 2000 366 fisheries out of a total of 1519 collapsed (*i.e.* one in four fisheries collapsed during this 50-year period). The most notable such collapses were the Peruvian anchovy fishery in the early 1970s (Pauly *et al.,* 2002) and the Atlantic cod fishery in 1991 (Hilborn *et al.*, 2003). The former was attributed to a combination of overfishing and the environmental effects of an *El Niño* event (Pauly *et al.,* 2002), while the latter was seen to be the result of overfishing (Myers *et al*., 1997). The potential involvement of environmental factors in the Peruvian anchovy collapse meant that the collapse was not blamed on overfishing; a situation that permitted "business as usual" in other fisheries elsewhere (Pauly *et al.,* 2002). On the other hand, closure of the Atlantic cod fishery resulted in considerable social upheaval (Hilborn *et al.,* 2003) and to date there has been no sign of a recovery (Schrank, 2005).

Taking such considerations further, Daw *et al.* (2009) have highlighted some key considerations to be noted when examining potential climate change effects on fisheries. Such considerations are seen to represent an accumulation of industrial pressures that include increasing commercialisation, globalisation, over-investment and excess fishing capacity (Allsopp *et al.,* 2009) (Table 10.2). In effect, fishing pressures have been shown to combine with environmental pressures and profoundly impact fisheries such as that for Icelandic herring (Drinkwater, 2002; Perry *et al.,* 2010a). Accepting that there might have also been antecedents in the environmental-fishery nexus in relation to the Atlantic cod collapse above (Perry *et al.* 2010a), the collapse of the Atlantic herring and cod fisheries sound a warning that highlights a fracture between the scales over which decisions concerning target stock sustainability should be considered, when compared to consideration of socio-economic needs. As Perry and Ommer (2003) note there are potential scale mismatches between "social-ecological" systems and the connectivity

between social and ecological systems *per se* (see "Climate and the socio-ecology of ocean systems", below).

Table 9.2. Consequences of some key fisheries status and trends in the context of potential climate change impacts

Trend	Consequences
Increased production	Marine fisheries production peaked in the 1980s with over half of global stocks exploited to maximum capacity, one quarter overexploited , collapsed or in decline, and only one quarter with potential for increased production (FAO, 2009)
Excess (surplus) fishing capacity	Surplus fishing capacity may lead to excess fishing effort in a manner that compromises productivity of fishery resources and their sustainable utilisation (FAO, 1995; 1999). ftp://ftp.fao.org/docrep/fao/006/x3170e/X3170E00.pdf
Overfishing	Overfishing has reduced revenues and economic efficiency while increasing catch variability and reducing stock resilience (Hsieh *et al*., 2006). Has led to "fishing down the food web" as fish at higher trophic level decline and fisheries focus more on lower trophic levels (Pauly, 1998; Allan *et al,.* 2005). Extinctions (Sadovy and Cheung, 2003), biodiversity impacts (Worm *et al*., 2006), ecosystem effects (Myers *et al.,* 2007; Allan *et al,.* 2005) and changed genetic character of certain stocks are possible (Hutchings, 2000)
Industrialisation	Over investment and surplus fishing capacity (Hilborn *et al.,* 2003) minimise possibility of scaling back fishing to rebuild stocks or match biological productivity (Ludwig *et al.,* 1993)
Stock collapses	Increasing awareness of socio-economic and human aspects of fishing leading to focus on fisheries governance as well as management. Wider application of co-management, sustainability incentives (Hilborn, 2003) and ecosystem approach to fisheries (EAF), as well as holistic, approach to fisheries management (FAO, 2003)
Increasing commercialisation & globalisation	Role of developing world in particular and high global demand lead to pressure on resource sustainability and even stock collapses (Berkes *et al.,* 2006)

Source: Daw *et al.*(2009).

On the high seas, the extensive geographic distribution of stocks necessitates deployment of highly mobile fishing fleets. Equally, the extent of high seas habitats (*i.e.* neritic, oceanic, pelagic and demersal), and associated working conditions for the fishery (*i.e.* remote locations, adverse weather, *etc.*) also mean that considerable capital investment underpins the need to secure essential fishing capacity. As a consequence, high seas fisheries are predominantly large-scale, technologically advanced, capital intensive and expensive, so ascribing to Ackefors' (2009) definition of "industrial fisheries". Japp and Wilkinson (2006) indicate that this has tended to focus such fisheries on commercially-lucrative species to secure better profit margins. Therefore, high seas fisheries tend to fish "down-the-food-chain" from high-value to lesser-value species (Zeller and Pauly, 2007). The risks of overexploiting target stocks is consequently heightened in relation to the biological capital available; a situation often aggravated by

high seas stocks predominantly comprising slow-growing/long-lived species (Cochrane and Doulman, 2005; Pauly *et al.,* 2005).

The pressures emphasised above are consequently magnified by long-term biological effects such as diminishing stock productivity, ecosystem/biodiversity impacts and genetic variability (Allsopp *et al.,* 2009). Furthermore, as already highlighted, there is increased likelihood of stock collapses, followed by fishing down the food web, thereby mandating that high seas capture fisheries in particular should be considered in all their human, economic, social, biological and ecological dimensions (Cochrane and Doulman, 2005).

It is generally accepted that high seas fisheries are diverse in terms of their geographic and temporal range, species being targeted, technologies being used, markets being serviced, management measures being applied and the political/socio-economic constraints in place (Berkes *et al.,* 2001; Jennings *et al.,* 2001). As a result, there are major differences in the way different high seas fisheries go about their business and in the various attendant considerations attached thereto. Daw *et al.* (2009) posit that the resultant complexities of purpose and function determine how specific fisheries are likely to be affected by climate change.

As a first step, it is possible to clarify the differences between large-scale (predominantly industrialised) and small-scale (largely artisanal) fisheries (Table 9.3). These provide the industrial, and socio-economic, framework in which climate change impacts are likely to be felt and in which they can be assessed (see below: "Socio-economic context of high seas fisheries"). However, they also provide a temporal and spatial context for examining the direct and indirect bio-ecological effects of climate change itself on target stocks.

Table 9.3. Some differences between large-scale and small-scale marine fisheries

Property	Large-scale	Small-scale
Participation	mainly developed countries	mainly developing countries
Location	mostly offshore/high seas	mostly nearshore/coastal
Vessels/equipment	mechanised fishing with advanced technology and distant-water capabilities	manual fishing with simple/limited technology in local waters
Fuel use	high (14-19 million tonnes/yr) 2-5 tonnes fish/tonne fuel oil	low (1-2 million tonnes/yr) 2-5 tonnes fish/tonne fuel oil
Catch use	high value (international) markets food reduction to meal	increasingly high value (global) markets mostly local food
Catch per unit effort (productivity)	high	low
Employment	~500 000 fishers worldwide	~50 000 000 fishers worldwide

Table 9.3. Some differences between large-scale and small-scale marine fisheries (cont.)

Property	Large-scale	Small-scale
Fishers' economic status	full time professionals high income relative to norm	full and part time often poor
Fishery complexity	limited relatively few fishing units similar gear relatively few species	high large number of fishing units diverse gear large number of species
Management	extensive large bureaucracy wide scientific advice extensive scientific capacity	low distanced from government limited community participation limited/no scientific advice

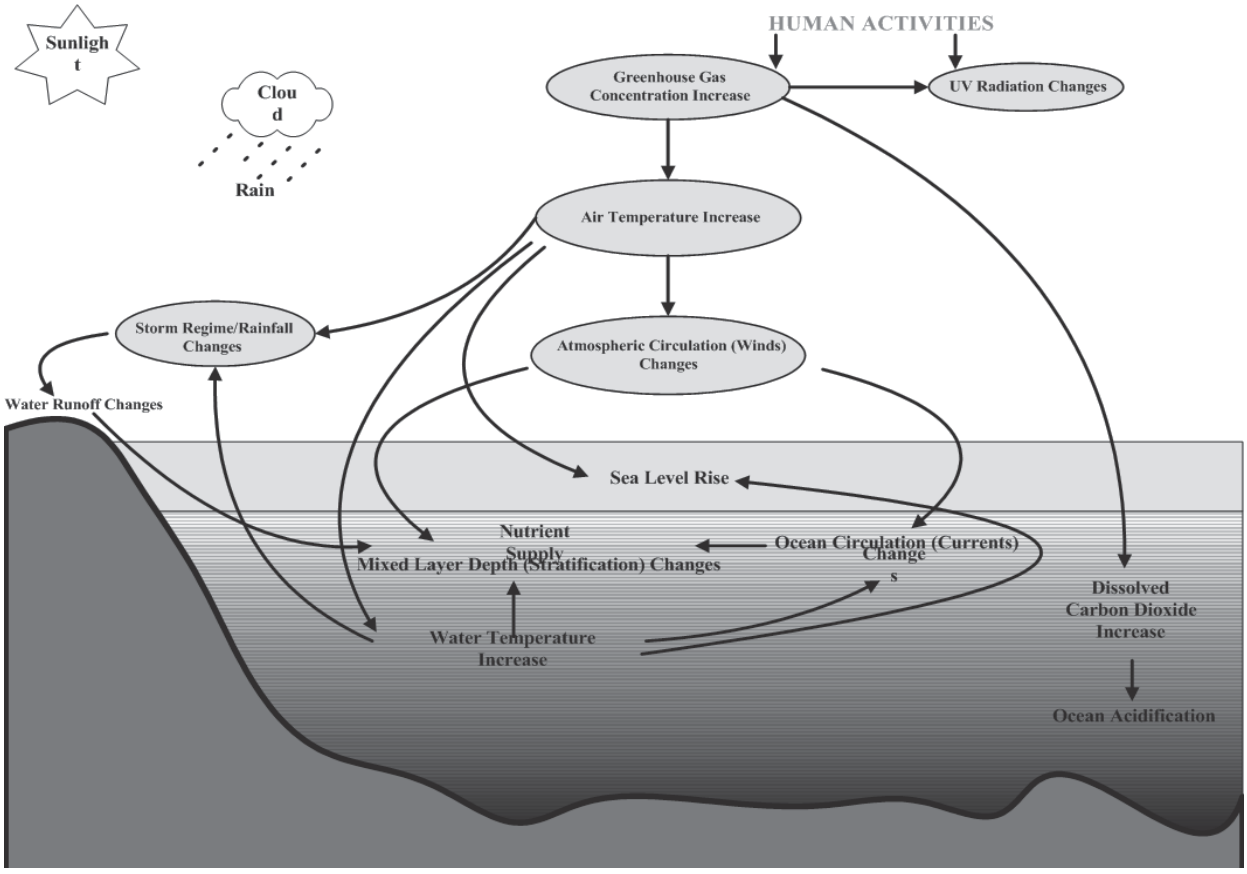
Source: Berkes *et al.* (2001); Pauly (2006); Daw *et al.*(2009)

Climate change impacts and high seas stocks

Climate variability and oceanic systems

The interactions between climate change and high seas fisheries are potentially wide-ranging and complex. Recent indications are that climate change impacts long-term oceanic "forcing" in the physical "realm" (currents, water temperature, etc.) underpinning the biological production systems that support the eco-physiology of targeted fish stocks (Perry *et al.,* 2010b). Barange *et al.* (2009) suggest that such physical forcing includes "atmospheric circulation, intensity and variability patterns, ocean currents, stratification, hydrological cycles and seasonal patterns". In turn, physical forcing is confounded by anthropogenic effects (Perry *et al.,* 2010a), with links between human activities and physical forcing being thought to be widespread in affecting coastal waters as well as the high seas and deep ocean (Figure 9.3).

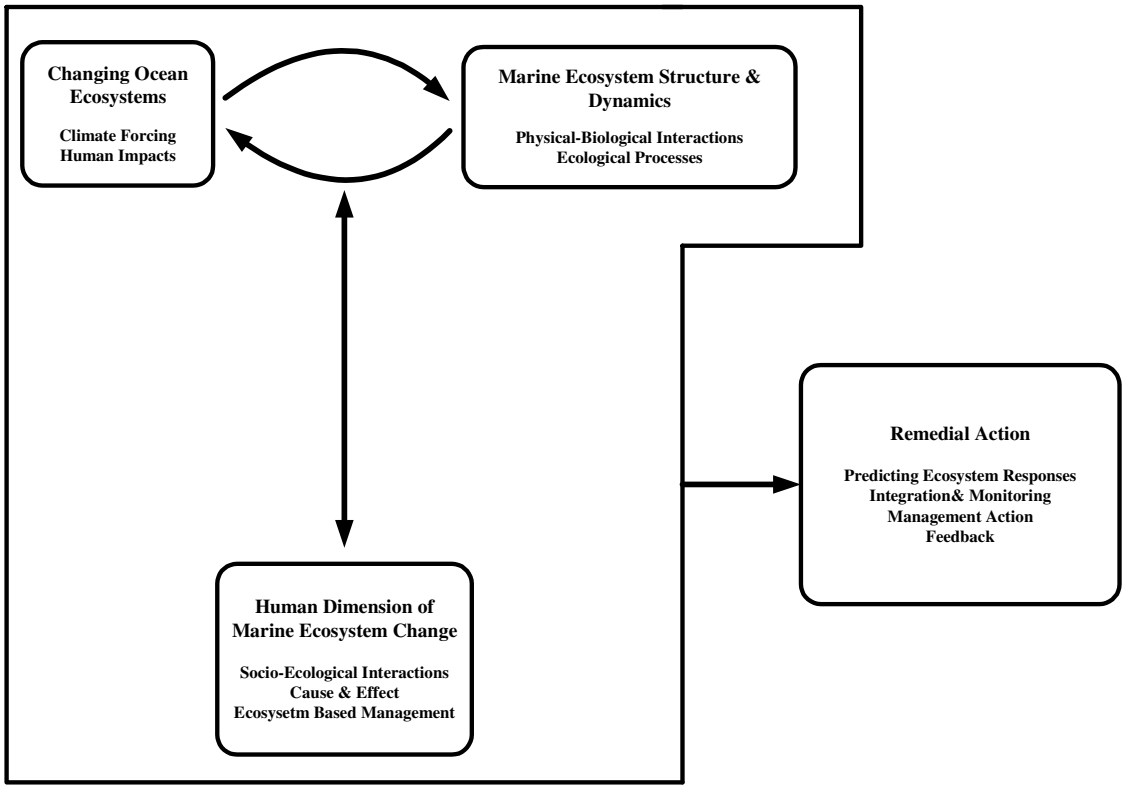
Figure 9.3. A schematic representation of key physical processes in the oceans attributed to global climate change



The effects of variable physical forcing on ocean dynamics are observable at global, regional and ocean basin scales (Barange *et al.,* 2009). They are manifest by observed changes associated with the biological processes supporting marine fish and fisheries production. Such changes are often used as proxies for climate-induced impacts (Drinkwater *et al.,* 2010) and may be extremely complex (Rouyer *et al.,* 2008).

Recent literature on marine ecosystem dynamics, and associated physical-biological interactions, is substantive (*e.g.* deYoung *et al.,* 2010). While a detailed review of current knowledge is beyond the scope of this paper, a generalised outline of the current knowledge field (Figure 10.4) illustrates the extent of, and potential interconnectivity between, physical, biological, ecological and human factors when considering interactions between climate change and fisheries management (see below).

Figure 9.4. Structural outline of the knowledge field underpinning broad understanding of interactions between climate change and fisheries management



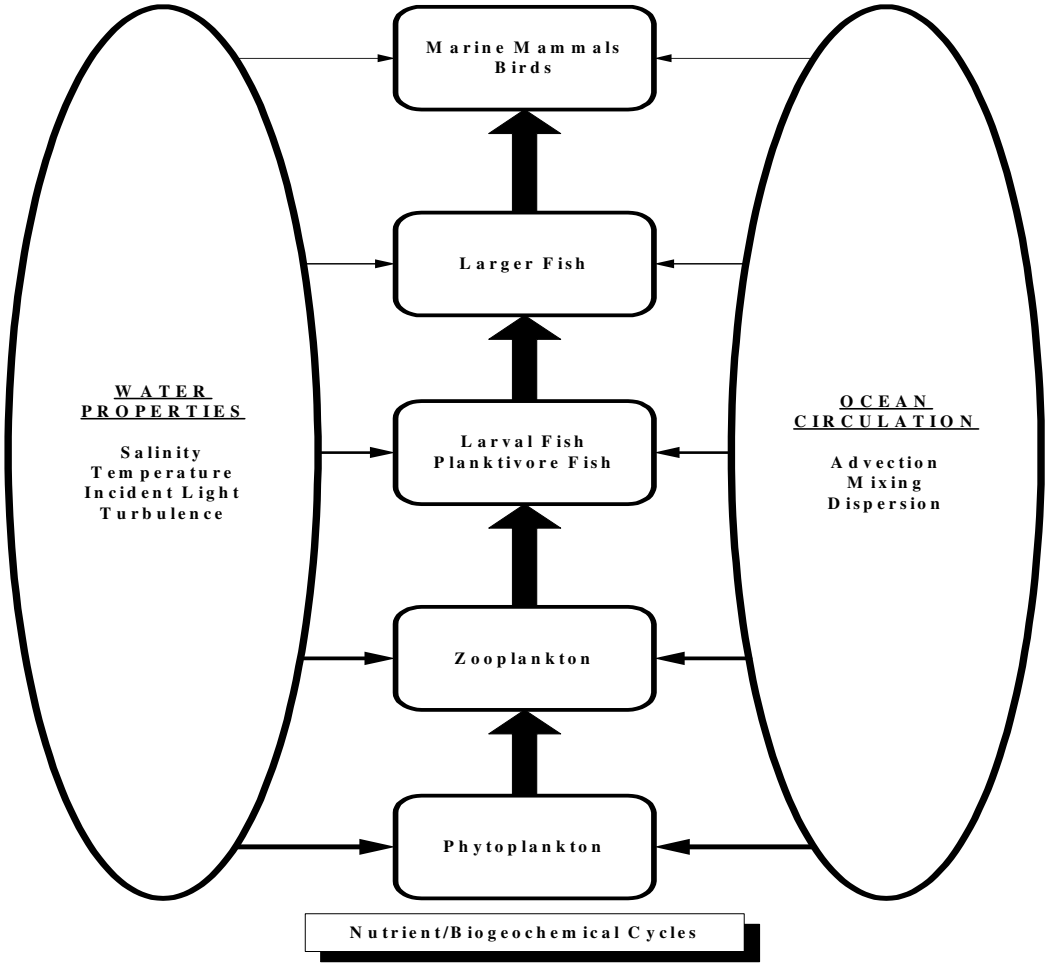
Source: Modified from Barange, Field and Steffen (2010).

Physical and biology factors on the high seas can be summarised in terms of: (a) the physical basis for climate change (Table 9.A1.1 in annex), and (b) the effects of climate variability on ecosystem/fish production processes (Table 9.A1.2 in annex). Examples of the former include the ocean's heat content and temperature, its salinity and stratification, and its circulation, including consequent effects on upwelling. They also include sea level rise and changes in water quality, most notably acidification or other chemical properties, atmosphere-ocean or land ocean exchanges, and low frequency climate variability. From Tables 9.A1.1 and 9.A1.2, it is evident that climate variability effects generally comprise the physiological responses of key organism processes to ambient conditions. The processes affected include primary and secondary production, changes in distribution and abundance, phenological changes, species invasions, disease transmission, foodweb impacts, regime shift and other ecosystem events. These two tables thus illustrate the potential, extent and complexities of climate change's physical basis in respect to its process effects.

Equally, local physical factors (*i.e.* water properties and oceanic circulation) influence marine species ecology and productivity at a fundamental level (deYoung *et al.,* 2010).These influences are reflected in potential interactions between climate and high seas fisheries through two main effects. First, local properties such as temperature, salinity and light affect the behaviour, physiology and growth of key species. Second, attached biological responses are manifest by changing fish production and/or by consequent ecosystem interactions (Figure 9.5). These interactions occur over a variety of

temporal and spatial scales (Figure 9.6a) and effectively provide the "boundaries" for management action over fisheries (Figure 9.6b). The behavioural organisation, and inherent eco-physiology, of a fish stock thus constitute essential links between the "physical-biotic environment" where climate change is felt, and the "management world" where fisheries activity is regulated. The conditions and scales for "remedial action" attached to management measures will be discussed later in "Implementing high seas fisheries climate change mitigation".

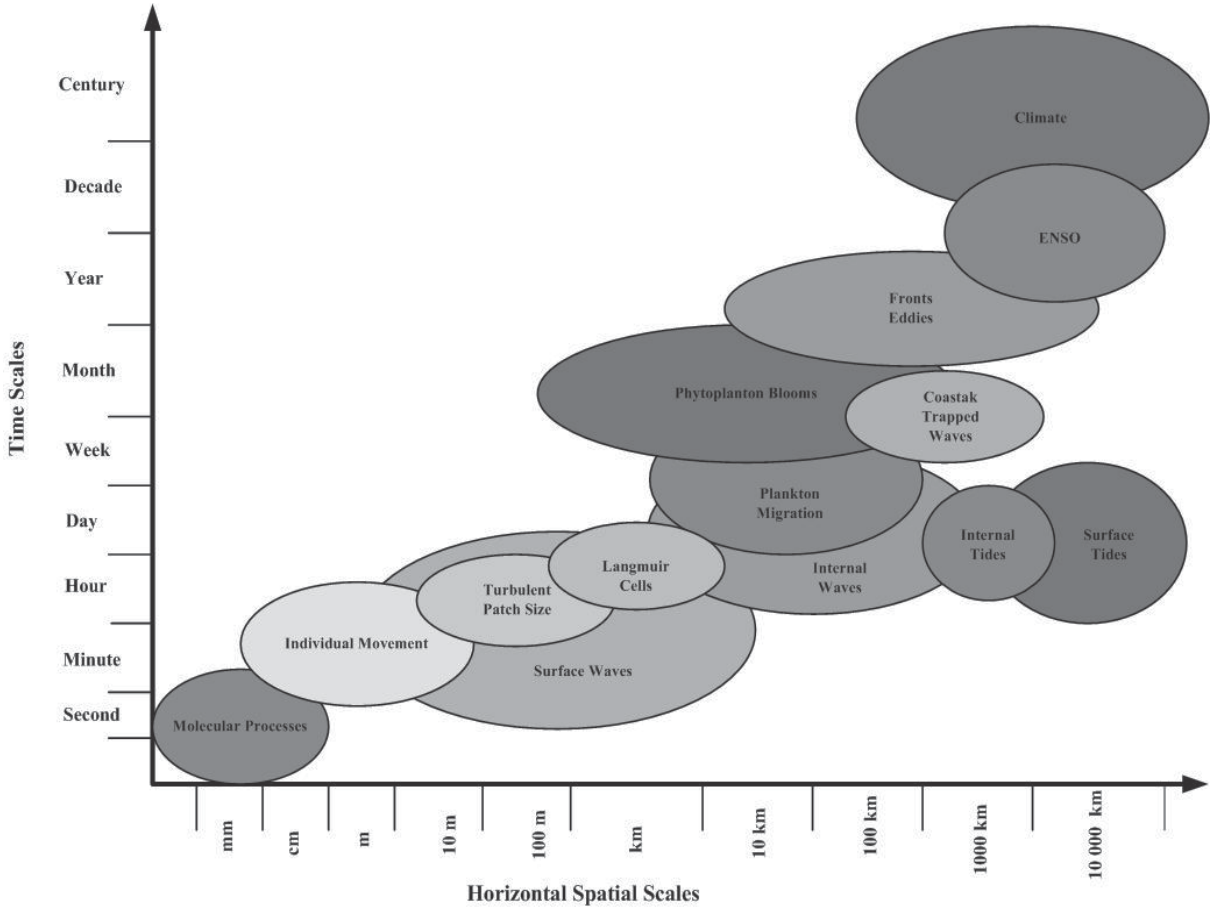
Figure 9.5. Oceanic and climate effects on marine ecosystems



Local properties affect organism behaviour and life history. The dynamics of coupled ocean-climate system(s) in turn affect population interconnectivity and biogeography at larger space, and longer time, scales.

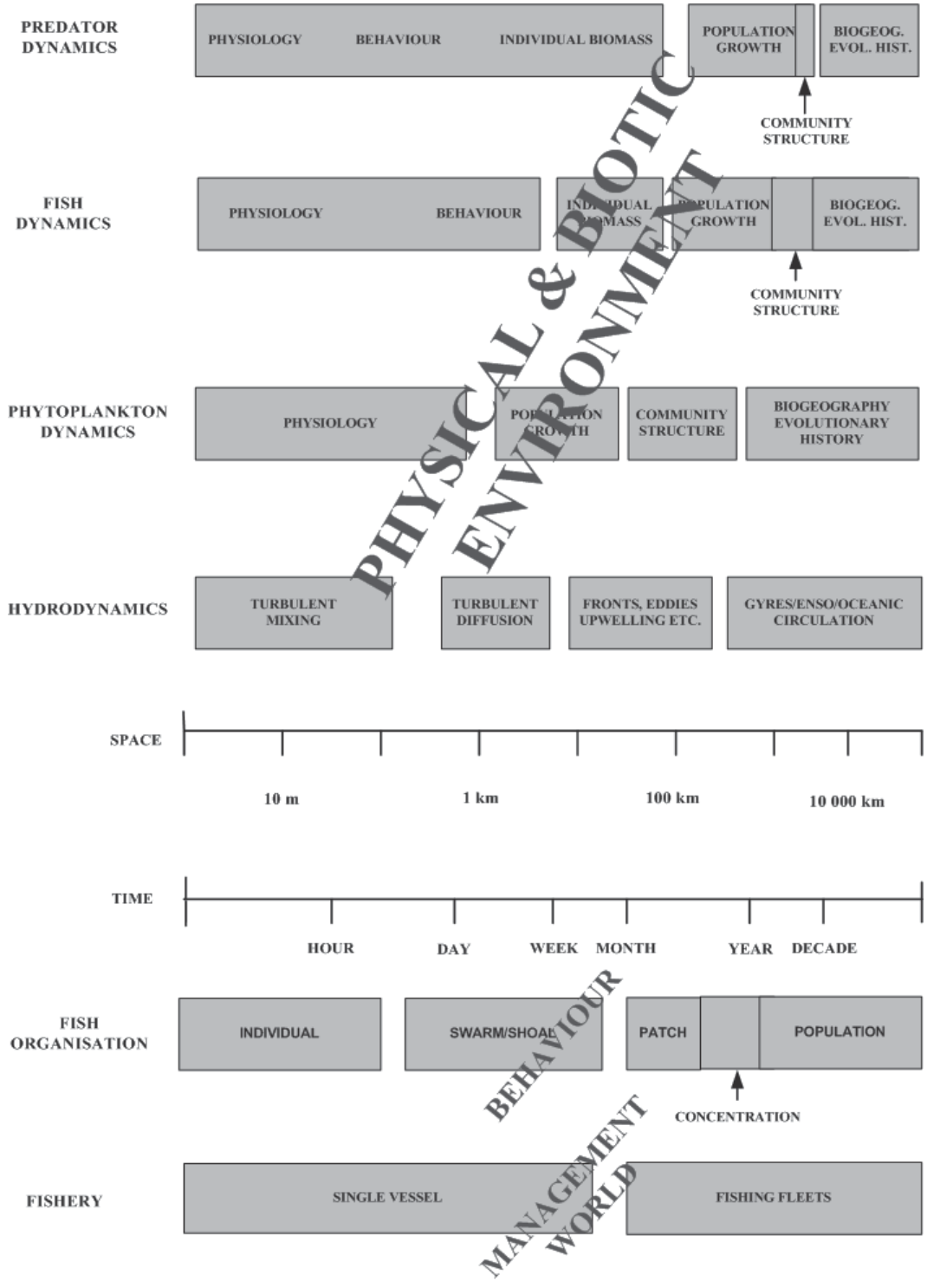
Source: Sundby 2006 and deYoung *et al.* 2010.

Figure 9.6(a). Schematic representation of dominant space and time scales for physical processes and biological populations in the marine environment



Source: Haury *et al.* (1978); Murphy *et al.(* 1988).

Figure 9.6 (b). The spatial and temporal structure of fish stock(s) in relation to fisheries, and key ecosystem components, as a function of the physical environment



BIOGEOG. = biogeography; EVOL. HIST. = evolutionary history.

Source: Murphy *et al.* (1988); Miller (2002).

Climate and the socio-ecology of ocean systems

Using climate variability and ocean systems information, it is possible to schematically link marine ecosystem elements with socio-economic factors in what Perry *et al.* (2010a) call a "marine socio-ecological system" (Figure 9.7). The concept allows further elaboration of the spatial and temporal considerations attached to physical, biological and social driving forces associated with fishing. In other words, the information presented in Figures 9.5 to 9.7 is condensable into a suite of interactive physical, biotic, social and economic processes involving the spatial and temporal characteristics of activities associated with high seas fisheries (Figure 9.8).

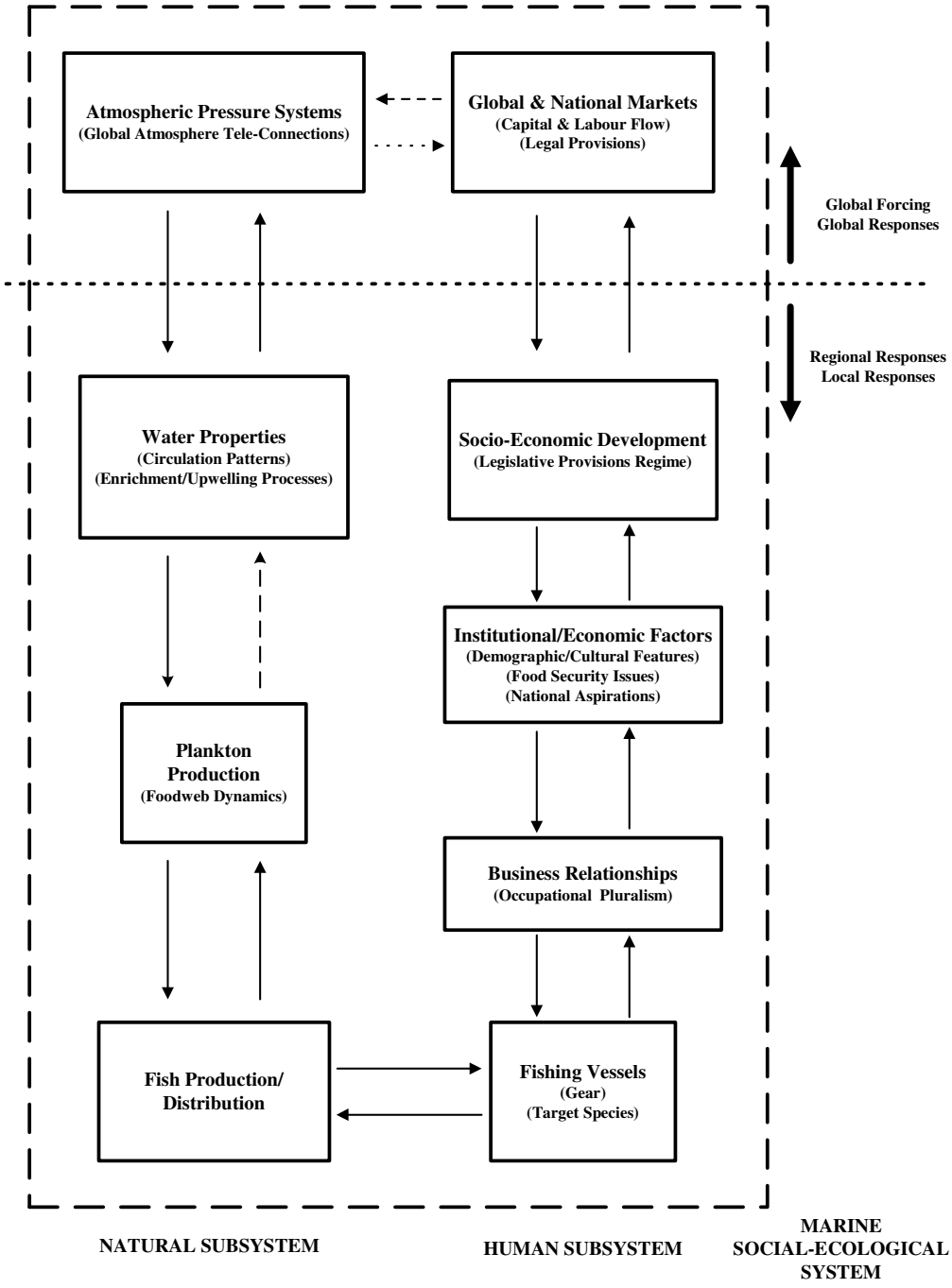
Figure 9.8 clearly emphasises that scale (space or time) is a dominant factor affecting any perception of pattern in high seas fisheries activities/processes. For example, small-scale events, phenomena and/or interactions may be "nested" within larger confines of time and space. As noted by Perry and Ommer (2003), (a) methods to manage fisheries should cover all the relevant time/space scales necessary (*e.g.* local to global), (b) management needs to account for the potential range of the natural phenomena being considered, (c) "shifting baselines"[3] plague both natural and social events, and (d) predictive models need to be employed with caution, especially in human social systems, where the statistical degrees of freedom are high due to the large number of variables which need to be taken into account.

It follows, therefore, that the processes driving change in natural, as opposed to human, subsystems not only interact but may also vary at different scales. This tends to complicate important interactions with the drivers of change in natural marine subsystems. Such drivers (after Perry *et al.* 2010a) include:

- climate variability/trends (biophysical changes);
- ecosystem dynamics (*i.e.* predator-prey functional relationships, disease);
- fishing;
- habitat degradation;
- alien species introduction (including new diseases).

Another key consideration is that regime shift(s) (deYoung *et al.,* 2008) are profound manifestations of change in natural climate variability. Current global warming trends thus constitute a persistent directional change in the climate system. Furthermore, drivers of change act in concert to directly affect a natural subsystem's resilience to such drivers. Notable examples of when this can occur have already been highlighted and may comprise cumulative effects of environmental change, such as sea temperature, combined with fishing, or interactions between fishing and habitat degradation.

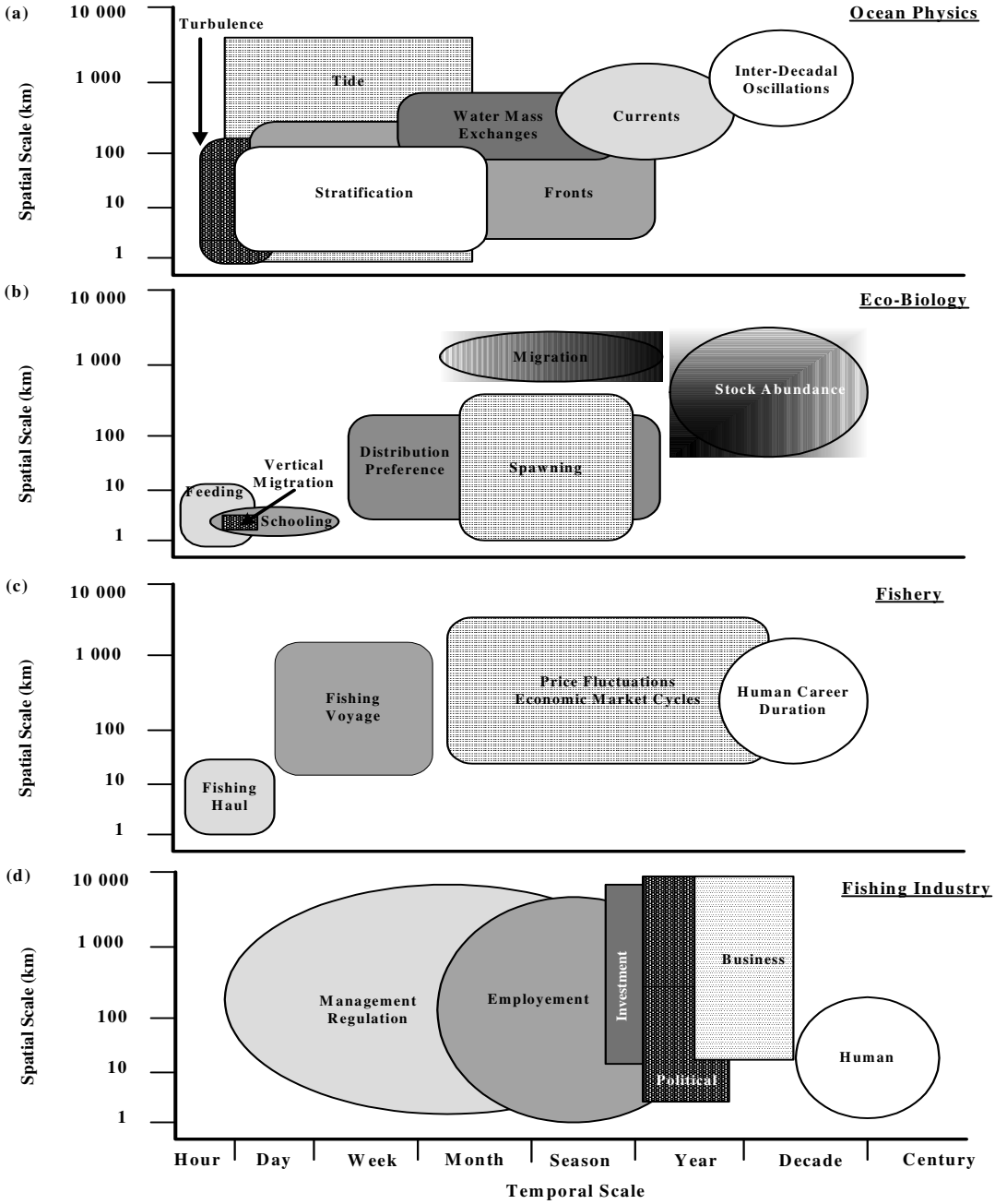
Figure 9.7. Schematic representation of interconnections in a natural and human subsystem of a "marine socio-ecological system"



Interconnection strength is indicated by the weighting of the arrows concerned.

Source: Modified from Perry *et al.* (2010a) to reflect commercialised high-seas fisheries.

Figure 9.8. Spatio-temporal characteristic for high seas fisheries processes/activities in terms of (a) physical, (b) biological, (c) fishing and (d) fisheries factors



Overlapping processes or activities are likely to interact.

Source: Modified from Perry and Ommer (2003); Perry *et al.(* 2010a).

In human communities generally, and in high seas fisheries in particular, drivers of change include, but are not limited (after Perry *et al.,* 2010a) to:

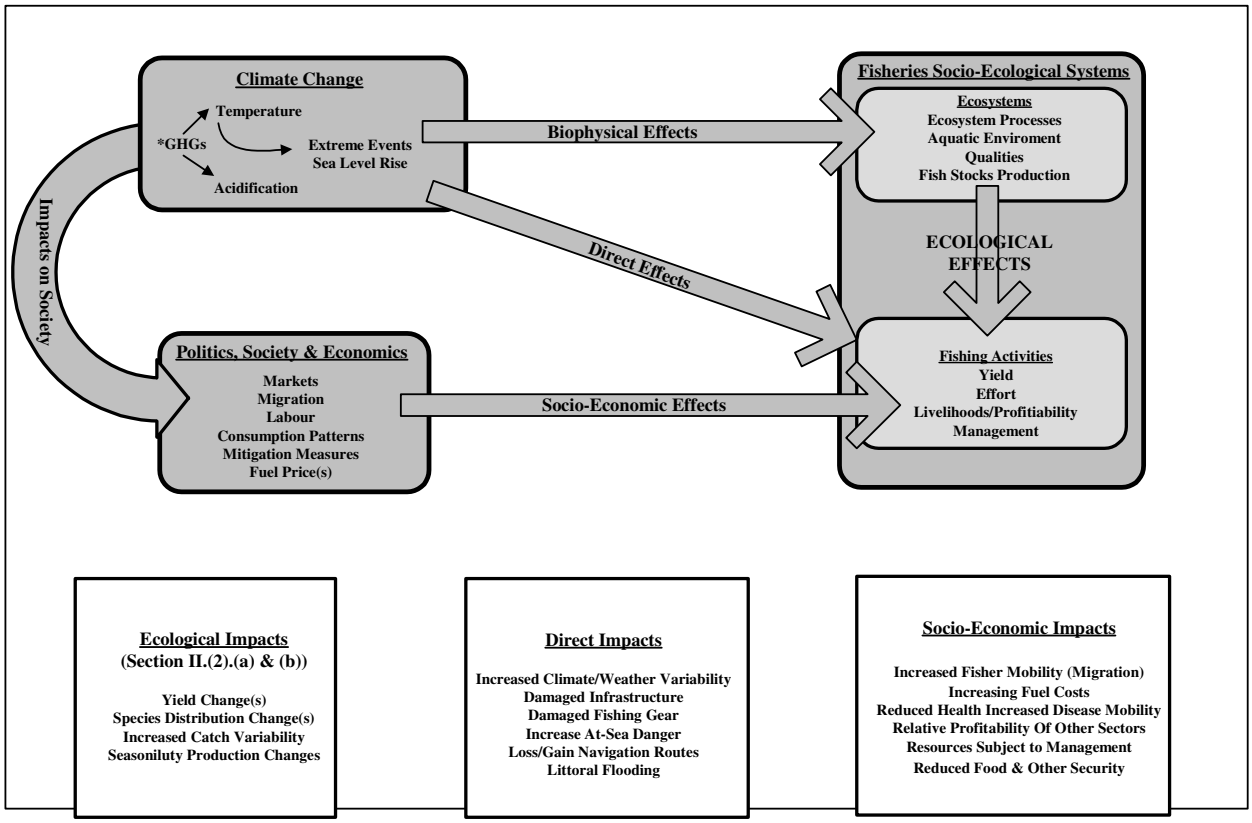
- resource changes;
- environmental change(s);
- demographic changes (harvested and dependent stocks; fishing communities);
- economic/market changes;
- technological innovations;
- law and property relations;
- governance and policy changes;
- shifting societal values.

It is noteworthy that the 1995 *FAO Code of Conduct for Responsible Fisheries* (FAO, 1998) attempts to take account of socio-economic drivers, such as societal values, in striving to promote responsible fishing practices globally.

As with natural subsystems, the high seas fisheries community/social-ecological system drivers of the kind listed above interact with other subsystems (*e.g.* environmental/ecological). Just like natural subsystems (Figure 10.7), the associated marine social-ecological ("human subsystem") changes exhibit the spatial, temporal and organisational dimensions illustrated in Figure 10.8.

For high seas fisheries specifically, it is possible to summarise the ecological, direct and socio-economic impacts of climate change (Figure 10.9) in terms of potential ecological, direct and socio-economic effects along with their inferred consequences ("impacts") for such fisheries (Table 10.A1.3 in annex) (specific examples will be considered in "Vulnerability, resilience and adaptability to climate change exposure" below). Therefore, the key elements to be addressed, in determining the likely effects and consequences of climate drivers on high seas fisheries in the broadest sense, comprise: (a) the exposure of such fisheries to climate drivers, (b) the resultant sensitivity of the fisheries in terms of the social-ecological and social human subsystems affected, and (c) the steps to be taken to mitigate potential detrimental effects. A key consideration in evaluating the cost-efficacy of (c) is the extent to which the social-ecological ("human subsystem") and ecosystem ("natural subsystem") are valued (see "Socio-economic context of high seas fisheries", below).

Figure 9.9. Climate change impacts in terms of potential ecological, direct and socio-economic effects



GHGs – Greenhouse gases

Source: Daw *et al.* (2009)

High seas fisheries' vulnerability, resilience and adaptability to climate change

General considerations

From the various examples already given, it can be seen that high seas fish and fisheries are essentially nested within an environment that comprises physical, eco-biological, fishery and governance elements. The latter provides a responsive core through which the human system attempts to "adapt" to climate change impact(s) through active management to address resource and fishery needs ("High seas fisheries' vulnerability, governance and climate change mitigation", below).

Bakun and Broad (2002) have indicated that human interactions with marine ecosystems may be incorporated into a two element, nested model (Table 10.4). One component of the model, the "fish habitat system" (FHS), comprises the marine ecosystem. This includes the climatology, physico-chemical habitat and fish resources of any particular region. The other component is the "marine resource system" (MRS) which encompasses the range of interactions between the non-human and human ecosystem. In other words, the MRS includes the FHS, the relevant fisheries, associated economic activities, management frameworks/institutions and the socio-political *milieu* in which management and economic activities take place (Perry *et al.,* 2010a). As Perry and Ommer (2003) have emphasised, the FHS and MRS are interconnected, with the former

being represented by the marine physical-ecological system where direct human involvement is absent. On the other hand, the MRS and FHS are also interdependent since the human ecosystem relates to the culture(s), socio-economic networks and management institutions linked to any particular fishery (Ommer *et al*., 2007, 2008).

Table 9.3. Interdependence/interconnections between fish habitat (FHS) and marine resource systems (MRS) on the high seas

FISH HABITAT SYSTEM (FHS)	Fish resources High seas marine ecosystem(s) Climatology & physico-chemical habitat characteristics Fishery/fisheries on stock Associated economic activities Management framework/institutions Socio-political context for management & economic activities	**MARINE RESOURCE SYSTEM (MRS)**

Source: Bakun and Broad (2002); Perry *et al.* (2010a).

In terms of the combined impacts of climate change on high seas fisheries, it can then be asked (after Perry *et al.,* 2010a):

- What are the social-ecological system characteristics that contribute to high or low vulnerability, or resilience, to climate change disturbance(s)?
- What can be learnt from marine social-ecological systems associated with high seas fishing in terms of the sustainability of relevant interactive subsystems?

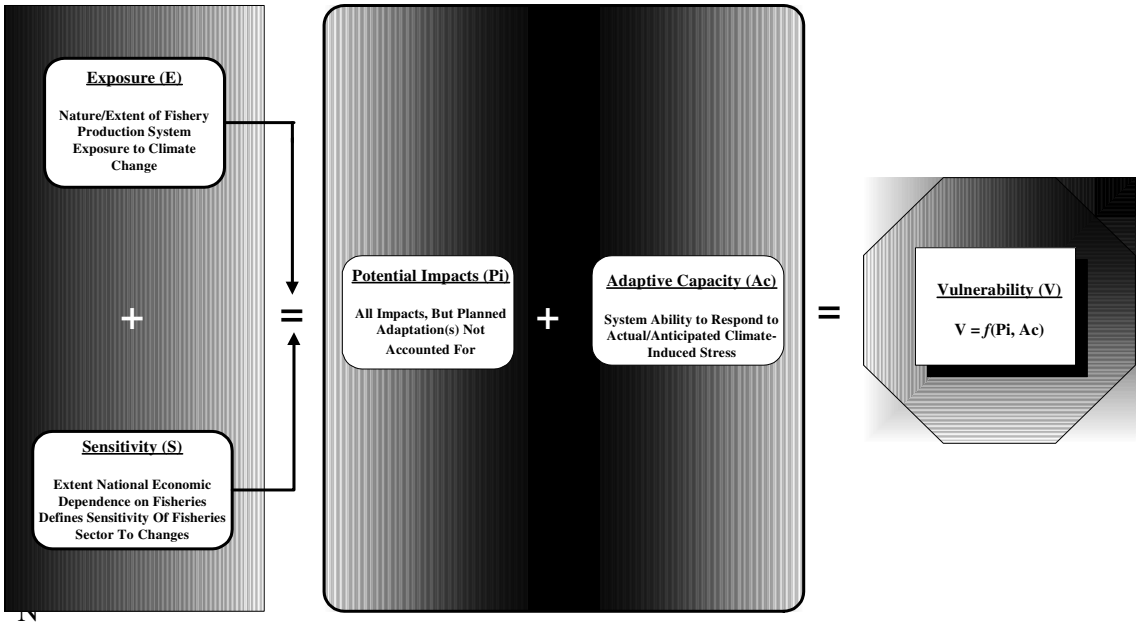
Vulnerability, resilience and adaptability to climate change exposure

The "resilience" of the high seas FHS and MRS to potential climate-induced impacts is crucial to addressing the above two questions effectively. In the first instance, as defined by Holling (1973), *biological resilience* is the ability of a natural system to "absorb and accommodate future events in whatever unexpected form they may take". This definition can be adapted and extended to apply to ecosystem and social system resilience in terms of, amongst others, the structural, functional and organisational changes the two systems are able to absorb (Gunderson and Holling, 2001; Perry *et al.,* 2010a).

Over the past decade, the Intergovernmental Panel on Climate Change (IPCC) has subsumed consideration of resilience, vulnerability and adaptive capacity into its discussions on the effects of global climate change on human communities. Consequently, and in the second instance, the definition of resilience has been essentially recast as

social-ecological resilience where the capacity of interlinked social-ecological systems is the ability to absorb potential disturbances/impacts while still retaining essential "structures", "processes" and "feedbacks" (Adger *et al.,* 2005). To put simply, as illustrated in Figure 9.10, the *exposure* of high seas fisheries production to climate change effects combined with the consequent economic *sensitivity* to such effects determines *potential impact(s)*. *Adaptive capacity* can then be considered to be the ability of a system[4] to respond to environmental change, impacts or contingencies in a manner that promotes resource sustainability and retains economic and social opportunities. The IPCC (2007) thus sees adaptive capacity as "the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damage, to take advantage of opportunities, or to cope with the consequences".

Figure 9.10. Conceptual representation of system vulnerability as a function of system response(s) to potential, or anticipated, climate-induced stress/stresses



N

A system may be viewed as biological system or a country, region, sector etc.

Source: Adapted from Allison *et al.* (2005); Daw *et al.* (2009).

In conclusion, *vulnerability* can be viewed as the functional culmination of the four factors discussed in the previous paragraph (Figure 9.10). Therefore, the IPCC has defined the term as the combination of *potential impact* (comprising both *sensitivity* and *exposure*) and a system's *adaptive capacity*. As such, climate change *vulnerability* of high seas fisheries is a function of the nature, magnitude, rate of change and variation to which fisheries may be exposed plus their *sensitivity* and *adaptive capacity* to such exposure (IPCC, 2007).

Socio-economic context of high seas fisheries

Just as Perry *et al.* (2010a) have outlined for small-scale fisheries, it is possible to apply the concept of sustainable livelihoods (Chambers and Conway, 1992) to high seas fisheries in the form of an *industrial sustainability framework* (ISF). This approach

recognises that there are five types of capital assets that can be built on, drawn upon and mobilised to ameliorate any perceived vulnerability in high seas fisheries. The five assets concerned are human, natural, financial, social and physical (Table 9.5).

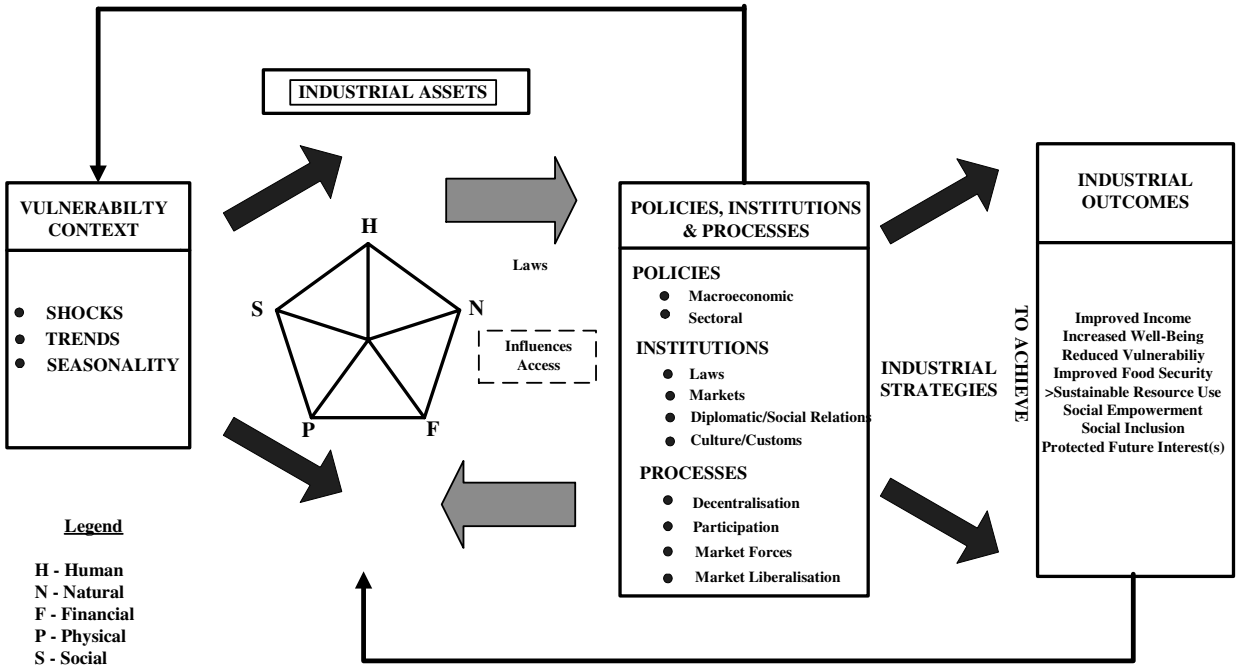
Table 9.5. Assets associated with an industrial sustainability framework for high seas fisheries

Natural capital	Resource stocks (e.g. fish, genetic, ecosystem) and/or environmental attributes (e.g. oceanic conditions) underpinning resource production and from which industrial benefits are derived
Physical capital	Physical assets required to support and derived from high seas fisheries, including basic infrastructure and producer goods to support such fisheries and associated industries (e.g. ship building)
Economic/financial capital	Capital base (e.g. cash, credit, investment, savings and other economic assets) essential for pursuing a viable industrial sustainability framework strategy for high seas fisheries
Human capital	Accumulated skills, knowledge, labour, health and physical capability for successfully pursuing a viable industrial sustainability framework strategy for high seas fisheries
Social capital	Social resources (e.g. networks, claims, co-operation) which require co-ordinated actions to pursue different industrial sustainability framework strategies for high seas fisheries

Source: Daw *et al.* (2009)

Daw *et al.* (2009) have indicated that access to such assets is contingent upon prevailing policies, institutions or processes (PIPs) as depicted in Figure 9.11. For example, extreme events, persistent negative trends, seasonal changes, and even variations in the fuel price may individually, or in concert, provide a vulnerability context for specific high seas fisheries at various time, and/or space scales. Such an approach not only promotes understanding of potential linkages between high seas fisheries and the social-ecological system at large, it also illustrates the importance of the context in which climate change effects are likely to be manifest. Not only does this make it possible to undertake a wider and more comprehensive analysis of the potential interactions between high seas fisheries and climate change, it also illustrates the point that high seas fisheries are part of a broader socio-economic system also affected by climate change (Daw *et al.,* 2009). As reviewed by Allison *et al.* (2005), climate change not only impacts on each of the five assets identified in Table 9.5, it also changes the vulnerability context and impacts of policies, institutions and processes. Specific industrial strategies are then required to achieve objectively defensible outcomes – a concern discussed in more detail in respect to climate change mitigation for high seas fisheries in "Ocean governance" below.

Figure 9.11. An industrial sustainability framework for high seas fisheries



Source: Allison and Horemans (2006); Daw *et al.* (2009).

Finally, a key factor to determining how an ISF may be implemented and play out rests with the notion of the value ascribed to the framework and the contingent costs associated with it. This requires that marine ecosystem benefits are valued to include long-term economic, conservation and cultural advantages (Sumaila, 2004; 2008; Sumaila and Walters, 2005; Berman and Sumaila, 2006). From an economic perspective, valuation is based on economic preferences (Arrow *et al.,* 1993). However, economic preferences in turn are based on choices and trade-offs related to the target resource(s) and associated time constraints or economic expectations.

Cochrane and Doulman (2005) go as far as to suggest that unsustainable fishing practices are the end result of a widespread failure in the balancing of biological, and ecological, sustainability with socio-economic objectives/expectations. In these terms, current valuations may be considered to focus on economic benefits alone with marine ecosystems being viewed solely as suppliers of derived commodities which are then sold (Perry *et al.,* 2010a). It is therefore worth noting that there may be counterintuitive consequences when such considerations are applied too narrowly. For example, the switch by north-west Atlantic fisheries to invertebrates following the collapse of groundfish stocks has resulted in increased economic benefits for Newfoundland (Schrank, 2005). While this illustrates that ecosystem values may be determinable in the absence of ecological, cultural and social values (Sala and Knowlton, 2006), it further highlights the danger of defining values too narrowly when attempting to relate such values to climate change impacts. Not all impacts should thus be seen to be detrimental. Nevertheless, there is an attached and attendant danger where the fishery has so much invested in its operation that there is a general resistance to close, or leave, the fishery even when income, profits and livelihoods are declining (Pollnac and Poggie, 2008). Such "self-

actualisation" is at the core of the on-going debate concerning fishing subsidies (Cochrane, 2000) and it goes without saying that great care should be taken to avoid its influence on future efforts to ameliorate the impacts of climate change on high seas fisheries.

Climate variability

An underlying subtext to the climate change impacts already highlighted is the implication that high seas fisheries have always been subject to the vagaries of climatic variability. These include extreme events such as changes in the extent, or nature, of upwelling, other ocean circulation changes due to atmospheric forcing, *e.g. El Niño*-Southern Oscillation (ENSO), and habitat changes (Table 10.A1.4). In this respect, Daw *et al.* (2009) have noted that: "climate change is likely to be experienced as an increased frequency of extreme events". For such reasons, it is important to appreciate that social-ecological systems may be forced into states that pose specific challenges for high seas fisheries management and sustainability, when some threshold or "tipping point" is exceeded (Daw *et al.,* 2009). Therefore, it is not enough to assume that the increased severity of familiar climate change impacts will be sufficient as a basis for long-term[5] mitigation policies, strategies or actions.

High seas fisheries' vulnerability, governance and climate change mitigation

General considerations

Perry *et al.* (2010a) have indicated that the social-ecological systems associated with fishing in general have been involved in various ways to overcome potential crises in the marine ecosystems where harvested stocks are found. While the various strategies employed may vary (*e.g.* Ommer *et al.,* 2007); four classical case studies (Table 10.6) illustrate the point that the high seas sustainability framework has tended to focus on industrial outcomes (Figure 10.11) as a means of addressing substantial changes in the natural subsystem through flexible adaptive responses by the human subsystem.

Table 9.6. Case studies of social adaptive responses and strategies to cope with high seas fisheries crises

Fishery	Event(s)	Coping strategies
Newfoundland groundfish	High seasonal & interannual environmental variability. Early 1990s stock collapses. Moratoria imposed in many areas (including on high seas under NAFO).	Harvest target species changed to shellfish, shrimp, small pelagics & seals. Move to more distant fishing grounds. Catch value in 2003>1992, but wealth distribution different.
Iceland herring	Early 20th century increased herring fishery & warming North Atlantic. Improved fishing success from technological development. 1969 collapse followed mid-1960s spike in catches. Overfishing drove herring stock decline post-1950. Climate change & cooling Greenland &	Population declines in catch landing ports. Changing social conditions induced search for economic alternatives.

	Iceland Seas meant two decade herring collapse post-1965.	
Chilean jack mackerel	Eastern South Pacific very productive & subject to *El Niño* Southern Oscillation Fish spawn in offshore oceanic waters & feed inshore. Post-2001 foreign fleets fishing on oceanic component of stock. Declines of Chilean stock 1995 - 99 Adult fish decrease & more small fish in catches post 1997.	Much social unrest. Loss of jobs & fishing vessels induced by adaptive social responses. Responses useful in addressing crisis in Chilean hake fishery since 2003. Negotiation of high seas RFMO to deal with jack mackerel fishery concluded in late 2009 after three years negotiation.

Source: Perry *et al.* (2010b)

In terms of the high seas industrial sustainability framework outlined in Figure 9.11, the adaptive flexibility of human subsystem responses to the detrimental effects of impacts on fisheries in the short-term[6] tend to be based on four basic strategies (after Perry *et al.,* 2010a):

- *Intensification*: Entails fisheries deploying more effort to compensate for decreased catches and/or moving to new fishing grounds to increase their catch potential.

- *Diversification*: Entails fisheries moving to species or stocks other than those customarily fished and may involve spreading fishing grounds and varying the fishing season(s). Diversification is frequently manifest as "fishing down the foodweb" (Pauly *et al.* 1998).

- *Migration*: Entails fisheries "following the fish" or seeking alternative livelihoods in other commercial sectors or fisheries (Hamilton *et al.,* 2004). This may depend on factors such as legal controls on fishing access, alternative supplies of protein etc. Notably migration of fishing effort has characterised illegal, unregulated or unreported (IUU) fishing for Patagonian toothfish (Miller, 2007).

- *"Enduring the storm"*: A common short-term strategy, this may comprise subsidised income payments for fisheries operators and political lobbying to "buy time" for operators to continue fishing. It is very much a function of how long the "storm" takes to pass, which if too long requires longer-term strategies as the fisheries become less sustainable (see below).

Over longer time scales (more than five years) human subsystem responses comprise five additional strategies:

- *Diversification*: Includes diversifying fisheries capital and capacity into other sectors such as aquaculture, or even the offshore oil and gas sector.

- *Networking*: The building of industrial alliances, sharing technology and information exchange(s) are all ways that fisheries operators may maximise co-operation to promote corporate advantages in countering potential fisheries losses.

- *Education*: Includes skills upgrading, capacity building and the development of associations with academia as strategies to reduce dependency on fisheries (Corbett, 2007) or provide more transparent information on fisheries challenges.

- *Political action*: Introduces new, or alternative, strategies, to improve human subsystem adaptation to fish habitat system changes.

- *Termination*: This a "last resort" strategy that clearly recognises that solving a fisheries problem can only be achieved by terminating exploitation of the resource(s) concerned. A restructuring of the human subsystems involved is usually necessary, although the application of fishing moratoria can offer intermittent relief to allow fish stock rebuilding.

Following Perry *et al.* (2008), the basic strategies outlined above would result in high seas fisheries becoming more diverse and variable in the short term. However, in the long-term, strategies requiring more intense fishing or diversification of target species are unlikely to be sustainable. Fishing down the food-web (Pauly *et al*., 1998) is a very "real and present danger" in such circumstances, as is intensive fishing on "new" target species about which very little is known (Devine *et al.,* 2006). Translocating fishing effort to underexploited regions (Bremner and Perez, 2002), consolidating fishing capacity into large companies, more intensive globalisation of fishing enterprises and increased IUU fishing are all high risk strategies for high seas fisheries adapting to fish habitat system changes attributable to climate change.

High seas fisheries' vulnerability

The discussion above and Figure 9.10 have shown that the vulnerability of high seas fisheries to climate change is a function of their exposure, sensitivity and adaptability to impacts. It follows therefore that a key requirement for managing high seas fisheries climate change mitigation is the identification of regions, fishing grounds and fishing states that are most likely to be affected by climate impacts. Only then will it be possible to guide policy development and strategise any interventionary action necessary. This not only requires a systematic approach, but also recognises that effective ocean governance has an important role to play (see next section) and that RFMOs in particular should be up to the task at hand (Lodge *et al*., 2007). Examples of such vulnerabilities include:

- *Geographic regions with high potential exposure to climate change effects*: from the information in above ("Climate change impacts and high seas stocks") and Figure 9.9, only some climate change impacts on high seas fisheries are likely to be mediated by air temperature. Climate change forecasts based on air temperature are thus rather poor proxies for the potential exposure of high seas fisheries resources to climate impacts. Consequently, low latitude regions may actually be more exposed to potential climate change impacts than higher latitudes where the most dramatic changes in air temperature are predicted to take place. Other factors that might also need to be considered are expanding storm "belts" in the tropics (IPCC, 2007) increased risk of freshwater flooding, saline intrusion and erosion in coastal nursery grounds where high seas fish stocks breed (Nicholls *et al.,* 2007).

- *Vulnerable economies*: developing states have long been recognised as having fewer adaptive capacities than more developed economies or societies. Although developing states, with the exception of some in the south-west Pacific and parts of Africa, may not be heavily involved in high seas fishing, the political and economic dangers of not allowing them "fair access" to high seas resources is clearly a global concern. In fact, and in the "interests of levelling the playing field" (Aqorau, 2003), special mention of developing state needs has been made in most modern regional fisheries agreements,

starting with the *1995 UN Fish Stocks Agreement* (UNFSA) (FAO, 1998). It is interesting to note that, based on an assessment of 132 economies; Allison *et al.* (2005) have indicated that a number of countries are vulnerable economically to predicted climate change impacts on their fisheries. The most notable of these are located in north-west South America (where fish landings are large), Asia (where fishery markets are substantial), and in Russia and the Ukraine where environmental extremes of air and sea temperature are common on the fishing grounds being targeted. For obvious reasons, it is therefore essential that every effort be made to improve current data on, and understanding of, the implications for high seas fisheries resource production, use, trade and sustainability in terms of their sensitivity and adaptive capacity to climate change impacts.

- *Vulnerable fisheries*: these fisheries are really a combination of the above two examples in terms of the unique combination of interests that particular high seas fisheries exhibit as a result of the cultural, social, economic and fisheries management/enforcement constraints under which they operate. In these terms, the displacement of high seas fisheries from one area to another as a result of declining target stocks (for whatever reason) offers significant motivation for vulnerable fisheries to go "rogue" and indulge in unregulated fishing (Vidas, 2004). High value stocks, such as tuna and Patagonian toothfish, are at the greatest risk of this kind of behaviour, which also greatly compounds any uncertainty likely to arise from trying to assess the extent of climate change impacts on the fisheries and stock concerned.

Ocean governance

The final example in the previous section clearly illustrates the point that good ocean governance is fundamental to the sustainable management of high seas fisheries. According to the FAO (2001), fisheries governance comprises "the legal, social, cultural, economic and political arrangements to manage fisheries". In these terms, the effective implementation of fisheries policy may be viewed as an action hierarchy comprised of an integrated process of goal setting, objective identification, priority setting, operationalisation, reference point identification, decision taken, governance action and review (Figure 9.12). Monitoring at the review, governance and decision-making levels ensures that the entire process is adaptable, flexible and modifiable if necessary.

Ocean governance has global, international, regional, national and local dimensions, particularly on the high seas (Lodge, 2004). As indicated, Cochrane and Doulman (2005) have emphasised that the global need for good fisheries governance has dramatically increased in recent years due to a growing preponderance of unsustainable fishing practices.

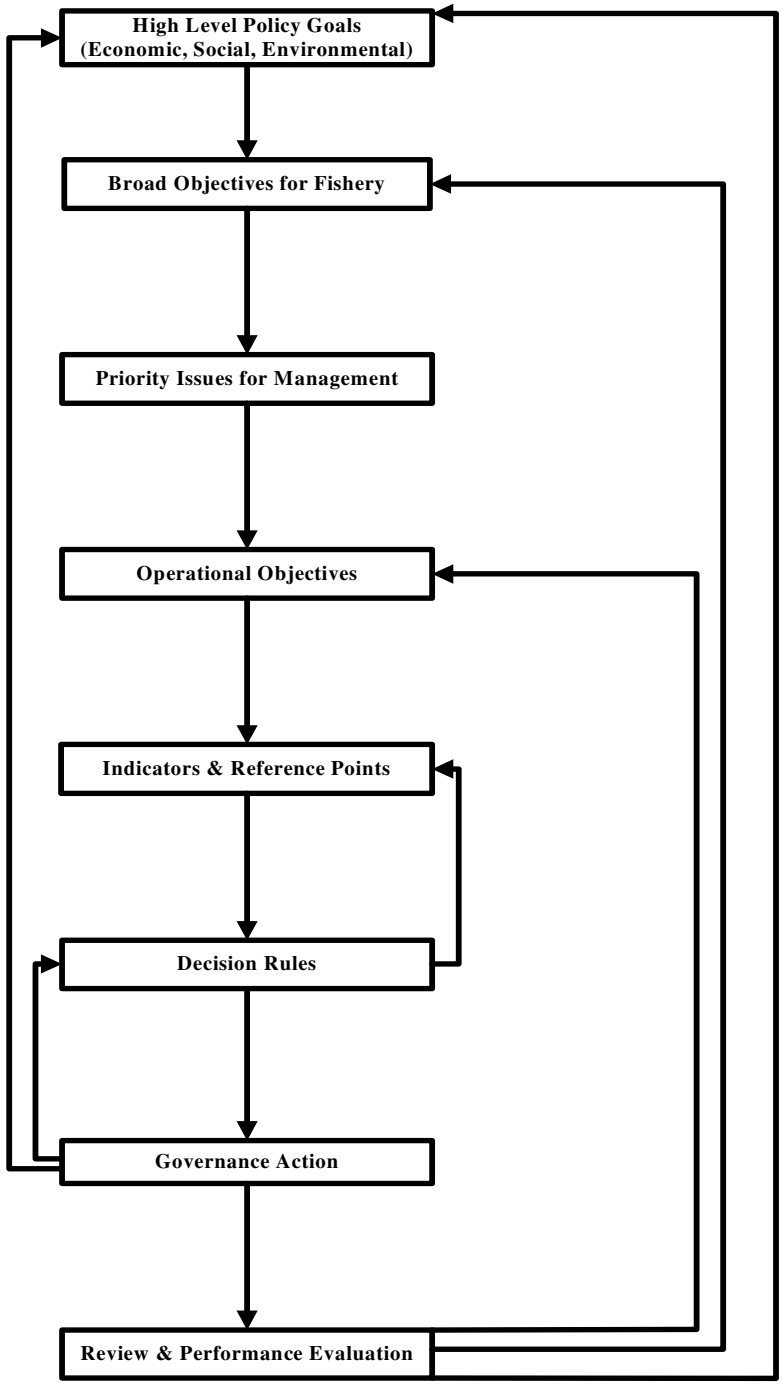
Key issues to be addressed in efforts to improve ocean governance for high seas fisheries (after Perry *et al*., 2010a) include:

- *Environment:* combining the need to address climate change by balancing marine ecosystem capacity to support fish production with human impacts on such production caused by fishing*, pollution, etc.*

- *Social:* accounting for the maintenance of an industrial sustainability framework, as depicted in Figure 9.11, and core principles outlined in the FAO Code of Conduct for Responsible Fisheries.

- *Legal:* standardising and implementing global practices through international agreements. These agreements may be aimed at codifying current soft law (e.g. the FAO Code of Conduct for Responsible Fisheries) into more binding legal arrangements and/or at developing new agreements to address fisheries practices more widely (e.g. through regional co-operation instruments such as the Southern African Development Community Protocol on Fisheries – Miller and Molenaar, 2006).

Figure 9.12. Policy, governance and performance implementation and monitoring in high seas fisheries management



Source: FAO (2003).

Increased globalisation and the difficulties associated with accommodating widely divergent interests in large international fora have meant that there has been a growing trend to address the governance of fisheries, and other environmental, issues in a variety of "soft" instruments. These include codes of conduct, market incentives and private sector-government agreements. Initiatives along these lines have led Allison (2001) and Oosterveer (2008) to conclude that new governance approaches face extreme difficulties as a consequence of cross-scale interactions, complexity and the sustained international political will necessary for them to succeed. Not only is there a need for a concentrated push to encourage governments to sign/ratify current international fisheries agreements, future agreements need to follow a number of key principles (Table 9.7).

Table 9.7. Key principles on which future fisheries agreements should be based, as applied to high seas fisheries (DWFFs - distant water fishing fleets).

Principle	Description
Co-operation	As per Articles 117 to 119 of UNCLOS requires measure account for conservation of high seas fisheries resources through arrangements to determine sustainable stock levels and management measures. Includes need for co-operation between DWFs and coastal states on scientific research as well as accurate reporting of fishing catch and effort.
Sustainable fishing levels	Best scientific evidence to be used to determine sustainable catch levels. In absence of essential fisheries information, precautionary approach (*e.g.* Article 6 of 1995 UN Fish Stocks Agreement) to be applied to protect fisheries resources and preserve the marine environment. Fisheries access arrangements should aim to utilise surplus fish stock production and/or account for other ecosystem needs. Arrangements to be subject to scientific review to set optimal fishing levels, promote conservation and restrict fisheries (*e.g.* by seasonal closures) if necessary.
Environmental costs	Such costs to be shared equally by all with access to fish stock(s) concerned.
Development of fishing capacity	Required to enhance equitable access to high seas fisheries resources, particularly in respect to developing States and any assistance so required (*e.g.* as set out in Articles 25 and 26 of 1995 UN Fish Stocks Agreement).
Review	Initial and periodic review of agreements essential for promoting fisheries' sustainability as well as to maximise ecological and socio-economic sustainability of access.
Transparency	Negotiation of agreements should include all interested, and potential, stakeholders. As far as is practicable, agreement negotiations, texts, implementation information and fisheries assessments should be freely available in the public domain (*e.g.* as outlined in Article 12 of 1995 UN Fish Stocks Agreement).
Monitoring & enforcement	Monitoring, control and surveillance (MCS) is vital to promote compliance with agreement provisions. May require development assistance and technology transfer along lines of Article 25.2 of 1995 UN Fish Stocks Agreement.

Implementing high seas fisheries climate change mitigation

Climate change mitigation for high seas fisheries may be considered to be confined within two categories: (i) direct, and (ii) indirect.

Direct mitigation

As the fisheries sector does not make a substantial contribution to global greenhouse gas (GHG) emissions, Troadec (2000) has indicated that substantial consideration of direct mitigation measures for fisheries CHG emissions is not essential. Despite the fact that many medium-sized and larger fishing vessels use less polluting light diesel fuel, a number of large, older, high seas fishing vessels still use heavy diesel oil. Globally, Tyedmers *et al.* (2005) have calculated that the oil consumption of fishing fleets is roughly equivalent to that of the Netherlands. Using various estimates from Eyring *et al.* (2005), Tyedmers *et al*. (2005) and FAO (2007) (Table 10.8), Daw *et al.* (2009) have calculated that the total emissions for large fishing vessels is in the order of 69 Tg[7] of CO_2 , or about 8.5% of all shipping emissions.

The emission estimates shown in Table 9.8 are highly variable, an indication of the need for additional study. Furthermore, FAO (2007) has demonstrated that demersal trawling is a relatively energetically inefficient method of fishing (Table 9.9). Again the attached information is rather limited and there is a recognised need to fully examine the energy efficiency of different fishing operations (Daw *et al.,* 2009).

Table 9.8. Fuel consumption and CO_2 emission estimates for fishing vessels

Source	Vessel type	Year	Fuel consumption (million tonnes)	CO_2 emissions (Tg)	Fuel/CO_2 emissions ratio
Eyring (2005)	>100 tonnes (23 000 vessels)	2001	23.6[a]	69[a]	2.9
Tyedmers *et al.* (2005)	All vessels	2001	42	134	3.2
FAO (2007)	1.3 million decked vessels	2005	14	43	3.05[b]

a. Calculated from the proportion of large fishing vessels that are factory or catcher vessels
b. Average of ratios used by Tyedmers *et al.* (2005) and Eyring (2005)

Source: FAO (2007).

Table 9.9 also illustrates the fact that developing countries may spend up to 50% of their catch revenue on fuel (FAO, 2007). While developing world fleets are often less fuel efficient than those in the developed world, it is hard to estimate absolute levels of fuel consumption by fisheries in different countries. This difficulty is largely attributable to variable fuel pricing (particularly imposition of different taxes and levies) and the stocks being targeted (*e.g.* nearshore as opposed to farther away).

Fisheries management also has a role to play in reducing fuel efficiency. For example, "Olympic-style" catch access (*i.e.* non-allocation of individual catch quotas) induces a

"race to fish" with the attached consequence of a need for increased fuel usage to facilitate rapid transit to the fishing grounds (Daw *et al*., 2009). Equally, fishing search times increase, along with fishing effort, when overfished stocks are encountered less frequently due to low abundance and/or have a wider areal distribution.

Table 9.9. Fuel costs as a proportion of total fisheries revenue

	Fishery type	Fuel cost (Proportion of total 2005 fisheries revenue) (%)
Developing Countries	Active demersal	52.3
	Active pelagic	33.4
	Passive gear (*e.g.* pots)	38.7
Developed Countries	Active demersal	28.7
	Active pelagic	11.0
	Passive gear	9.2

Fuel costs may vary from country to country.
Source: FAO (2007).

There is little doubt that rising fuel costs continue to motivate the efficiency of high seas fisheries in the interests of minimising one of their most pervasive costs and for keeping operations profitable. More efficient vessels and fishing gear offer up to a 20% reduction in fuel use (FAO 2007), while other options may include the use of sails to reduce transit times (Thomson, 1979) and investigations are underway to improve fishing efficiency through the use of different gear (*e.g.* more widespread use of deepwater "pots" rather than longlining to fish for toothfish – [Guerrero and Arana, 2009][8]).

Currently, considerably more information is required to clearly determine global GHG emissions from fisheries trade. Table 9.10 illustrates CO_2 emission estimates associated with the transport of agricultural products. Assuming that the same estimate coefficients proposed by Saunders and Hayes (2007) apply to fish exports (although emissions may be higher if refrigeration is widely used) and high seas fisheries constitute 25% of the global fish trade, crude estimates of trade-linked emissions from high seas fisheries are possible. Intercontinental air freight would thus comprise 2.2 kg of CO_2 per kilogram of high seas fish transported, assuming that the 8.5 kg CO_2 emission level ascribed to air freighting general agricultural products depicted in Table 10.10 is equivalent to that for fisheries in general. Therefore emissions from air freighted high seas fish would be similar to the 2.4 kg CO_2 emission level from sea freight of such products and about 40 times the transport emissions of fish consumed within 400 km of their source. Emissions from the remaining, non-air freighted 6.25 million tonnes of internationally traded high seas fish would depend on the type of transport used and the distance(s) involved. From Table 9.10, the short-distance truck and non-bulk sea freight emission for high seas fisheries trade would be between 0.75 and 85 Tg CO_2, which is equivalent to between 0.5% and 85% of operational high seas fisheries emission estimates. Although more work is obviously needed, it would appear that GHG emissions from high seas fish trade are probably equivalent to those of the fishing operations themselves. Greater globalisation of fish trade will undoubtedly increase the GHG emissions contributed by fisheries in general, and by high seas fisheries in particular. However, if use of bulk-sea freight increases

along with more local consumption of catch, then emissions from the transport of fish will decrease.

Table 9.10. CO_2 emissions from different modes of transport associated with (a) general agricultural, (b) fish/aquaculture, and (c) high seas fisheries products

Transport mode & Distance	Transport type	General (g CO_2/kg)	All fisheries (g CO_2/kg)	High seas (g CO_2/kg)
short distance (<400km)	road freight	55	55	14
intercontinental	air freight	8510	8510	2130
	sea freight	2430	2430	610
	bulk	2400	2400	600
	non-bulk	6400	6400	1600

Source: Saunders and Hayes (2007); Daw *et al. (*2009).

Both aviation and shipping are currently outside international efforts (such as emission trading schemes) to mitigate the direct effects of GHG emissions on climate change (Daw *et al.,* 2009). The potential omission of DWFFs is of particular concern not only given their involvement in high seas fisheries generally, but also as they often source fuel at locations not bound by the domestic taxes and levies to which they would be subject if they fuelled in their home ports. In these terms, the price of fuel remains a key cost of "doing business" for all fisheries; a fact clearly demonstrated by the doubling of the diesel fuel price between 2004 and 2005 which caused the demise of many individual fishing operators (FAO, 2007).

Various post-Kyoto negotiations (*e.g.* EEA 2007) raise the very real possibility that aviation and shipping will be addressed as the 2012 Kyoto deadline for reducing global GHG emissions approaches. Any attendant costs involved will thus not only be important for the fish trade (Delgado *et al*., 2003), they may also impact on the food security of poorer countries that import fish.

Indirect mitigation

The preceding sections on climate change impacts and high seas fisheries' vulnerability, resilience and adaptability, and Tables 9.A1.1 to 9.A1.4 in the annex, have outlined the wide range of impact pathways associated with effects of climate on high seas fisheries. Table 10.4 highlights the notion that manifest changes in the high seas FHS are interconnected with the MRS. Consequently, applying mitigation to any climate change effect is likely to have implications, great or small, for other components of the marine social-ecological system illustrated in Figure 9.7.

From Table 9.11, it can be seen that various measures ("adaptation responses") can be applied in efforts to counter the effects of climate-induced impacts on high seas fisheries based on timing and responsibility of the responses. In these terms, mitigation measures aimed at countering such impacts can be consolidated into three key actions (Figure 9.13):

(a) increased fisheries resilience, (b) long-term adaptation planning and (c) improved fisheries management. In specific terms, these actions can be broken down further into integration, institutional reform and fisheries management which will be dealt with in "Managing high seas fisheries in a changing world", below.

Figure 9.13. Summary of actions required for mitigation of potential climate change impacts on high seas fisheries

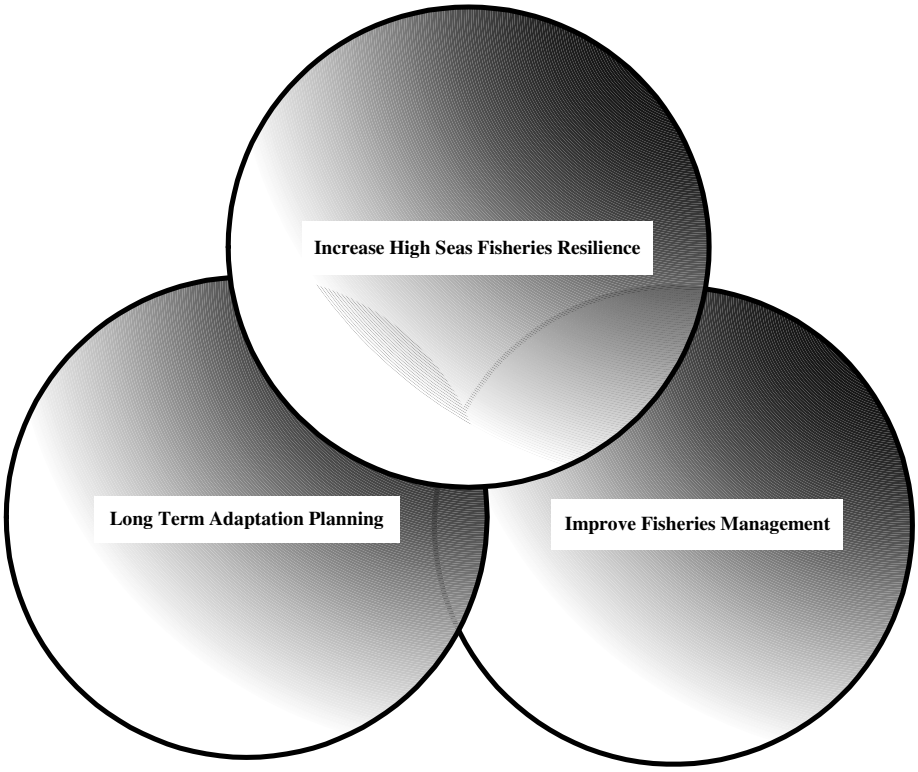


Table 9.11. High seas fisheries adaptations to climate impacts

Impact on fisheries[1]	Potential adaptation measures[2]	Responsibility	Response[3]
Reduced fisheries productivity/ yield[(a)]	Access higher value markets	Public/Private	E
	Increase fishing effort/ power*	Private	E
Increased yield variability[(a)]	Diversify industry portfolio	Private	E
	Promote risk insurance	Public	A
	Precautionary management for ecosystem resilience	Public	A
	Implement integrated/adaptive management	Public	A
Changes in fisheries distribution[(a)]	Private research & development technology investment to predict fish migration	Private	A
	Relocate fishery*	Private	E
Reduced profitability[(a&b)]	Reduce costs/increase efficiency	Private	E
	Diversify industry	Private	E
	Leave fishery & move to other sectors	Private	R
Increased fishing risks[(c)]	Insure capital/asset investment	Private	A
	Adjust insurance market(s)	Private	R
	Underwrite insurance	Public	R
	Improve extreme weather forecasting	Public	A
	Invest in improved vessel stability/safety	Private	A
	Compensation for impacts	Public	R
Trade/market events[(b)]	Diversify markets & products	Private/Public	E
	Information to anticipate price/market variability	Public	R
Fisheries displacement & influx new fishers[(b)]	Support existing management institutions	Public	E
Various	Public research & development	Public	A

1. (a) Indirect ecological impact; (b) indirect socio-economic impact, and (c) direct 1mpact
2. * Enhances overexploitation risks by increasing fishing pressure & impacting habitats
3. A – Anticipatory response; R – Reactive response; E – Either anticipatory or reactive response).

Source: Smit *et al. (*2000); Tompkins and Adgar (2004); Daw *et al.* (2009).

Positive impacts

Finally, any discussion of climate change mitigation is not complete without some consideration of potential positive impacts. While positive climate change impacts are neither well studied nor understood, some specific examples present themselves. For example Barange and Perry (2009) highlight several instances where fisheries production might increase or where new fisheries might evolve. During the *El Niño* of 1982/83 and 1997/98, panaeid shrimps and rock lobsters appeared in Peruvian waters from farther north (Arntz *et al.,* 2006). Along with straddling and migratory species such as *mahi-mahi*, tuna and diamond sharks, new economic opportunities were created (CAF, 2000).

Possible new fisheries in the Arctic Ocean are also likely as the region becomes less susceptible to the influence of sea-ice as a result of global warming. Not only will the adaptive capacity of the high seas fisheries determine how such opportunities will be maximised, they are also without precedent in terms of the uncertainties associated with their potential sustainability. The governance and management approaches to be applied are also unprecedented, although the precautionary, ecosystem-based, approaches being pursued by such organizations as the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (Miller *et al.,* 2004) may provide important markers to be considered in managing new fisheries development.

Managing high seas fisheries in a changing world

General considerations

With few exceptions, post-war fisheries management has predominantly been based on assessment of stock productivity (such as maximum sustainable yield - MSY), taking into account natural (M) and fishing mortality (F). These approaches have been explicitly subsumed into Article 61.(b) of UNCLOS and Article 5.(b) of the UNFSA. Annex II of the latter goes as far as to provide guidelines for the application of precautionary reference points in the conservation and management of straddling and highly migratory fish stocks. For example, recent efforts to rebuild cod stocks in the North Seas have recognised the possible effects of climatic influences (Anonymous, 2007), but no formal mechanism stands in place to subsume environmental considerations into management deliberations or measures. Obviously, as climate change impacts increase in relation to the marine ecosystems in general, and for fisheries stocks in particular, so does the need to implement an ecosystem approach to fisheries (EAF) to facilitate precautionary, holistic, integrated, participatory and sustainable management of fisheries globally (FAO, 2006). In these terms, Constable *et al*. (2000) have clearly indicated that CCAMLR is one of the few RFMOs to have attempted to implement management measures that expressly take ecosystem conservation into account as per Article II of the CAMLR Convention.[9]

Integration

General

Various institutions are involved in the management of high seas fisheries. These include national governments, RFMOs, industry groups, non-governmental (NGO) interest groups and civil society in general. Varying levels of responsibility are attached to the institutions concerned. In turn, their performance is usually measured by how

effectively they fulfill management goals in implementing policy decisions, ensuring adequate levels of governance for sustainable resource management, promoting compliance with regulatory provisions, monitoring management effects etc. There are also cultural, normative and political antecedents, ranging from minimalistic to draconian, that guide high seas fisheries management in terms of the anticipated outcomes of management action.

Coulthard (2009) has indicated that over-elaborate fisheries management institutions can also impede the necessary levels of flexibility required to manage climate impact adaptation; a situation clearly demonstrated by the "locking-in" of Newfoundland cod fishers to the fishery to the extent that advantage could not be taken of expanding shellfish fisheries as cod stocks collapsed (Hilborn *et al*., 2003). Let us now examine some key institutional aspects to be addressed to improve integration of key factors in the management of high seas fisheries climate impacts.

Social-ecological integration

Many RFMOs, in particular, have very narrow competencies in terms of their management mandates (Swan, 2000, 2003). They are usually confined to managing fishing, and closely, associated activities alone with very little latitude to deal with broader considerations such as implementing trade-related measures or accounting for social-ecological concerns. For example, the lengthy and antagonistic debates concerning potential listing of toothfish under the 1975 Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (CCAMLR, 2002 – paragraphs 9.1 to 9.71), and other equally contentious international debates, required FAO and CITES to formalise their working relationship in a 2006 memorandum of understanding (MOU)[10].

Furthermore, the clear associations between civil society, fisheries operators and policy institutions illustrated in Figure 9.11 clearly show that is a strong need to bring together the necessary knowledge, expertise, information, data and stakeholders to provide an integrated forum where all aspects of the climate change-high seas fisheries paradigm can be considered. In particular, there are strong indications that the transformation of scientific advice into fisheries management policy must be the product of a participatory and transparent process (Mora *et al.,* 2009). Such integration is at the core of achieving high seas fisheries sustainability.

Institutional reform

Data procurement

The section above, "Fishery status and trends", highlighted the difficulties associated with procuring accurate catch data for high seas fisheries due to mismatches between high seas fisheries data and those provided later from EEZs. In an attempt to improve information on high seas catches, oceanic species in the FAO capture fisheries database that are likely to have been taken on the high seas are classified into "epipelagic" and "deep-water species" (FAO, 2009). Catches for these two groups of species are then considered as a proxy for high seas catch trends

The above arrangement is obviously not completely satisfactory and is likely to be an impediment to future efforts to monitor high seas fisheries in relation to potential climate change impacts. Therefore, every encouragement should be given to improving

collaboration between FAO and RFMOs on modifying FAO statistical division boundaries to allow catch returns to be separated between those from within, and those from outside, coastal state EEZs. The 2008 International Guidelines for the Management of Deep-Sea Fisheries in the High Seas are an important development in this respect.

RFMO performance

A key outcome of the Ministerially-led Task Force on IUU Fishing on the High Seas was that progressive reform of RFMOs should be promoted and encouraged to ensure that they are able to fulfill their roles under "new generation" international fishery agreements, such as the UNFSA and *FAO Code of Conduct for Responsible Fisheries* (Anonymous, 2006). More recently, the 2006 UN General Assembly Resolution 61/105 urged RFMOs to "strengthen their mandates, and to modernize their measures for, and approaches to, fisheries management". The Resolution also "called upon States to develop and apply best practice guidelines to RFMOs" and to undertake reviews of their performance, based on transparent criteria. An independent panel was tasked with developing such guidelines (Lodge *et al.* 2007).

Since the best practice guidelines were developed, a number of RFMOs have carried out reviews of their respective performance. These have generally comprised reviews by mixed panels of internal participants and external advisers (North East Atlantic Fisheries Commission [NEAFC] [2006]; CCAMLR [2008] and the Indian Ocean Tuna Commission [IOTC] [2009]) or independent reviewers (International Commission for the Conservation of Atlantic Tunas [ICCAT] [2009]).

Although RFMO reviews to date have essentially focused on institutional management and administrative issues, only the CCAMLR review makes specific mention in its recommendations on a need to take into account climate effects on fisheries, particularly in the krill fishery (Anonymous, 2008). This prompted CCAMLR to place consideration of climate change firmly on its agenda (*e.g.* CCAMLR, 2008). Therefore, it is strongly recommended that RFMOs in particular, as well as other management bodies, make additional efforts to formally review available information on possible climate impacts on important fisheries.

Improved fisheries management

General

Along with the need to adopt an EAF and facilitate adaptation to climate change effects (see above), an important challenge facing modern fisheries management is the complexity and unpredictability posed by such impacts. This makes it difficult to predict how all MRS elements may respond to climate-induced changes; a situation largely dependent on the increasing levels of uncertainty associated with climate change impact pathways (Daw *et al.,* 2009) (Figure 10.14). In the context being considered here, the greatest uncertainty thus becomes the prediction of synergistic impacts on high seas MRS (Table 9.4), in the face of multiple climate, and non-climate, stressors (Barange and Perry, 2009). Such stressors, in turn, are likely to manifest themselves in non-linear dynamics, functional relationships and interactions (Scheffer *et al.,* 2001).

Constable (2002, 2005) has clearly indicated that evaluating management procedures for a particular fishery is largely contingent on developing plausible models for the

underlying ecosystem in which the fishery is located. Such models should: (a) clearly outline the model elements, (b) deal explicitly with uncertainty, and (c) link physical, biological and social character elements. Furthermore, in a management and climate impact context, models would need to provide a basis for decision-making in terms of inherent uncertainty and risk.[11]

Modelling

Work by the IPCC (2007), and more recently by deYoung *et al.* (2010), has greatly improved our ability to model the dynamics of physical-biological processes at scales ranging from ocean shelves to basins, and individual plankton to higher trophic levels (Figure 10.6.b). The Global Ocean Ecosystems Dynamics (GLOBEC) Program has made a substantial contribution to such advances.

Notable examples of physical-biological process models include Bakun's (1996) ocean triad. This spans a wide range of physical and biological processes at the center of enrichment processes in the Benguela coastal upwelling system. Mullon *et al.* (2002) have taken the process further and have explored the evolutionary implications of fish spawning in the Benguela. Similar conceptual models have shown that the contiguous distribution of Antarctic krill (*Euphausia superba*) around the Antarctic is driven by the underlying oceanic circulation. As Atkinson *et al.* (2008) have indicated this hypothesis for Southern Ocean ecosystem structure and function is crucial to understanding how the system will respond to climate change effects.

While the above models improve conceptual understanding of physical-biological processes, their explanative power is not altogether convincing (Houde, 2008). Additional work is still necessary to improve current understanding and this requires longer/better data time series, improved coupled models and additional consideration of the full life histories of the biota involved. Spatially explicit, coupled models are considerably more complex than the conceptual models of the kind alluded to above. In these terms, the development of new and more sophisticated biophysical models will not only provide opportunities to test existing hypotheses about the interrelationships between environmental forcing and high seas fish stocks, it will also allow for "simulation exploration" of potential climate impacts in an exploratory and predictive sense (Miller, T.J., 2007).

For example, complex model studies of skipjack tuna (*Katsuwonus pelamis*) have improved understanding of this species' life history dynamics at an ocean basin scale (Lehodey, 2001). While focusing on skipjack, the model also simulates the species' prey which in turn is coupled to a biogeochemical, ocean circulation model (Chai *et al.,* 2003) that captures *El Niño* events and the regime shift of the late 1970s. Preliminary studies with a similar approach have shown potential shifts in the distribution of skipjack and other species attributable to global warming (Loukos *et al.,* 2003; Perry *et al.,* 2005).

The current state of biophysical models has moved deYoung *et al.* (2010) to state that "biophysical models, coupled with future scenarios of climate conditions are crucial for assessing and forecasting what might occur in the coming decades". A tantalising example of the kind of results that could be expected is illustrated by Ito and co-workers' (Ito, 2007; Ito *et al.,* 2007) modelling of Pacific saury responses to future climate changes. The net effect indicated was an increase in saury abundance with an accompanying reduction in the weight of individual fish. A subtly complex result such as this also

illustrates the inherent dangers of accepting a deducted net effect too soon; more fish is not the same end result as more fish weighing less.

Climate impact prediction and fisheries management

As understanding of climate change impacts improves, there is growing awareness that improved forecasting of fish abundance/availability is essential to ensuring long-term sustainability of high seas fisheries in the face of the growing demand for protein from the sea globally.

Basson (1999) has suggested that two major issues determine the likely benefit(s) of explicitly considering environmental factors as a component of fisheries management. First, such consideration needs to recognise the critical importance of (a) the environmental factor's predictability, and (b) its relationship to fish recruitment. Therefore, uncertainty will only be reduced if the environmental factor is accurately predictable and its functional connection to recruitment is strong. Second, the extent of such benefit(s) relies heavily on the fish stock's life history and fisheries-specific parameters. These findings lead Basson (1999) to conclude that: "In the examples considered here, there was essentially no gain in terms of the long-term average yield and conservation".

Basson (1999) also concluded that in certain situations the explicit inclusion of environmental factors in the management paradigm may make management outcomes worse. For example, it is a particularly risky approach if predicted outcomes are out of step with the actual environmental series because of less than optimal prediction capabilities (*e.g.* high temperatures are predicted when real temperatures are low).

More work is obviously needed; a point well recognised by RFMOs such as CCAMLR and the South-East Atlantic Fisheries Organisation (SEAFO) which have placed climate impacts, and environmental considerations, firmly on their management approach agendas. As Basson (1999) has indicated, it would certainly be interesting to consider "how information on changes in the statistical distribution of an environmental factor might be incorporated into a management procedure".

It would be shortsighted to underestimate the contribution(s) to be made by the various approaches discussed above to decision making attached to an EAF. However, additional consideration is obviously required to extend assessments, improve understanding of ecosystem function, address uncertainty and risk, improve forecasting ability, "apprehend natural variability", and delineate objective scientific device from advocacy (Garcia and Cochrane, 2005; Reid, 2007). Obviously, the complexities inherent in the multi-dimensional climate impact – fisheries issues outlined here only serve to compound the potential management task(s) at hand – a point well illustrated by Figure 9.6 in Barange *et al*. (2010). Significant challenges requiring credible and pragmatic approaches include, to name a few, the need to deal with data-sparse situations, resolving apparently conflicting signals, broadening the information base and specifically linking scientific knowledge of the resources concerned with their socio-economic antecedents.

However, sight should not be lost of the fact that models play two very different roles in the process of developing management approaches and procedures. For example, "decision models" (Butterworth and Plagányi, 2004), are used to integrate information gathered by monitoring specific environmental, biological and fisheries parameters, usually with a "control rule" attached to refine scientific advice on specific management

measures. Such models are not intended to provide accurate representations of underlying interactions between various parameters, but rather provide a basis for simulations aimed at achieving robust meeting of management objectives.

"Operational models" on the other hand seek to accurately elucidate alternative scenarios for the situation, or situations, being examined. A high degree of realism is usually sought and this quite often results in operational models being quite complex. Nonetheless, they are a way to project parameter trends into the future to provide a basis for simulating and testing how candidate decisions may meet management objectives.

The inherent complexities attached to high fisheries climate impacts illustrated in this paper tend to suggest that it will be many years before multi-parameter models can be used routinely as decision models for climate impact mitigation and management.[12] This is directly attributable to the uncertainties attached to appropriate selection of the numerous parameter values and the interactive functional relationships between component interactions illustrated in "Climate and the socio-ecology of ocean systems" and Figures 10.8 and 10.9, above. Nevertheless, operational models offer a convenient and practical way to build necessary insights to underpin robust management approaches for the management of high seas fisheries in the face of climate impacts, both direct and indirect.

As already noted, few RFMOs have formally included consideration of high seas fisheries climate impact issues on their agendas (see "Integration", above). Therefore, there appears to be considerable merit in formalising such consideration, and in commencing development of interactive risk-based approaches to augment the current fisheries climate impact management "toolbox". For example, a decision-making schema could be formalised. As a first step, management decision pathways are identified in terms of their physical, ecological, economic/social, and management/ monitoring/research scope. These are included in a matrix of stated objectives for such considerations as GHG emissions, physical, harvested species, fisheries and socio-economic factors. Specific model attributes are then linked within a decision-making model schema matrix (Miller, 1987). The value of the schema is that it may then be used within one, or more, decisions scenario (Starfield *et al.,* 1988). This allows trade-offs to be identified and evaluated in terms of a specific parameter level (*e.g.* fishing level), and in relation to a dramatic change in some other attribute (*e.g.* harvested stock) combined with a specified impact (*e.g.* sea temperature). The same model could then be used to assess improved precision in the estimation of key parameters, thereby reducing the variance of potential outcomes when identifying research priorities.

To date, no procedure has been put in place to specifically evaluate high seas fisheries performance in the face of potential climate impacts. Building on the approach outlined above, key elements, and sub-elements, of the high seas fisheries-climate impact paradigm would need to be selected and prioritised. The prioritisation process must also be risk-based and should comprise:

- indentifying potential risks attached to high seas fisheries performance through the analysis/assessment of performance breakdowns;
- nominating high items to be addressed;
- precisely defining high risk items to be targeted;

- developing metrics (*e.g.* numerical ranks ranging from "low" to "high") to assess the potential impacts of targeted risk items;

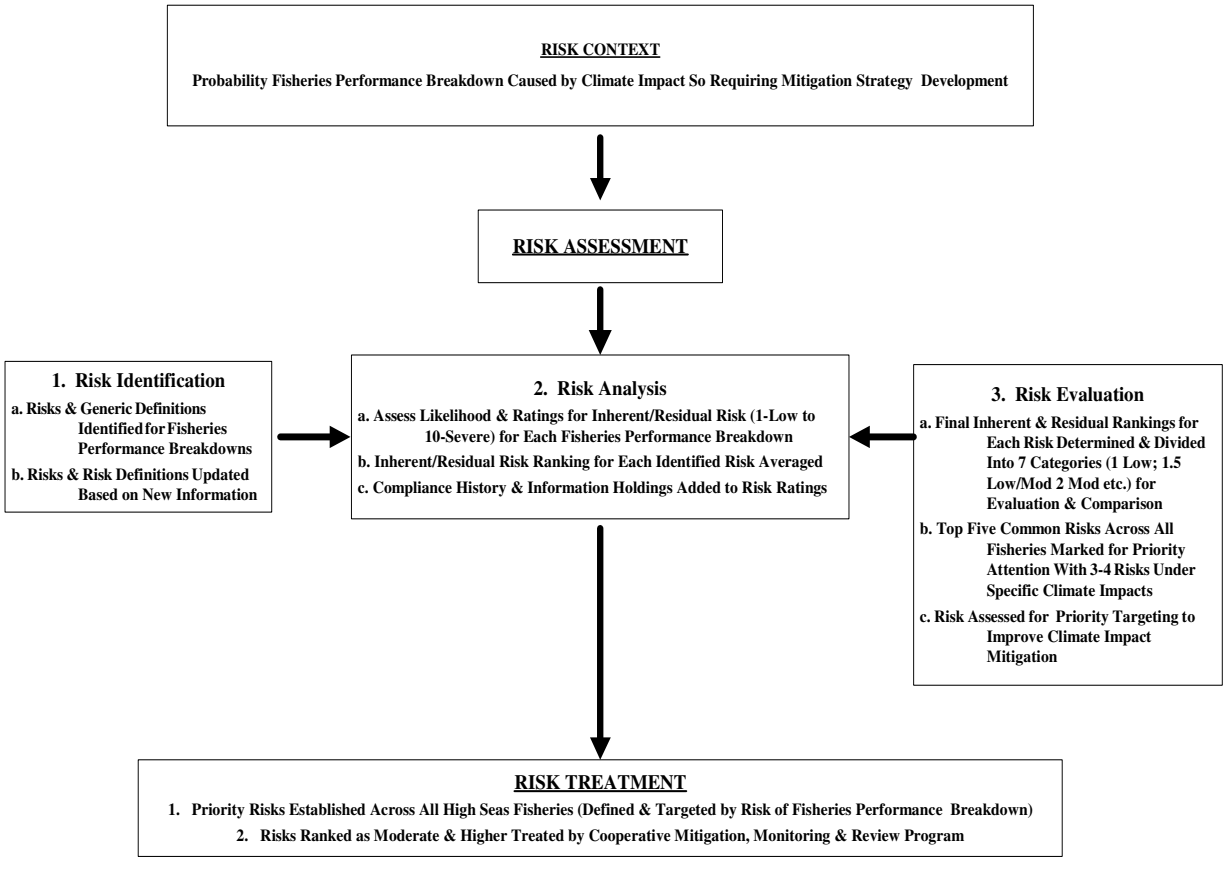
- developing strategies, unique to targeted risk items, to provide remedial action and reduce negative effects of high seas fisheries performance breakdowns;

- developing and implementing formal climate impact management plans to monitor, review and adjust remedial action for, including risk mitigation of, high seas fisheries breakdowns;

- developing appropriate reporting procedures to disseminate information on the above.

Such an evaluation procedure and risk management process is illustrated in Figure 9.15 and comprises three basic steps: (a) setting a high-order objective to bound the context of risk attached to any high seas fisheries performance breakdown in terms of potential climate impacts, (b) an assessment process to identify, analyse and evaluate risk, and (c) a treatment of risk. In its entirety, the process provides a systematic, and objective, approach aimed at providing a systematic and objective approach to address high seas fisheries performance breakdowns and improve mitigation of climate impacts.

Figure 9.15. High seas fisheries climate impact risk management process.



The collaborative nature of this type of approach cannot be over-emphasised. Prototype expert management systems being developed for small pelagic fisheries in the southern parts of the Benguela Current system hold promise for advancing such initiatives (Barange *et al.,* 2010). Jarre *at al.* (2006, 2008) have concluded that knowledge-based approaches warrant development as they (a)synthesise complex problems in a logical and "transparent" framework, (b) assist scientific application of cross-disciplinary issues, and (c) facilitate delivery of state-of-the-art science to a more representative audience comprising affected stakeholders with an interest in the issues being considered. Equally, the potential of enhancing Geographical Information System (GIS) support of EAF has recently been recognised (Carocci *et al.,* 2009) and there seems to be no reason why a similar approach could not be investigated for potential climate impacts on high seas fisheries.

Conclusions

In general terms, climate change is predicted to impact fisheries widely, and by extension the societies, industries and individuals that depend on them. Daw *et al.* (2009) have succinctly summarised the issue in stating – "As is common across climate change science, there is a significant body of knowledge on the biophysical impacts of climate change on aquatic ecosystems, but much less knowledge on how these impacts will be mediated by the socio-economic context of fisheries and how adaptation will proceed". In these terms, and based on the information presented here, it is logical to assume that climate change impacts affecting high seas fisheries socio-economic conditions (*i.e.* product supply, market demand, fishing/processing technology and collective resource management) (Figure 9.7) are of a similar order to physical-biotic effects (Figure 9.5). Together these effects determine the vulnerability of high seas fisheries to climate impacts in the broadest sense and for the foreseeable future.

It has been shown that high seas fisheries' vulnerability to climate impacts depends not only on the extent of the impact, but also on the sensitivity of the industrial sustainability framework components, individually or collectively (Figures 9.10 and 9.11). Adaptive capacity is therefore a key factor (Figure 9.10) in ensuring the viability of a high seas industrial sustainability framework and as the context for understanding climate change impacts on it.

For such reasons, one of the key priorities for the global community at large is to pursue GHG emission reduction. While the long-term consequences of climate change are uncertain, and even contested, the role of GHGs as drivers of change is largely accepted along with the fact that climate change is highly complex, currently "unknowable", potentially irreversible and essentially "here to stay" (Daw *et al.,* 2009). This generalised scenario is not only applicable to high seas fisheries; it requires governments and international institutions, such as the OECD, to investigate ways of facilitating climate impact adaptation in vulnerable sectors of civil society. This vulnerability is a function of exposure, sensitive and inadequate adaptive capacity (see above). It is therefore recommended (after Daw *et al.,* 2009) that essential research should be initiated to:

- identify the most vulnerable high seas fisheries sectors as well as other fisheries sectors generally;
- investigate/implement improved adaptation(s) to climate effects on high seas fisheries;

- consider ways to ensure "common good" adaptations to climate impacts rather than individual initiatives;
- seek long-term vulnerability adaptations to climate change impacts rather than short-term strategies that may result in enhanced longer-term vulnerability.

According to Sharp (2003), high seas fisheries are likely to be least affected by climate variation compared to other fisheries. However, this paper has demonstrated that there is sufficient global uncertainty and concern to warrant a cautionary consideration of the potential consequences of climate impacts on high seas fisheries and on the socio-ecological systems associated with them. As stated in early IPCC documents (IPCC, 1990; 1996), several options for addressing potential climate change impacts on fisheries have been around for some time. Of these, options that are likely to provide tangible benefits to the high seas fisheries sector as whole (after Sharp, 2003) include:

- ensuring that national and international fishery management, including relevant institutions involved, are tasked to consider shifting species distributions, abundances and accessibility so as to balance species conservation with sustainable fishing, and account for socio-economic efficiency and stability of the fisheries concerned;
- supporting innovative research on fisheries management in the context of linking ecosystems with fishing activities in terms of the ecological, and other, effects depicted in Figure 9.9;
- improving fisheries management between coastal and high seas areas;
- striving to minimise human-induced impacts (such as introduction of alien species) that might thrive under climate change and/or harm high seas fish stocks/fisheries.
- The above considerations clearly indicate the need for policy development to cope with climate change adaptation by fisheries in general, and high seas fisheries in particular. First, it must be recognised that there are synergies between GHG emission reduction, energy savings and responsible fisheries (Tyedmers *et al*., 2005). Some adaptive measures to address these synergies include:
- raising climate change impact awareness to specifically account for the fisheries sectors concerned. Raised awareness should serve to plan responses and the setting of mitigation targets (e.g. as alluded to by the Kyoto Protocol);
- reducing fisheries fuel subsidies to optimise fuel efficiency and reduce overcapitalisation;
- supporting use of static fishing gear (e.g. pots and longlines) to reduce fuel usage;
- managing/promoting aquaculture where suitable to optimise carbon retention, reduce energy use and minimise habitat impacts;
- raising awareness by campaigns to promote endeavours such as "catch and eat local" seafood initiatives (i.e. to reduce transport costs) and corporate social responsibility in the seafood sector.

Obviously, great care will be necessary to make sure that adaptive measures do not themselves become sources of concern in respect to consequent effects on fisheries sustainability etc.

Second, any fisheries climate impact adaptation policy should aim to reduce exposure to climate-related risk, reduce socio-economic dependence on climate-sensitive resources and support global capacity to anticipate, and/or address, climate-related changes. Table 9.12 identifies some key stakeholders along with the policies and actions that could be implemented to advance high seas fisheries climate impact adaptation. Initially, it is suggested that the attached implementation plans follow the kinds of action identified above in "Climate impact prediction and fisheries management".

The point has already been made that good fisheries governance is essential for ensuring stock sustainability. It is also crucial to developing the practical climate change adaptive measures necessary to build resilient fish stock and fisheries. This raises the question of whether there is a need to provide additional interventions to enhance adaptation.

Table 9.12. Stakeholder/policy development to address fisheries climate impact adaptation by high seas fisheries

Stakeholder	Policy Development
National/international institutions responsible for fisheries governance & management	Climate change risk assessment to identify adaptation costs
	Build institutions/capacity to integrate research, management & policy development to consider, & respond to climate change as well as other pressures such as overfishing, habitat degradation, pollution & changing hydrological conditions.
	Enhance institutional capacity for fisheries to move safely in response to resource distribution changes. requires development of cooperation agreements & functional transboundary fisheries governance regimes, including deterrence of IUU fishing.
	Link fisheries management with martine/coastal disaster management & risk reduction planning.
	Enhance fisheries sector resilience through adaptive socio-economic strategies & management institutions to support climate variability/impact adaptation. includes sustainable reciprocal access agreements.
	Address other issues affecting fisheries sector vulnerability (*i.e.* market/services access, political representation, improved governance etc.).
	Facilitate long-term adaptation planning to promote fisheries related climate issues & address longer-term trends and/or extensive shifts in harvested resources or ecosystems.
NGOs & fisheries industry/community organisations	Identify fisheries' risks, potential impacts & resilience/recovery mechanisms. Promote broad consultation & preparedness planning across civil society.
	Communicate risks of fisheries climate impacts to policy makers.
	Build/support fisheries' resilience by supporting institutional development & vulnerability reduction programmes.
	Support fisheries' climate impact risk reduction initiatives through conservation, early warning systems, preparation strategies & disaster recovery processes.

Adaptation planners, donor agencies & economic analysts	Assess range, combination, economic & potential impacts of climate impacts on fisheries.
	Assess future risks/consequences of harvested stock variations & likely resource collapses. formulate sectoral security plans as required.
	Assess cross-sectoral factors that may augment climate change impacts (*e.g.* loss of coastal breeding locations for high seas fish stocks).
	Address fisheries in National Adaption Programmes of Action, particularly for developing countries.
	Develop risk reduction initiatives to address vulnerabilities (*e.g.* early warning systems, disaster recovery plans & ecological resilience initiatives).

There is little doubt that additional resources, both human and fiscal, are required to promote "good fisheries governance" globally so as to avoid current options for fisheries climate impact adaptation measures being overwhelmed. As Perry *et al.* (2010a) have emphasised, this will probably require international development assistance beyond that already being provided if an acceptable degree of equity is to be attained in spreading the burden attached to "solving" climate change-fisheries problem (Ayers and Huq, 2009). In this context, noteworthy work is currently being undertaken by the United Nations Framework Convention on Climate Change (UNFCCC) and the World Bank/United Nations Environment Programme Global Environmental Facility (GEF) to fund National Adaptation Programmes of Action. Nevertheless, fisheries sector plans are often only poorly considered due to a lack of appropriate expertise and knowledge. It is therefore recommended that current OECD initiatives be expanded to specifically include enhancement of fisheries-based adaptive capacity to climate impacts for key fisheries, and in areas where associated vulnerabilities are extreme.

Finally, like climate change adaptation in other sectors, fisheries adaptation is constrained by the need for "value-based decisions and trade-offs" (Daw *et al*., 2009). An inability to adapt and fisheries closure(s) are therefore likely to be seen as symptoms of "failure" to address the consequences of climate impacts on the fisheries involved. The ramifications of such failures are obvious in terms of the other systemic difficulties faced globally by fisheries, as highlighted above in "Fishery status and trends". The solving of such difficulties and identifying effective fisheries adaptations to climate impacts are both fraught with political, social, economic and value-based implications. Considerably more work, political lobbying and educational outreach are required to uphold the need "for equitable and just deliberative processes" (Daw *et al.*, 2009) to advance current efforts to mitigate climate impacts on high seas fisheries in particular.

Notes

1. Unless otherwise identified by name, and for convenience, the three fishery categories/stocks in Table 1 will collectively be referred to as "high seas" stocks. Consequently, responsibility for their management is assumed to rest largely with regional fisheries management organisations (RFMOs) as provided for in Articles 63, 64 and 118 of the 1982 United Nations Convention on the Law of the Sea (UNCLOS): *www.un.org/Depts/los/convention_agreements/convention_overview_convention.htm*

2. According to Allsopp *et al*. (2009), a fishery "collapse" is considered as a sustained period of very low catches following a period of high catches.

3. "Shifting baselines" refer to situations where/when observed variables may differ significantly as a function of the time period over which they are observed (Pauly, 1995).

4. A "system" may be considered as a region, state, fishery, fishery sector or fishery operator in the high seas context.

5. "Long-term" refers to time periods in excess of a decade.

6. "Short-term" responses are usually only limited to periods in the order of five years.

7. 1 Tg (teragram) equals 1 million metric tonnes.

8. *www.scielo.cl*

9. The CCAMLR fisheries concerned are those for Antarctic krill, icefish and toothfish.

10. *www.fao.org/newsroom/en/news/2006/1000410/index.html*

11. Various definitions are available to describe "uncertainty" and "risk". These often depend on the context in which the terms are being used. For this paper: uncertainty is taken to mean a lack of certainty where a limited state of knowledge makes it impossible to exactly describe an existing state or future outcome, and/or where more than one possible outcome may exist. On the other hand, risk is taken to represent a state of uncertainty where possible outcomes may have an undesired effect or induce a significant loss of some key quality.

12. It should be noted that climate impact mitigation and associated management initiatives are not about managing the biosphere per se (an unrealistic expectation given the inherent complexities), but rather about managing human activities in therein, and contributions thereto.

Annex 9.A1

Table 9.A1.1 Summary of findings for the physical basis of climate change in marine systems

Oceanic physical properties	Potential climate change effects
Heat content & temperature	Ocean warming
	Geographical differences
	Some decadal variability
	Warming not exclusive to surface waters
	Clear indications deep atlantic ocean warming
Salinity & stratification	Salinity changes
	Increasing salinity changes in evaporative region surface waters
	Decreasing trend in high latitudes
	Large past salinity anomalies with important ecosystem consequences
	Stratification changes
	Combined temperature/salinity changes - climate warming reduced density of surface ocean
	Increased vertical stratification
	Changed surface mixing
	Some geographical differences
Ocean circulation & upwelling	Meridional overturning circulation
	30% reduction in second half 20th century
	Further reduction from freshwater input in arctic sub-arctic & antarctic
	Increased stability of surface mixed layer
	Reduced salt flux
	Reduced ocean convection
	Less deepwater formation
	Profound Physical & biological consequences in North Atlantic
	Same consequences for ocean basins under Antarctic bottom water influence
	Increased upwelling some areas (California, NW Africa, Arabian Sea)
	Hypothesised global warming intensifies alongshore wind stress & upwelling
	Alternatively different pole-equator warming increases stratification counter such wind effect
	No discernible pattern in upwelling response to warming globally
	Close to equator reduced upwelling response to warming may occur
	Indications upwelling seasonality affected by climate change with food web consequences

Oceanic physical properties	Potential climate change effects
Sea level rise	Sea level rise
	Global average rise 1.8 mm/yr since 1961 accelerating to about 3.0 mm/yr since 1993
	Higher rate of rise in future likely & rise not geographically uniform
	Largest sea level rise losses - Atlantic & Gulf of Mexico coasts of Americas
	Losses also high in Mediterranean, Baltic & small island regions
Acidification & other chemical properties	Acidification
	Surface water pH decrease 0.1 units over past 200 years
	Models estimate further reduction 0.3 to 0.5 pH units over next 100 years
	Acidification effects uncertain as sensitivities unknown
	Probably severe for shell-borne organisms, tropical reefs & Southern ocean cold-water corals
	Oxygen & nutrients
	Oxygen concentration in ventilated ocean (100 to 1000 m) decreasing since 1970s
	Decreased oxygen concentration due to reduced intermediate water renewal rate
Atmosphere-ocean & land-ocean exchanges	General effects
	Consequences of processes not able to be generalised
	Impact near shore fish & plankton community composition, production, seasonality
Low frequency climate variability	Atmospheric patterns
	Possible increase intensity & frequency of some patterns (*e.g.* North Atlantic Oscillation [NAO], ENSO)
	Generally models predict spatially uniform warming trend for ocean basins
	Continued presence of decadal variability as for 20th century
	Strong teleconnections between patterns within single ocean basins
	Inter-basin teleconnections & climate change biological synchrony weaker for several decades

Source: Barange *et al. (*2009)

Table 9.A1.2. Summary of findings for climate variability effects on ecosystem and fish production processes in marine systems

Ecosystem processes	Potential climate change effects
General summary	Physiological performance
	Possible response range to conditions (*e.g.* temperature) impacting key physiology
Primary (1°) production	General
	Suggested 6% reduction in global oceanic 1° production early 1980s to late 1990s
	Substantial regional differences (e.g. higher latitude chlorophyll increase past 20 years)
	Differences may lead to changes (e.g. diatom dominance over small phytoplankton)
	Increased vertical stratification & water column stability
	Reduced euphotic zone nutrient availability – less 1° & secondary production
	Higher latitudes – euphotic zone residency increase – increase growth season /1° production
	Overall small increase 1° production globally – large regional differences
	Climate warming
	May reduce productive marginal sea ice biome
	May reduce seasonally stratified subtropical gyre
	May expand low productivity permanently stratified subtropical gyre biome
	May expand subpolar gyre biome
	Simulations suggest global warming may delay onset diatom spring bloom
	May also reduce diatom spring bloom biomass
	Possible changes in phytoplankton assemblages
	High latitude reduction ice cover, warmer water, longer growing season
	Higher latitude increases plankton/algal abundance & productivity
	Reduced productivity may prevail at lower latitudes
	Hydrological Cycles
	Cycle intensification expected to affect limnological processes substantially
	Increase run-off, estuary discharge & flooding may boost near shore productivity
	Flooding timing changes may lead to loss of near shore production
Secondary Production	Regional effects
	No global assessment of climate change effects on oceanic secondary production
	Results dominated by local or regional conditions – area of active research (Mackas and Beaugrand, 2008)
	Regional results suggest effects reflected in zooplankton distribution not abundance

Table 9.A1.2. Summary of findings for climate variability effects on ecosystem and fish production processes in marine systems (*cont.*)

Ecosystem processes	Potential climate change effects
Distributional changes	Distributional changes
	Expected most marine distributions driven towards poles
	Expansion warmer-water species causing contraction colder-water species
	Distributional changes in North Sea, North Atlantic & North American east & west coasts
	Species affected include copepods, demersal invertebrates, intertidal & fish species
	Most rapid fish community changes for pelagic species
	Fish community changes include vertical movements to avoid warming effects
	Migration patterns
	Migration timing follow decadal trends in ocean temperature
	Migration later in cool decades & 1-2 months earlier in warm years
Abundance changes	Abundance
	Population abundances at poleward extent of ranges tend to increase
	Population abundances in equatorial areas of range tend to decline with warming
	Growth
	Increased growth rate responses to higher temperatures only when adequate food supply
Phenological changes	Phenology
	Over 50% marine species studied exhibit measurable phenological changes in past 20-140 years
	Systematic & predominant changes in expected direction attributable to regional climate
	Community structure & trophodynamics
	North Sea plankton community changes observed
	North Sea dinoflagellate season peak advance in response to warming
	No consistent pattern of change in North Sea diatoms as reproduction mainly light-induced
	Concern marine trophodynamics altered by warming due to predator-prey mismatch
Species Invasions/diseases	Consequences
	Little evidence linking disease outbreaks to global warming
	Pathogen spread to higher latitudes been observed
	Harmful algal blooms appear more common but link to climate change unclear
	Anticipated change in ratio of diatoms to dinoflagellates in warming ocean may play role
	Climate change induced extinction risks possible – no known examples to date
	Evolutionary adaptations likely
	Evolutionary adaptations probably with species-dependent time scales/characteristics

Table 9.A1.2. Summary of findings for climate variability effects on ecosystem and fish production processes in marine systems (*cont.*)

Ecosystem processes	Potential climate change effects
Foodweb impacts (zooplankton to fish)	Impacts
	Both direct & indirect effects of climate change likely through food processes
	Predominance direct/indirect changes function top-down, bottom-up or middle-out structure
	Suggested ecosystem control correlated with species richness & temperature
Regime shifts	Regime shift
Other extreme ecosystem events	Climate change variability affects ecosystem dynamics through non-linear "regime shifts"
	Ecosystem sensitivity may amplify climate signals for gradual, even stochastic, changes changes may provoke sudden/unpredictable biological responses
	Responses may occur as ecosystems shift from one state to another

Source: Barange *et al. (*2009).

Table 9.A1.3. The potential impacts of climate change on high seas fisheries

Change	Change effects	Processes affected	Potential fisheries impact(S)
	Increased CO_2 & ocean acidification	Affects calciferous animals (corals, molluscs etc.)	Reduced production calciferous marine resources & ecologically related species
			Yield declines calciferous & related species
		Warm-water species replace cold-water species	Distribution Shifts Marines Species to North & South
Physical environment (ecologically indirect)	Upper ocean layer warming	Plankton species move to higher latitudes	Reduced Diversity Tropical Marine Species
		Changed timing of phytoplankton blooms & zooplankton composition	Potential mismatch predators (fish) & prey (plankton)
			Reduced production & biodiversity
			Increased yield variability
	Sea level rise	Loss coastal fish breeding & nursery habitats (coral reefs)	Reduced production & yield (nearshore & related fisheries)
	Higher water temperatures	Sex ratio changes	Altered timing/reduced productivity marine systems
		Altered spawning, migration peak abundance time changes	
Fish stocks (ecologically indirect)	Ocean circulation/current changes	Invasive species, disease & algal bloom increases	Reduced productivity target species
		Changes fish recruitment success	Affected abundance juvenile fish
			Reduced productivity marine systems
	Increased frequency ENSO events	Changes upwelling timing/latitude	Distribution changes pelagic fisheries
		Coral bleaching/die-off	Reduced productivity coral reef fisheries

Table 9.A1.3. The potential impacts of climate change on high seas fisheries (cont.)

Change	Change effects	Processes affected	Potential fisheries impact(S)
Coastal infrastructure fishing operation disturbance(s) (direct)	Sea level rise	Change coastal profile infrastructure losses (harbours, landing sites etc.)	Increased coastal vulnerability to storm damage etc.
		Increased coastal area storm damage exposure	Reduced profitability/increased costs
	Increased storm frequency	Increased sea/fishing day losses (increased bad weather/accident risk)	Increased fishing risks/costs
		Installations more prone to damage/destruction (*e.g.* tuna pens)	Reduced profitability/increased costs notably higher insurance risks

Source: Modified after Daw *et al,.* 2009 as adapted from Allison *et al.*, 2005

Table 9.A1.4. Various climate change impacts on marine fish production and ecosystems

Region	Climate Change Impacts	Consequences
General	Temperature, wind, acidification changes	General Some confident predictions of general impacts on marine systems Rapid time scales[(a)] High confidence increasing temperatures negatively impact fish physiology Physiology constraints may change distribution, abundance & recruitment processes Intermediate time scales[(b)] Temperature-mediated physiological stress & phenology changes Impact recruitment success & change abundance Impacts most acute at limits of species range & for short-lived species Abundance changes marine community composition/structure Possible consequences for marine ecosystem structure & productivity Intermediate confidence predicting net community impacts due to compensatory dynamics Prediction increased vertical stratification reducing vertical mixing & productivity some areas Resulting changes in species composition Long time scales[(c)] Predicted impacts depend net 1° production changes & transfer to higher trophic levels High variability in model outcomes so low value predictions Improved knowledge of regional processes lead to better predictions Most models show decreased 1° production with changes to smaller phytoplankton Regional variability high Uncertainties Considerable uncertainties & research gaps remain Particular uncertainties on synergistic interactions between stressors

		Uncertainties due to extrapolating beyond historical conditions Also due to reduced resilience to climate variability from fishing induced changes And to locations/roles of critical thresholds And to ability of marine species to adapt to change & evolve as a result
Antarctic	Physical changes ecological consequences	<u>Physical changes</u> Antarctic Peninsula temperature increase of 3°c over last 50 years about 10 times global average On current indication of warming in rest of Antarctica Collapse of ice shelves near Peninsula may lead to increase glacier flow Cause of loss of ice shelves not fully identified West Antarctic Ice Sheet thinning due to surface water warming of about 1°c since 1955 Deep ice cores show current atmospheric CO_2 higher than any time in past 800 000 years Increased Western Antarctic freshwater runoff may affect bottom water formation & salinity <u>Ecological consequences</u> Reduction in High Antarctic species possible Variable sea ice extent & timing may affect krill recruitment Krill stocks may have declined since the 1970s Chinstrap penguins appear to be replacing adélie penguins around Peninsula Adélie penguins require pack ice for most of year & feed mainly on krill Gentoo penguins have started nesting on Peninsula recently

Arctic	Physical changes ecological consequences	Physical changes 5°C air temperature increase 6% precipitation increase 15 cm sea level rise 5% cloud cover increase 20 day reduction sea ice duration 20% reduction winter ice with substantial summer ice-free areas Ecological consequences 1° production increased 2-5 times present levels Reduced ranges cold-water fish & benthic species Expanded ranges Atlantic & Pacific species northwards Long-lived Arctic species may disappear in more southerly habitats for physiological reasons Physiological reasons due to narrow ambient temperature tolerance(s) & late reproduction Migration timing changes & increased growth rates Increase non-native species in Arctic waters Unlikely extinction of any present Arctic species
North-east (NE) Atlantic	Physical changes Ecological changes	Physical changes Continue to vary with state of North Atlantic Oscillation (NAO) North Sea, Barents Sea & Nordic Seas sea temperatures (ST) increase 3-5°c over next 50 years Largest ST changes in northernmost regions Increased wind-induced flux of warm Atlantic waters into northern regions Increase vertical stratification Reduced ice cover Ecological changes Increased 1° production in Barents Sea Decrease zooplankton production as Arctic zooplankton production declines Northward shifts in distribution of all species Increased species biomass production in Arcto-Boreal regions

		Fish species from south of North Sea likely to appear In North Sea Barents Sea capelin spawning areas likely to move eastwards North Sea dominated by pelagic species such as herring & mackerel in north North Sea dominated by sardine & anchovy in south Total North Sea system productivity may not be too different from today Baltic Sea Likely to become warmer & fresher, with significant vertical stratification increases Exclusion of marine-tolerant species in Baltic with more low saline tolerant species favoured Non-native species may enter Baltic, But colonisation unlikely due to salinity stress
North-west (NW) Atlantic	Physical changes Atlantic cod changes	<u>Physical changes</u> Predicted distribution & migration changes similar to NE Atlantic Populations at range limits most affected Some locations/times decreased temperatures from more Greenland glacier melt Greenland glacier melt may provide refuge for some coldwater species Greenland glacier melt may induce lethal shocks to species such as Atlantic cod Cool & narrow temperature adapted species (Atlantic salmon) extirpated current habitats <u>Cod changes</u> Gulf of Maine simulations show decline cod survival with warming offsetting growth increases Capelin (important cod prey) spawning Mid-NW Atlantic susceptible to delay from glacier melt Simulations suggest cod decline in NE Atlantic from increase temperatures in North Sea
North Pacific	Physical changes ecological Changes	<u>Physical changes</u> Anthropogenic induced warming likely in 30-50 years as large as current climate variability Decadal variable Pacific Decadal Oscillation (PDO) pattern will continue into 21st century PDO in 21st century will occur in addition to upward sea surface temperature trend Mixed layer depth (shoaling) & temperature (increasing) changes Retreat of sea ice in Bering Sea

		Sensitivity to increasing acidification effects Likely under-saturation of aragonite from sea surface to floor <u>Ecological changes</u> Latter half 20th century climate-ecosystem-fisheries links not resilient to 21st century changes Subpolar plankton systems change from strong variability & winter lows More constant subpolar plankton winter levels & decreased annual average 1° production Other (*e.g.* coastal) area species may experience higher growth rates as temperatures increase Expect seasonal pattern changes in 1° production due to warmer north-west Pacific conditions Predicted northward shift of fish populations off North American West coast Pacific sockeye salmon possibly restricted to Bering Sea Loss cold-water species & increasing abundance North Pacific species in Bering Sea Various species impacted by low pH concentrations
Wind-driven coastal upwelling systems	Physical changes Ecological changes	<u>Physical changes</u> Contradictory coastal-wind-system-driven upwelling reponses to global warming Increase alongshore wind stress may increase coastal upwelling Increased coastal upwelling may be offset by increasing temperatures & vertical stratification Other model studies predict decreasing upwelling favourable winds <u>Ecological changes</u> Global 1° production models show contradictory responses to warmer conditions One model (Sarmiento *et al.*, 2004) shows no consistent global response by upwelling regions to climate change Intensified Benguela Upwelling may increase nutrient output, 1° production & low O_2 events Benguela-similar events may occur in other upwelling systems Considerable local variability makes upwelling system generalisations difficult

Tropical & subtropical areas	Physical changes Ecological changes	<u>Physical changes</u> Not clear if tropical Pacific becomes more "*El-Niño*-like[1]" or more "*El-Niña*-like[2]" #Australia – models predict physical changes similar to other regions #Increasing vertical stratification, acidification &strengthening poleward coastal currents #Increasing Sea level rise, altered storm & rainfall regimes <u>Ecological changes</u> Highly diverse habitats & biology poorly studied Tropical Pacific 1° production decline from increased stratification/decreased nutrient supply Tuna prey availability & habitat affected by circulation, temperature, nutrient effects Tuna prey availability & habitat also affected by 1° production cascade up foodweb Tuna habitat east of Date Line could improve – similar to *El-Niño* events *Australian/New Zealand waters - greatest impacts on coastal species & subtidal nursery areas *Impacts on temperate endemic species rather than tropical & coastal species *Impacts on demersal species rather than deepwater & pelagic species #Australia – models predict physical changes similar to other regions Warming & increased stratification alter plankton community composition/poleward distribution Also change timing plankton bloom dynamic to impair higher trophic transfer Southward shift & possible abundance decline for benthic/demersal fish Pelagic species distribution shift southwards & some species[3] benefit increased local upwelling
Coral reef systems	Physical changes Ecological changes	<u>Physical Changes</u> Increasing temperatures, acidity, storm intensity & sea level rise <u>Ecological Changes</u> At risk due to physical changes

		Risk from non-climate factors like overexploitation, non-native species introductions Non-climate risks also from increasing nutrient & sediment loads Risks not evenly spread Increasing temperature significant for warm-water systems Increased acidity & decalcification significant for both warm & cold-water systems Direct human impacts significant in more populous regions Three time scales of effects identifiable: Years – increased temperature effects on coral bleaching Decades – increasing acidification & carbonate structure dissolution of reefs Multidecades – weakening reef structural integrity increasing storm susceptibility Multidecades – weakening reef structural integrity increasing erosion event susceptibility Increasing acidity (decreasing pH) significant/pervasive longer-term threat Adaption potential to such environmental stress uncertain Symbiotic zooxanthellae may adapt to higher temperatures Migration of corals to higher latitudes unlikely Coral declines negatively impact on reef fish biodiversity in one study at least To date little evidence link between climate warming & bleaching events Little evidence link between climate warming & bleaching events impacting coastal fisheries

Source: Barange et al., 2009

( ) (a) A few years; (b) Few years to a decade; (c) Multidecadal

For Australian Waters

* For Australian and New Zealand Waters

1. East-west gradient in sea surface temperature (SST) reduced.
2. East-west gradient in sea surface temperature (SST) increased.
3. For example, anchovies.

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PART III
NATIONAL STRATEGIES FOR ADAPTING FISHERIES TO CLIMATE CHANGE

Chapter 10

Fisheries governance in the UK: challenges and opportunities in a changing climate

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With increased storminess, rising sea levels and changes in ocean circulation, the British seas are becoming warmer and more acidic, entailing changes in the location and distribution of species. Alongside endemic problems such as overfishing, overcapacity and discarding the biological sustainability of stocks, climate change poses an additional pressure.

This paper outlines the potential barriers that the fishing industry may face and the role awaiting the UK government for building adaptive capacity within the industry. It also discusses the challenges and opportunities that fishers will face and the range of adaptation strategies available to the UK fishing industry. In order to minimize the negative consequences of climate change, already occurring, here we recommend that the UK Government take an integrated and ecosystems-based approach to the management of marine resources. An important role will be the removal of institutional barriers to adaptation.

These challenges are not confined to the domestic management of fisheries. Indeed, an additional challenge resulting from the close proximity of other EEZs is the issue of access to fishing grounds/to fish stocks.

Introduction

Over the coming years and decades, the UK's marine area is expected to be subject to a range of environmental changes at a rate that is faster than has been experienced before. These changes include UK seas becoming warmer and more acidic as well as experiencing increased storminess with rising sea levels and changes in ocean circulation. These trends are expected to trigger changes in the location and distribution of species that have traditionally been targeted by the UK fishing fleet, to affect the recruitment and catchability of some species and to create new fisheries within UK waters as warm-water adapted species move northwards.

The UK's existing fisheries governance structures have evolved over time and are designed to address market failures that are common to fisheries around the world. Endemic problems such as overfishing, overcapacity and discarding have the potential to jeopardise the biological sustainability of stocks and dissipate the wealth embedded in fisheries to the detriment of the fishing industry and society more widely. Climate change poses an additional pressure in an already challenging policy framework that has the potential to exacerbate existing inefficiencies (for example by nudging stocks or ecosystems towards tipping points) but also to act as a catalyst for addressing some of these fundamental issues for the long-term benefit of the industry and the ecosystems on which they rely.

The UK Government's approach to climate change adaptation is to support people and organisations in preparing for the effects of a changing climate. Whilst the fishing industry makes a relatively modest contribution to national income, accounting for less than 0.05% of the UK's gross value added, the regulatory structure has a significant effect on the incentives and options available to fishers in adjusting their business practices and thus provides an interesting case study. An examination of the fishing industry highlights that it is vital that the UK's institutional arrangements embed the principles of good adaptation policy to ensure that the negative consequences of climate change on the marine environment are minimised and that UK businesses are well placed to benefit from any emerging opportunities that arise.[3] A review of fisheries governance structures in light of a changing climate also needs to be contextualised against a recognition of the need to take an integrated and ecosystems-based approach to the management of marine resources. This paper outlines the potential barriers that may face the fishing industry in adapting to a changing climate and the role for the UK government in facilitating appropriate adaptation.

The anticipated impact of marine climate change

The UK is undertaking a wide range of research to understand the implications of a changing climate and to ensure individuals and businesses are well placed to adapt to any changes that arise.[4] The anticipated impacts of climate change on the UK's marine area are difficult to predict, are highly uncertain (especially with respect to winds and storminess) and in many cases will be highly localised and thus will require locally-tailored solutions. The latest scientific research suggests that changes are already occurring and by the year 2100 we could see:

- *Increase in average temperature*: shelf seas around the UK are projected to be 1.5-4ºC warmer

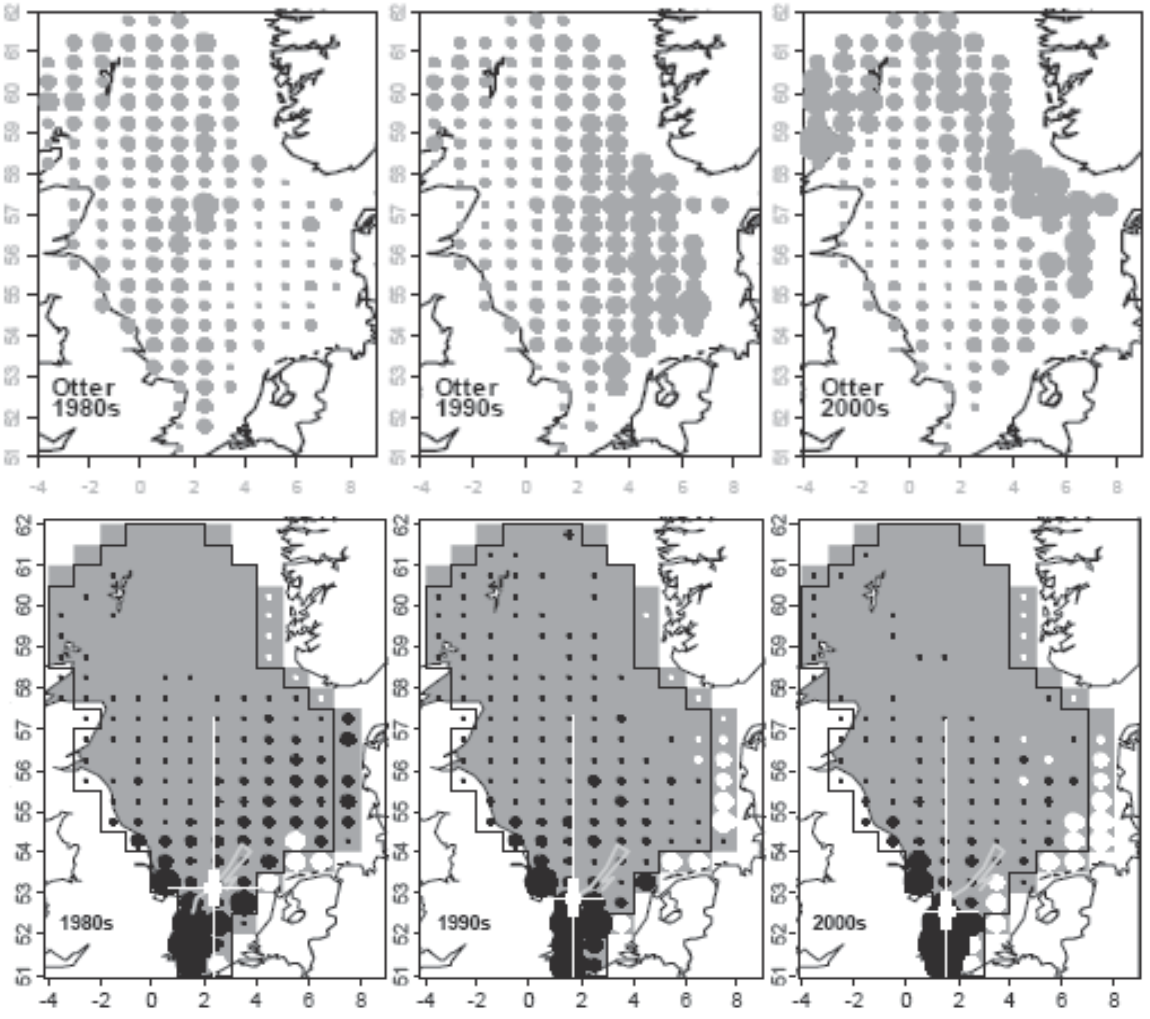
- *Increase in global mean sea level*: projected to rise by 0.18 - 0.59 m
- *Ocean acidification*: the acidity of the ocean could double (represented on the pH scale as decrease in pH of 0.3).
- *Changes in storm intensity, changes in ocean circulation*: predictions currently very uncertain (Pinnegar *et al*., 2009).

This will lead to a wide range of impacts on UK fisheries. This section focuses on a small number of these changes to introduce the challenges and opportunities that will face UK fishers while the next highlights the range of adaptation strategies available to the UK industry and the role of regulators in shaping these.[5]

Temperature is one of the primary factors, together with food availability and suitable spawning grounds that determine the large scale distribution patterns of fish. Since most fish species prefer a specific temperature range it may be expected that long-term changes in temperature and/or climate are accompanied by changes in the location and productivity of UK fish species. Recent warming in the north-east Atlantic has been accompanied by a northward shift in the distribution of fish species from southerly latitudes. Perry *et al.* (2005) demonstrated that the distribution of both exploited and non-exploited North Sea fishes have changed markedly over the past 25 years and concluded that further temperature rises are likely to have a profound impact on commercial fisheries.[6]

Looking forward, Cheung *et al.* (2009) anticipate numerous local extinction events as a result of these changes. Cold-water adapted species such as cod and herring are anticipated to suffer poorer recruitment (reducing the maximum sustainable yield) and shifts in distribution towards more favourable climatic conditions. There is evidence, for example, that they are moving further north and into deeper waters in search of more suitable temperatures (see Figure 10.1) (Dulvy *et al.*, 2008; Cheung *et al.*, 2009). Whilst these species are expected to be able to maintain sustainable fisheries in UK waters in the future, it is anticipated that these would be at much lower levels of fishing mortality than at present (Cook & Heath, 2005). At the same time there is evidence that warm-water adapted species such as sole, red mullet and seabass which are traditionally found in warmer European waters are becoming more common in the UK's southern seas (Pinnegar and Heath, 2010) and that these stocks have the potential to become an increasingly important component of the UK's catch.[7] Finally, it is anticipated that ocean acidification may have a profound effect on the UK's shellfish industry, with more acidic waters impeding the shell growth of commercially important species such as oysters, mussels and scallops. The physiological and population-level implications of ocean acidification are poorly understood, but shellfish fisheries have grown in importance to the UK in recent years and now represent more than 40% of landed value.

Figure 10.1: Changes in the distribution of selected North Sea species, 1980s-2000s



Top row: cod, a cold-water adapted species, middle row: sole, a warm-water adapted species and bottom row: plaice , a cold-water adapted species. Data collected by British North Sea otter trawlers, see Engelhard *et al.* (2008) for methods.

Source: Engelhard *et al.* (2008) for cod; G.H. Engelhard and J.K. Pinnegar (personal communication) for plaice and sole.

Shifts in the distribution of fish species[8] may have knock-on impacts upon commercial fisheries catches because of changes in location and spawning behaviour. For example fish populations may move away from (or towards) the areas where the fishing fleet traditionally operate which will affect the distance travelled by fishing vessels, fuel usage and the time spent at sea. There is also evidence that the behaviour of fish varies at different levels of light and temperature (Winger, 2005) and that the gear geometry and hence catchability of certain species can be greatly influenced by water depth (see Engås and Godø, 1989). Additionally, ocean acidification may change sound transmission in the ocean which may make certain species less vulnerable to capture through being better able to detect incoming trawl gear.

Adaptation and UK fisheries

There are a range of responses that may be expected to a changing marine environment and the adaptive strategies employed by fishers will depend on their individual circumstances and the incentives they face. In general, it may be expected that autonomous adaptation to climate change will be undertaken when it is in an individual's interest and power to do so. Whilst in some cases, private incentives to adapt should be a sufficient trigger for behaviour change and individuals will be guided to the efficient adaptation outcome by the price mechanism, in others the sum of autonomous adaptation responses may not lead to the socially efficient outcome. Reasons for this include a lack of adaptive capacity, the existence of institutional barriers to appropriate adaptation, the public-good characteristics of many adaptation measures and a lack of awareness about what adaptation measures should be undertaken (Cimato and Mullan, 2010). A selection of these challenges is considered below.

Adaptive capacity in the UK fleet

Faced with the challenges outlined in the preceding section, how will fishers respond? The answer is as varied as the industry is diverse. The UK fishing industry generated approximately GBP 204 million (gross value added) from quota and non-quota species in 2007. Nationally the landings of key quota species including nephrops, mackerel, monkfish, haddock and cod approached GBP 275 million in 2008 whilst landings of non-quota species including crabs, scallops and lobsters were worth almost GBP 110 million in the same period. There are substantial regional differences in the importance of the fishing industry to local economies as well as in the catch composition, technology, gear types and economic performance of UK fishing vessels. For example in 2008 average earnings per vessel for the over-40m pelagic[9] fleet were GBP 4.4 million whilst for under-10m vessels using passive gears[10] average earnings varied between GBP 3 000 and GBP 48 000 (Seafish, forthcoming).

Reflecting the heterogeneity of the UK's fishing fleet, the scope of individual vessels and crews to anticipate, autonomously adapt to, and benefit from the impacts of climate change vary widely. In many cases individuals acting from self interest will adapt efficiently to a changing marine environment. Large operations, like any business, will adjust their capital portfolio by investing in vessels, gears and quotas that maximise their long run profitability. Smaller operations may encounter more difficulty both in identifying and in pursuing their preferred adaptation strategies. The adaptation strategies chosen by businesses will be driven, to a large extent, by the institutional framework in which they operate (see Box 10.1 for an overview of the regulatory framework for UK fisheries).

Government can play a role in building adaptive capacity within the industry by providing information on the types of climate change impacts that may be anticipated so that the industry is well placed to autonomously adapt. The UK Government contributes to a number of projects that bring together information on climate impacts and disseminates this information to the public. These include the Marine Climate Change Impact Partnership (MCCIP),[11] Charting Progress 2[12] and OSPAR Commision's Quality Status Reports (QSRs).[13] In the future it may also be appropriate for the Government to invest in other adaptive capacity-building measures such as changing the geographic

resolution of weather forecasts to protect the health and safety of fishers if marine waters become more volatile.

Box 10.1 Fisheries governance in the UK

To fish in UK waters requires a registered vessel, a licence to fish with a particular gear type and, for quota species, a quota to land the catch. Quotas for EU vessels are allocated through the Common Fisheries Policy which agrees a total allowable catch for each fish stock each year as well as associated effort levels (in terms of days at sea) to catch the quotas. The total allowable catch, and the share of this allocated to the UK as quota, is agreed through a combination of scientific advice, political negotiation and the maintenance of "relative stability" in the historical level of fishing activity between member states.

The UK's quota is distributed to fishers in a two-tier system. Larger vessels (over 10 metres in length) are typically members of autonomous producer organisations and have fixed quota allocations which allow them to access a fixed share of the quota stock in a geographically defined area. The allocation of quotas among individual vessels varies between producer organisations, but there is a degree of transferability of fishing rights between vessels. Smaller vessels (under 10 metres) are referred to as the "inshore fleet" and typically share pooled quotas allocated via generic catch limits (usually monthly). The latter is essentially a regulated open access resource available to qualifying vessels.

Fisheries governance within UK waters is complex. The EU's Common Fisheries Policy, central government, the devolved administrations for Scotland, Wales and Northern Ireland, and local enforcement and delivery bodies (such as the Marine Management Organisation and Sea Fisheries Committees in England) all play a role in setting the rules to which fishers must comply. Governance arrangements are further complicated because some non-UK vessels have historical rights to fish in domestic waters (excluding the six nautical miles (nm) surrounding the domestic coastline) but are not necessarily bound by domestic regulations restricting fishing activity. The introduction of localised management measures that bind all vessels in UK waters requires the UK Government to negotiate changes through international channels in what is often perceived to be a protracted process. For restrictions in the area between 6-12 nm of the coast the UK must initiate bilateral agreements with the member states who fish in those waters whilst in the area between 12-200 nm any restrictions must be initiated by the European Commission and the agreement of all 27 countries in the European Union is required for any new restrictions to come into effect.

Institutional barriers to appropriate adaptation

An important role for government will be the removal of institutional barriers to adaptation. This can be achieved by mainstreaming adaptation into existing policies and addressing any inefficiencies within existing governance structures which may be exacerbated by climate change. To do this, the UK's governance structures should: (i) incentivise wealth creation in fisheries so that the productive value of the resource is captured rather than dissipated; (ii) sustain viable fisheries as part of a healthy and resilient marine environment; and (iii) provide the evidence and incentives for fishers to adapt to climate change in ways that benefit themselves, the economy and wider society. This "indirect" approach to climate change adaptation ensures that any "direct" measures taken to support adaptation (for example through the provision of subsidies to enhance adaptive capacity, see "Fishing subsidies" below) have appropriate incremental value. The UK Government is adopting a similar approach as part of its work on international development (see Box 10.2). Some of the institutional challenges posed under the current management structure are explored below.

The mismatch of species abundance, access to fisheries and the supply of quota

In the absence of institutional barriers fishers may be expected to adapt to the movement of fish species either by "following the fish" or by harvesting the species located in their traditional fishing grounds. For non-quota species, pursuing the latter strategy may involve purchasing new nets and licences and, as long as catch rates do not exceed the biological limits of species, this adaptive response may be expected to be appropriate at both the individual and societal level. An example of this type of adaptation is the recent creation of a UK anchovy fishery in the English Channel.[14] However, the adoption of this strategy for quota stocks will be more complicated. To pursue a quota species that has become newly abundant in their area fishers must access quota before they can target the species. Whilst there is some degree of transferability of quota within the UK – producer organisations distribute quota between their members (see Box 10.1) and quota is sometimes traded between producer organisations – trading does not take place in transparent markets and may be subject to high transaction costs.[15] These arrangements impede the efficient working of the market mechanism and may act as a barrier to autonomous adaptation by creating a mismatch between the abundance of the species and the supply of quota. In this scenario, if a fisher is unable to access quota for the newly abundant species in their area, or is unable to sell their quota allocation for a species that has moved out of their area, the optimal individual response may be to follow the species for which they already have quota, travelling further distances, incurring high fuel costs and potentially creating environmental damage. The adaptive strategy of pursuing the fish as they move to new areas may not be efficient at the societal level and would be an example of institutionally driven mal-adaptation.

These challenges are not confined to the domestic management of fisheries. For example Denmark holds much of the quota for North Sea whiting yet in recent years, large numbers of the species have been found off the United Kingdom's east coast. Once UK fishers have exhausted their supply of whiting quota any additional fish they catch, for example as by-catch when targeting other species, must be discarded even though much of the Danish-held quota goes unused. This represents a "lose-lose" situation as the stock's mortality rate is higher than that necessary to support the landings of whiting and the time spent discarding the fish costs, rather than generates, money for the fishing industry. In both examples governance structures need to ensure that fishers can adapt appropriately to the circumstances they face, for example by ensuring that quota can be traded efficiently and is priced transparently.

An additional challenge that results from the close proximity of European waters is the issue of access to fishing grounds. Once agreed, fishing rights are tied both to the species and a specific area of the sea. Fishers do not, for example, have access to the waters of other European countries unless they have historical rights in those areas. As a result in October 2009 Norwegian vessels, in pursuit of mackerel that are traditionally located in Norwegian waters but that, on this occasion, had travelled into the UK's Exclusive Economic Zone were escorted from UK waters by British enforcement authorities, despite holding quota for mackerel, because they did not have the appropriate access rights. As the movement of species becomes increasing common this issue of access to fish stocks may be faced on an increasingly regular basis.

There are a range of potential solutions to address the movement of (and access to) species. These include:

- The creation of efficient markets for trading quota both domestically and internationally

- The allocation of quota and access rights based on bio-geographically defined fisheries management units, rather than on the traditional geo-political location of the species

It should be noted that these options would potentially challenge the concept of "relative stability" in international fishing activity, a central consideration in the current Common Fisheries Policy. There is scope however, to reflect this concept in the design of governance structures, for example by leasing rather than selling quota allocations internationally.

Box 10.2. The UK's role in international development: approaching adaptation through better management

The UK's efforts at preparing for the effects of climate change are not confined to domestic waters. The Department for International Development (DfID) is working with developing countries in areas especially vulnerable to climatic shocks. Climate change is predicted to be particularly significant in Africa where many states are heavily reliant on the contributions that fisheries make to economies, food security and employment. Given the high degree of uncertainty surrounding the anticipated impacts of climate change, DfID's approach to adaptation in the fisheries of developing countries has been indirect, through the promotion of more effective fisheries that aim to capture and sustain resource wealth. Such fisheries can be built up through improved (primarily rights-based) management arrangements that tackle market failures and focus on optimising the asset value of resources over time, *i.e.* by rebuilding stocks, generating wealth and enabling fisheries to contribute to inclusive growth and food security.

Empirical evidence from well-managed, best practice fisheries, shows marked improvements in social, economic and environmental outcomes; an enhanced level of resilience that serves to buffer impacts from a range of exogenous factors. Resilient fisheries that are better able to withstand and adapt to external shocks, may also be expected to be better prepared to adapt to the kinds of impacts likely to emerge from future climate change.

In most cases, therefore, DfID believes that facilitating successful management outcomes from economic, social and environmental standpoints, can be regarded as an effective approach to adaptation. In many cases, however, it is not simply a question of managing fisheries better, rather it is about managing them differently. Creating incentives for fishers to invest in and conserve fisheries assets rather than racing to catch them are the key to effective fisheries and arguably represent amongst the most valuable contribution to climate change adaptation.

This box was written by Tim Bostock, Department for International Development, UK.

Targeting sustainable biomass

In addition to the existing challenges in ensuring fish stocks remain within biological limits, there is evidence that the maximum sustainable yield of cold-water adapted species in the North Sea is being eroded by climate change.[16] Whilst appropriate adaptation would require a reduction in harvest to match the decrease in stock productivity, the negotiation process by which EU quotas are agreed may not lead to the appropriate future reduction in quotas; even in our current climate, a large proportion of stocks have quotas which are above the sustainable level. For example, even though mortality in UK fish stocks is falling, the majority continue to be harvested at rates well above the levels expected to provide the highest long-term yield and discards mean that much of the mortality of UK fish stocks does not generate a positive economic return. In this case

climate change may exacerbate existing inefficiencies within the system and by supplying quota at inter-temporally sub-optimal levels, fishers are not provided with the appropriate incentive structure to adapt efficiently. Increasing the spawning biomass of fish species may be considered a "win-win" adaptation strategy since higher fish stocks will increase the catchability of the species,[17] reduce the negative externalities imposed on marine ecosystems (for example the skewing of food webs) and, by providing a larger "buffer zone" for the species may improve its ability to withstand climatic shocks.

Fishing subsidies

The EU's Common Fisheries Policy[18] is supported by a EUR 4.3 billion European Fisheries Fund[19] which aims to help secure a sustainable and profitable fisheries industry. The UK's share of the Fund is EUR 138 million, part of which is used to provide financial assistance to fishers in pursuit of a range of objectives including the reduction of overcapacity within the fleet and increasing the selectivity of fishing gears to reduce fishing mortality.[20] It is unclear whether payments made under the Fund or under the preceding Financial Instrument in Fisheries Governance scheme are effective in delivering improved environmental outcomes or whether the provision of this subsidy actually incentivises overcapacity and other undesirable outcomes within the industry.[21] The Fund has the potential to support the industry in facing a range of market failures including those posed by climate change. Examples of adaptive actions that could be financed through the Fund include the creation of a quota exchange mechanism to improve the liquidity of the domestic quota market or measures to improve the adaptive capacity of segments of the fleet (such as artisanal vessels) which may not otherwise be able to access the financial resources necessary to adapt appropriately. It should be noted however that the Fund could incentivise maladaptation, for example if socially inefficient measures are financed or if the market signals to which fishers are exposed are skewed.

The UK also provides a fossil fuel subsidy to some of its fishers.[22] This subsidy disproportionately benefits the fuel-intensive sectors of the fishing fleet which are widely viewed to be amongst the more damaging fishing practices, either due to their carbon footprints, their impacts on marine habitats and/or their impact on fishing mortality. In addition, the ongoing provision of fossil fuel subsidies may reinforce maladaptation by subsidising the fleet in pursuing species they have traditionally caught as they move across UK waters rather than changing their fishing practices.

Government (public good) adaptation

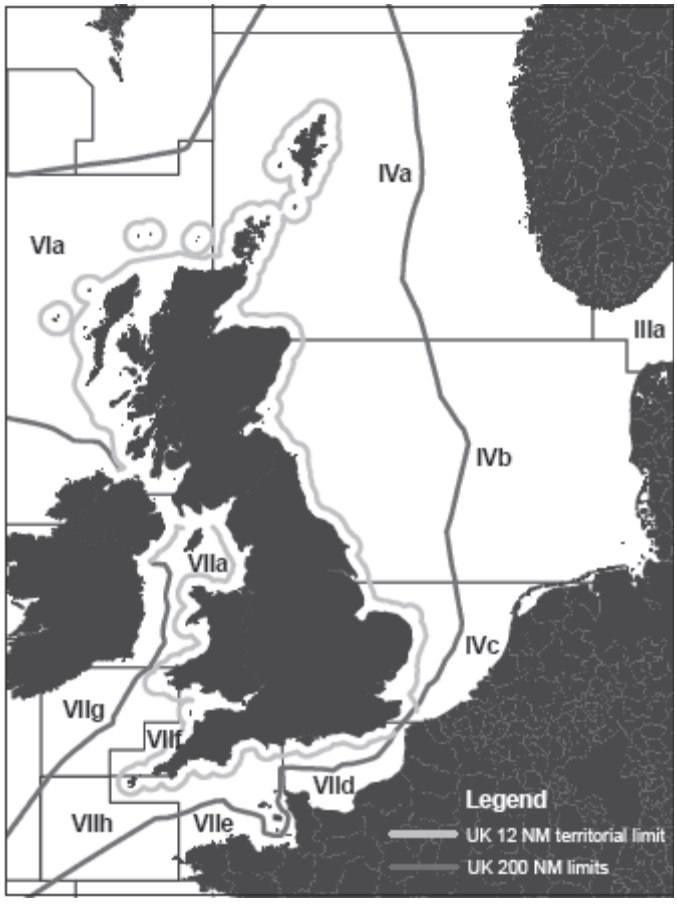
Some adaptive actions might have the nature of public or quasi-public goods, or result in social costs and benefits (i.e. externalities) that if not accounted for might not lead to the best outcome for society as a whole. In these cases private incentives will not be sufficient to trigger adaptation and government may be the most appropriate agent for undertaking action. For example in marine ecosystems, it is recognised that diverse ecosystems with balanced food webs may be better placed to adapt to climatic shocks. This resilience may be considered a public good since the benefits are diffuse, non-excludable and there are substantial positive externalities associated with resilient biodiversity. This section outlines measures that the government can undertake to support "green infrastructure" by boosting the resilience of marine habitats and ecosystems to future climatic shocks. Action may be a particular priority where climate or non-climate stresses risk permanent damage or extinction to marine species.

Local spatial protection measures

There are a number of localised protection measures in place that are designed to safeguard fish stocks in UK seas. These include the designation of permanent "no take zones" intended to protect fish spawning grounds and nurseries and "real time closures" where areas of the sea are temporarily designated if the catch of juveniles of certain species exceeds a pre-determined threshold. Permanent closures should be reviewed on a regular basis to ensure that the protection measures in place are fit for purpose and proportionate. For example, in a changing climate the changes in the distribution of fish species may result in a mismatch between a regulated geographic area and the specific habitat or species it was created to protect.[23] This rigidity may also restrict the effective targeting of any new species which move into these areas by local fishers, and governance structures must ensure that spatial protection measures do not outlive their usefulness. This flexibility is embedded in the design of real-time closures which ensure that juvenile fish are protected whilst the restrictions placed upon the fishing industry are minimised.

Many spatial protection measures are introduced through bye-laws by Sea Fisheries Committees in response to local circumstances. However, their jurisdiction extends only to 6 nm from the UK coast and it is often perceived that the restrictions they introduce simply displace fishing activity further offshore (see Figure 10.2 for a map of the UK's marine area). The process for introducing fisheries measures beyond 6nm is more involved: for measures in the area between 6-12 nm of the coast the UK must initiate bilateral agreements with the EU member states who fish in those waters and to introduce spatial protection measures in the area between 12-200 nm any restrictions must be initiated by the European Commission with the agreement of all 27 countries in the European Union. This process is often protracted and time-consuming and consequently the institutional arrangements act as a disincentive to the introduction of responsible localised management measures that would benefit both the industry and the species they target over the medium term. In doing so governance structures may undermine the confidence of the domestic industry that their long-term interests are being safeguarded. A streamlined process for the introduction of measures in UK waters would facilitate the introduction of local protection measures in response to emerging local evidence.

Figure 10.2: The UK's marine area and territorial limits



Source: Marine Management Organisation

Promoting ecosystem resilience

The UK has also designated a host of Marine Protected Areas including: Special Protection Areas designated under the EU Bird Directive, Special Areas of Conservation designated under the EU Habitats Directive, and Marine Conservation Zones designated under the UK's Marine and Coastal Access Act. Restrictions under the latter will be tailored to the specific conservation objectives for the sites and ongoing fishing activity is not necessarily incompatible with the designation of a Conservation Zone. It is hoped that the network of Marine Protected Areas will help the natural environment adjust to climate change by supporting robust marine habitats and ecosystems that are resilient to a changing climate. Recent policies, such as the designation of Marine Conservation Zones have ongoing monitoring and periodic reviews built into their design. For earlier policies a streamlined review process to amend or de-designate spatial protection measures would be a useful tool to ensure any restrictions are consistent with the stated objectives of the sites and are based on the best available evidence.

An integrated approach to marine management

The UK Government's introduction of the Marine and Coastal Access Act (2009) reinforces its commitment to a strategic approach to managing UK waters. The fishing sector is one of many industries that will be affected by changes to the marine environment, and the UK's regulatory framework recognises both the potential for competition for marine resources and the scope for synergies that may exist between these industries in an evolving climate. Consequently the UK's approach to marine management, supported by the introduction of a new marine planning system, includes the integration of robust wealth-creating fisheries alongside nature conservation measures and the recognition that marine assets are involved in complex and dynamic interactions that may potentially become more volatile as the marine climate changes. Other legislation that supports the UK's strategic approach to marine management includes the EU Marine Strategy Framework Directive which will explicitly embed the pursuit of healthy fisheries within a wider environmental context and foregrounds an ecosystems-based approach in the management of marine resources. Finally the UK's Climate Change Act (2008) enhances the UK's ability to adapt to the impact of climate change through the regular publication of climate change risk assessments and adaptation action plans.[24] In doing so domestic legislation is supporting individuals and businesses to autonomously adapt to climate change by providing information and addressing the uncertainties surrounding the anticipated impacts of climate change.

Better adaptation through information provision

There are two important aspects to any adaptation decision: what to do and when to do it. Answering these questions involves understanding the anticipated impacts of climate change, the costs and benefits of a range of adaptation strategies and an appreciation of the uncertainties that are inherent in a changing climate. The government has an important role in facilitating efficient adaptation and can help people and business by explicitly addressing information failures and identifying strategies for dealing with uncertainty.

Addressing information failure

The government may address information failure in a number of ways. These include investing in research on the anticipated impacts of climate change and ensuring the efficient dissemination of the existing evidence base. The UK Government aims to achieve the former by investing in scientific research (see above on building adaptive capacity in the UK fleet) while the latter will be achieved by raising the awareness of stakeholders of existing research on climate related impacts. This may be achieved for example through the co-ordination of stakeholder engagement and the requirement under the Climate Change Act (2008) to publish climate change risk assessments to ensure that marine industries base their adaptation decisions on the best available information.

Addressing inherent uncertainty

The efficient dissemination of climate related science will go some way to enabling the fishing industry to adapt to the environmental changes they face. However, the anticipated impacts of climate change are inherently uncertain and the existence of tipping points, feedback mechanisms and the limitations of existing scientific models

means that the impacts of climate change on a particular fishery or in a local area may be difficult to predict. As a result, adaptation decisions, which involve comparing the costs of adaptation to the short- and long-term benefits will also be inherently uncertain. For example Cimato and Mullan (2010) identify strategies for decision making in the presence of pervasive risk, including the prioritisation of "no regrets" or "win-win" adaptation strategies.[25] For example in the face of significant uncertainty as to the expected impacts of climate change a national strategy of targeting a reduced mortality rate for a species thought to be vulnerable to the impacts of climate change may be superior to a strategy of investing in specific gear types on the basis of an anticipated shift in the distribution of species that may not materialise. Government can play a role in supporting efficient adaptation in the fishing industry both by delivering adaptation measures directly and by facilitating the industry in pursuing efficient autonomous adaptation in a necessarily uncertain investment climate.

Conclusion

The marine environment is subject to a range of pressures from anthropogenic and natural sources. Marine users and the ecosystems on which they rely are involved in complex and dynamic interactions that may become more volatile as the marine climate changes. For example the combination of sustained pressure from commercial fishing combined with movement in the optimal climate space for a particular species may result in a traditionally harvested fish species approaching a biological tipping point and risking collapse. Government and industry will need to work towards the common goal of securing healthy fish stocks as part of a wider strategy to pursue biologically and economically sustainable seas. In support of this aim the fisheries management regime must:

- create incentives for wealth creation in fisheries where the productive value of this important natural resource is captured rather than dissipated;
- sustain viable fisheries as part of a healthy and resilient marine environment; and
- provide the evidence and incentives for fishers to adapt to climate change in ways that benefit themselves, the economy and wider society in the face of localised and potentially unanticipated changes in marine species.

The adaptive strategies employed by individuals will depend upon the personal and institutional incentives they face. The role of government is to ensure that society is adapting to the effects of climate change in an appropriate way and that the institutional framework – in particular, the management of quotas and the designation of Marine Protected Areas – is sufficiently flexible to accommodate changes to the underlying ecosystems without diluting the incentives to adapt appropriately. The Government can help to achieve this through:

- the identification and removal of institutional barriers to autonomous adaptation, ensuring that fisheries management measures facilitate and reward appropriate adaptation and minimise the instances of maladaptation;

- the full integration of fisheries management within the wider text of marine biodiversity, for example by introducing and supporting robust marine habitats and ecosystems that are resilient to a changing climate; and

- the provision of information, so that fishers are well placed to pursue appropriate adaptation strategies.

Notes

1. The opinions expressed in this paper are solely those of the authors and do not necessarily represent Defra policy.
2. The authors are grateful to the large number of people who reviewed and contributed to this paper and wish to thank John Pinnegar at Cefas and Tim Bostock at DfID in particular for their efforts.
3. See Cimato and Mullan (2010) for an overview of the principle of adaptation policy.
4. See for example, *www.mccip.org.uk/*, *www.ospar.org* and *www.defra.gov.uk* for forthcoming research.
5. For a detailed analysis of the anticipated impacts of climate change on UK fisheries please see Pinnegar et al. (2010) and Pinnegar and Heath (2010).
6. The Marine Climate Change Impact Partnership's 2007-2008 Report Card (available at *www.mccip.org.uk/arc/2007/PDF/ARC2007.pdf*) provides a comprehensive assessment of the anticipated impacts of sea temperature and other climate-induced environmental factors on commercially important UK fish species.
7. For example, biomass estimates for seabass in the Western Channel have quadrupled from around 500 t in 1985, to in excess of 2100 t in 2004/2005, with populations also increasing rapidly in the Eastern Channel, North and Irish Seas
8. See Cheung et al. (2009) for a prediction of the future distribution and productivity of fish stocks.
9. Pelagic species are found in the water column with little contact with or dependency on the seabed. Typical species include herring, mackerel and blue whiting
10. Passive gears include pots and creels. These are gears that are dropped and left in place for a period of time and rely on the movements of the fish to effect their own capture. These differ from mobile gears (such as trawls or nets) which are dragged along the seabed or through the water column by vessels
11. Available at *www.mccip.org.uk/arc/2007/PDF/ARC2007.pdf*
12. Forthcoming at *http://ww2.defra.gov.uk*
13. The OSPAR QSR 2010 has a particular focus on climate change and will be published in September 2010 (see *www.ospar.org*). See also OSPAR QSR assessments on the Impacts of Climate Change on the North-East Atlantic Ecosystem (*www.ospar.org/documents/dbase/publications/p00463_Impacts%20of%20Climate%20Change.pdf*) and on Climate Change Mitigation and Adaptation (*www.ospar.org/documents/dbase/publications/p00464_climate%20change%20mitigation%20adaptation%20final.pdf*)
14. Anchovy stocks in the English Channel (ICES area VII) are quota free unlike in other areas such as ICES areas VIII, IX and X where they are subject to quotas.
15. For example in drawing up legal contracts for the exchange of quota allocations.
16. Cook and Heath (2005) estimate that the maximum sustainable yield of cod has decreased at a rate of 32 000 tonnes per decade since 1980
17. A more abundant species would be expected to result in a higher catch per unit of effort and consequently lower average fishing costs

18. See *http://ec.europa.eu/fisheries/cfp_en.htm* for more information

19. EUR 4.3 bn is available over the period 2007-2013. For more information see *http://europa.eu/legislation_summaries/maritime_affairs_and_fisheries/fisheries_sector_organisation_and_financing/l66004_en.htm*

20. Selective fishing gears allow the target species to be caught without catching other species as by-catch. Due to quota restriction much by-catch has to be discarded overboard even if the fish are already dead

21. Globally fisheries subsidies amount to approximately USD 30 billion per year. At the same time it is estimated that the industry is missing out on approximately USD 50 billion per year in forgone rents and that, with better management, at least USD 80 billion of new revenues could be generated (World Bank, 2008).

22. UK subsidies apply to North Sea beam trawl (over 300 kW), area VIIa nephrops twin-rig trawl, Irish Sea demersal trawl, UK pelagic (over-40 m), UK pelagic (10-40 m) and potters and creelers (over-12 m)

23. For example, a "Plaice Box" established in 1989 to protect nursery grounds in the Wadden Sea is now almost entirely empty of the species it was set up to protect (see van Keeken et al., 2007)

24. See *www.defra.gov.uk/environment/climate/legislation/adaptation.htm* for more information

25. "No regrets" options are those that deliver benefits today regardless of the extent of climate change impacts in the future; "win-win" options reduce vulnerability to climate change whilst also contributing to the achievement of other social, economic or environmental goals (Cimato and Mullan, 2010). See also the Pew Center (2009) for a detailed discussion.

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Chapter 11

Korea's effective approach to adapting climate change in the fisheries sector

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Climate change has become an issue of increasing importance in Korea, as an average sea surface temperature has risen significantly over the last decades and affects fisheries production and the distribution of fish stocks. This is of particular concern to fishers and coastal communities as they experience the effects of climate change on a regular basis.

The Korean government has established national policies and strategies under the "Green Growth" framework, which is one of the top priorities of the country. They include the "Comprehensive Marine and Fisheries Policy Strategies for Climate Change" established in 2007, the creation of the "Council for Responding and Adapting to Climate Change in the Agriculture, Forestry, and Fisheries" in 2008, and the "Third National Master Plan of Fisheries Promotion Policies 2010-2014". Such plans are expected to enable more sustainable and flexible fisheries in Korea, as well as ensure a stable supply of seafood as fisheries is one of the most important food industries in Korea.

This paper addresses how climate change is affecting the marine ecosystem in Korean waters as well as fisheries production and distribution. It further discusses how Korea has dealt with climate change in the fisheries sector, and how the country will address future challenges.

Introduction

Fisheries are affected by many environmental factors related to climate change. Fishing grounds are distributed throughout Korean waters and their resilience depends on many factors such as temperature, oxygen, salt, and so on. Korea has a variety of fisheries resources, as it is surrounded by seas, has a peninsula, and each coast has different characteristics from both oceanographic (water depths, seabed shape, temperature, currents, etc) and biological perspectives. As Korea has four distinct seasons, access to fisheries resources vary accordingly (Choi, 2008; NFRDI, 2006; Park, 2008).

Climate change has become an issue of increasing importance in Korea, as an average sea surface temperature has risen significantly over the last decades and affects fisheries production and the distribution of fish stocks. This is of particular concern to fishers and coastal communities as they experience the effects of climate change on a regular basis.

This paper addresses how climate change is affecting the marine ecosystem in Korean waters as well as fisheries production and distribution. It further discusses how Korea has dealt with climate change in the fisheries sector and how the country will address future challenges.

Effects of climate change on Korean coastal fisheries

Sea surface temperature rise in Korean waters

The sea surface temperature in Korean waters has risen over the last 60 years; the yearly average increase has been 0.008°C. The temperature has recently begun to increase more quickly, represented by an average increase over the last 30 years has been 0.019°C, which is more than double the increase rate over the last 60 years. However, the annual increase in sea surface temperature varies from year to year, between 0.0074 and 0.0254°C. In addition, the rate of increase is different from coast to coast, with the southwest coast being somewhat cooler. A similar pattern is observed in water temperature at a depth of 50 metres from the surface. The temperature has increased by 0.25°C in the eastern coast and 0.41°C in the southern coast, although it has decreased by 0.36°C in the western coast.

This change in water temperature has increased the number of zooplankton, which in turn has increased the abundance and catch of warm water fish stocks. It also has numerous changes in the marine ecosystem, such as the frequent occurrence of typhoons and red tides (Kim, 2008; Park, 2008; Kong *et al.,* 2009; Yong *et al.,* 2010).

The effects of warmer water temperatures on Korean fisheries

Climate change is altering ocean conditions, which leads to productivity changes for marine fisheries. Marine fisheries are very sensitive to changes in temperature, oxygen and many other conditions. It is reported that there are 300~400 fish species living in Korean coastal waters, of which about 100 species are harvested for commercial purposes. However, recent reports (Kim, 2008; OECD, 2008; Park, 2008) indicate that the abundance of major fish stocks has decreased, as opposed to those of sub-tropical fish stocks. The catch of warm water species, including mackerel, anchovy, and squid, in coastal fisheries has increased, while that of cold water species, such as pollack and cod,

has decreased and new species, such as bluefin tuna, have emerged in Korean waters. Also, saury pike and mackerel, which are usually found around Korea's southern coast (around the Island of Jeju), have moved their way up to the eastern shores of the Korean peninsula. Along with this rare appearance of summer fish stocks, the catch of traditional winter species has reduced significantly. A good example of this is the disappearance of pollack, which has long been an essential part of the country's winter diet (Park, 2008).

Specifically, the 2007 fisheries production of warm current species such as squid and chub mackerel increased by 30% compared to 2006 because of the water temperature rise in Korean waters. Looking at the changes in the distribution of major winter species between the mid-1970s and late 1990s, it was observed that squid had moved northward in the month of February. Notably in the eastern coast, squid has moved 60 miles northward on the coast of Gangwon Province. Historically, there were almost no fishing grounds in the eastern coast during March in the mid-1970s, but since the late 1990s, fishing activities have been taking place on the coast from Gangwon to its southern neighbour Kyungbuk Province. Gradually, squid has been found farther northward than ever before as a result of increasing water temperatures (Joung, 2007; Joung, 2009; Park, 2008, Yeong *et al.,* 2010).

In the meantime, sub-tropical fish species are appearing in the sea areas around Jeju in the early winter, but the actual sizes of the caught fish, such as yellow corvina, cutlassfish and saurel, are getting smaller, which is believed to be affected by climate changes.

Effects on the marine ecosystem and seafood safety

Accelerating climate change has affected the marine ecosystem of Korean waters. The number of toxic jellyfish has increased in recent years and the damage they cause to fish farms and summer tourists also increase every year. The number and size of major fish species have decreased and new types of fish species are starting to be caught. Fisheries management policy should now develop strategies to effectively cope with these changes (Zhang *et al*., 2010; Yeong *et al.,* 2010).

In addition to environmental changes at sea, climate change has affected land based structures. For instance, the Uljin nuclear power plant located in the coast of Kyungbuk Province, has been recently disrupted by jellyfish which obstructed a seawater exit required for cooling the plant. The jellyfish are warm water species that have not previously inhabited the eastern coast. At the same time, poisonous jellyfish are appearing earlier than had been the case before, creating significant damage and interrupting summer tourism (Jhang *et al.,* 2010).

Recently, seaweeds such as gulfweed which used to live in inshore areas have decreased and lime seaweeds like coral have been taking their place instead. This change has led to alterations of the habitat in the spawning area, affected spawning patterns as well as the migration path of many fish stocks. Consequently, some small-scale fisheries are experiencing difficulties due to decreased catches that they rely on for their livelihood (Jung, 2009; Yeong *et al.,* 2010).

In addition, there are increasing concerns over the safety of seafood related to climate change, especially regarding shellfish. The possibility of shellfish contamination has recently become an issue due to extended periods of exposure to pollutants through torrential rainfalls in summer that have intensified due to climate change. The emergence

of new sub-plankton that had not previously appeared on the coast has led to shellfish toxins, increasing the risks of food poisoning.

Fisheries adaptation strategies to climate change in Korea

Context of adapting fisheries to climate change: Review of fisheries management measures in Korea

In Korea, fisheries are managed through technical measures such as closed season, no-fishing zones, mesh size regulations, etc., as well as input controls based on the permit system. In addition, an output control system has been utilized through the establishment of Total Allowable Catches (TAC) since 1999. In order to address vessel overcapacity, decommissioning schemes have been implemented since 1994. In addition, a community-based fisheries management system has been put in place in since 2001 (OECD, 2006).

However, there still remain some limitations in the conventional fisheries management system. These include a limited scientific evaluation on fish stocks and the effects of management measures on the stocks, unclear management objectives and as a consequence, lack of coherence among management measures. The coherence among coastal and ocean management in general, as well as conflicts among fisheries and regions are still challenging issues.

To address these issues and to rebuild fish stocks in a more systematic and comprehensive manner, the Fishery Resources Management Act (FRMA) was enacted in April 2009. This Act provides a legal basis for fishery resource management and stock rebuilding programs. Specific objectives of the FRMA are to strengthen stock assessment and research in the fisheries sector; to manage fishery resources in more effective and efficient way; and, to implement more comprehensive fish stock rebuilding plans. The main characteristics of the FRMA include: (i) strengthening research and assessments of fisheries resources; (ii) establishing a Basic Fisheries Resource Management Plan every five years to set med-term and long-term goals and to provide guidance for the yearly operation of fisheries management policies; (iii) self-regulation by fishers or community-based fisheries management is emphasized, such as institutionalization of dispute settlement process between fishers; and (iv) international principles such as promoting international cooperation, sharing information on fisheries resource management, using environmental-friendly fishing methods and precautionary approaches are incorporated into the FRMA.

Even though the Act does not address explicitly address the issue of climate change, adaptation measures will be developed and incorporated into the fisheries management master plan that is to be established every five years. In addition, it is noted that an ecosystem approach to fisheries management, which is embedded in the FRMA, will contribute to fisheries adaptation to climate change in Korea.

Against this backdrop, the Korean Government has developed policies to deal with climate change in the fisheries and aquaculture sector over the last couple of years that aim to achieve sustainable fisheries while responding to the effects of climate change. They also include efforts to mitigate greenhouse gas emissions from the fisheries and aquaculture sector under the national agenda of "Green Growth" that has been a top priority of the current Lee Myung-Bak administration. Examples of the policies and strategies which are described in the following section include:

- the Comprehensive Marine and Fisheries Policy Strategies for Climate Change established in 2007,

- the creation of the Council for Responding and Adapting to Climate Change in the Agriculture, Forestry, and Fisheries in 2008, and

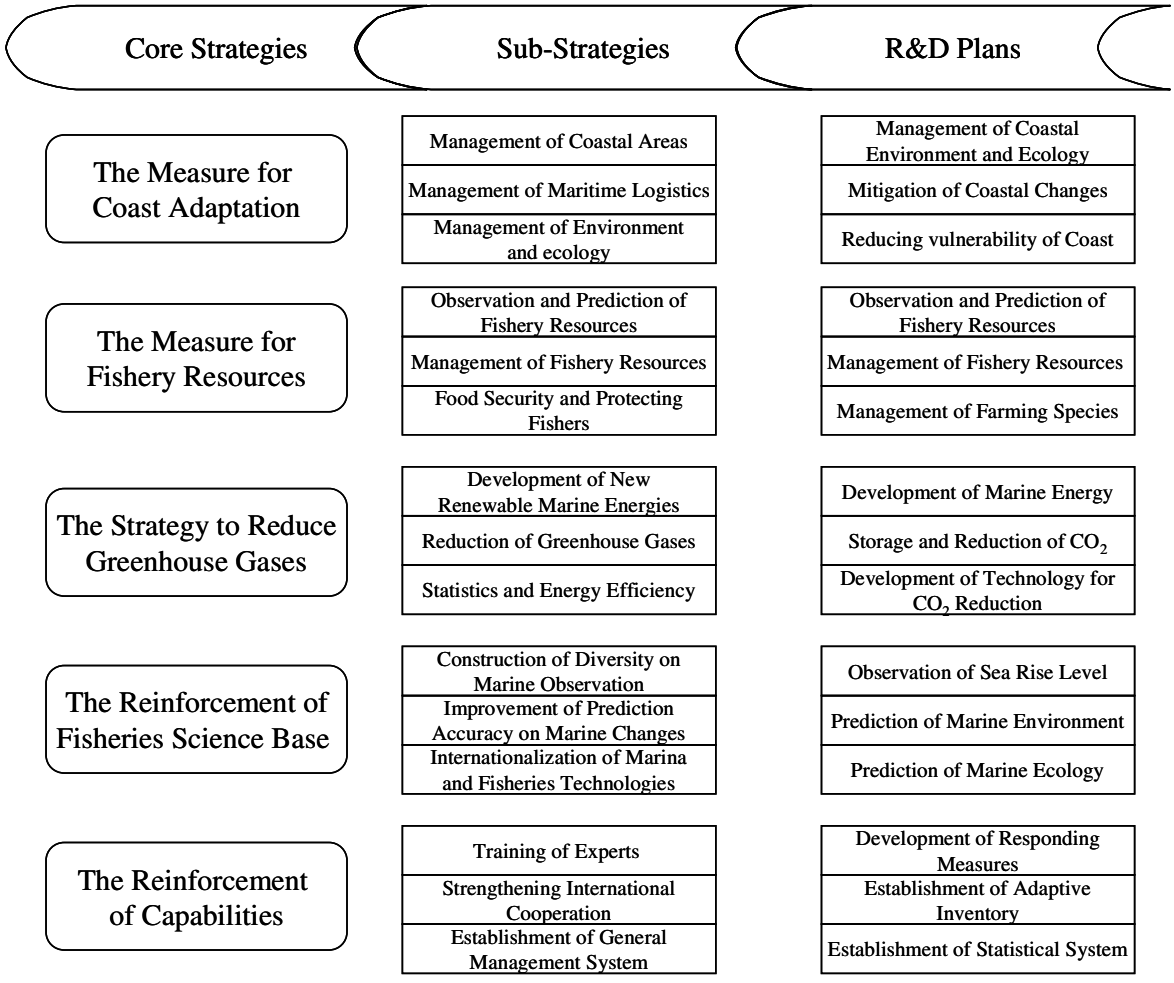
- the Third National Master Plan of Fisheries Promotion Policies 2010-2014. These strategies and adaptation measures have been incorporated in the National Integrated Plan for Responding and Adapting to Climate Change of 2008 and the National Action Plan to Adapt to Climate Change of 2009. Details of these plans are discussed in the following section.

Comprehensive Marine and Fisheries Policy Strategies for Climate Change (2007)

The Comprehensive Marine and Fisheries Policy Strategies for Climate Change of 2007 aims to deal with the changes taking place in the marine ecosystem. More specifically, this refers to measures designed to protect the lives and property of coastal communities by establishing infrastructure and systems to cope with potential climate change induced disasters such as floods, tsunamis and coastline loss; to contribute to mitigation of global warming through developing technologies to capture greenhouse gases in the ocean; and, to strengthen the monitoring and forecasting capacities regarding changes in the marine ecosystem.

To achieve such goals, specific measures were established in five core strategy areas illustrated in Figure 1. The five core areas include: measures to adapt the coastline to climate change and enable the construction of secure maritime spaces; measures to adjust to changes in fish stock abundance; strategies to secure carbon sinks in the ocean while also reducing greenhouse gas emissions; reinforcing marine and fisheries science in order to improve the ability to observe and predict climate change; and strengthening the capacity to adapt to climate change. In addition, research and development plans were also established so as to support the implementation of these strategies.

Figure 11.1 Strategies and R&D Plans for Climate Change



National action plan to adapt to climate change (2009)

The Council for Responding and Adapting to Climate Change in the Agriculture, Forestry, and Fisheries was established in 2008 and focussed on conducting research regarding the creation of artificial underwater seaweed forests, developing farming technologies for new aquatic species, establishing a climatic damage warning system, and constructing a marine ecosystem monitoring system.

These actions have been incorporated into the national climate change adaptation strategies. The National Integrated Plan for Responding and Adapting to Climate Change, established in 2008, provided the vision and direction for national adaption policies to climate change. Based on the Integrated Plan, the National Action Plan to Adapt to Climate Change was developed in 2009. Adaptation measures for the fisheries sector were also included in these plans.

These strategies include the development of capture fisheries techniques to take advantage of emerging warm water species while maintaining principles of sustainable fisheries. Concurrently, the development of fish farming technologies for new species with a greater tolerance to high temperatures and which also have a high commercial

value (e.g. bluefin tuna) is being pursued. The fish disease control system is a part of these strategies and aims to detect fish disease in a timely manner, to control virus outbreaks in farming sites, and to develop vaccines for emerging viruses. Furthermore, as part of the stock recovery and enhancement programs, marine ranching will be expanded with a view to increasing fish production so as to diversify sources of income of fishing communities. The construction of underwater seaweed forests is also proposed in order to provide fish with adequate spawning grounds while also contributing to the absorption of greenhouse gases. Specific details of the adaptation measures are as follows:

- In general, developing technologies to detect and catch warm water species through fishing gears that can selectively catch target species, and reduce the likelihood for bycatch.

- Improving stock assessments in the deep sea on the eastern coast within depths of between 200 metres and 1 000 metres, developing fishing gear to target the species (e.g. deep sea draft net) while also managing stocks in a sustainable manner.

- Reducing by-catch and discards from capture fisheries while also exploring new ways of utilizing unavoidable by-catch other than direct human consumption; this may include new functions.

- Developing technologies to farm new aquatic species that possess a high tolerance to high water temperatures and which also have significant commercial value. This may include species such as bluefin tuna, stary flounder, abalone, seaweeds and saltwater aquarium fish.

- Strengthening a fish disease control system that includes monitoring and detecting disease at farming sites in a timely manner while also developing new vaccines for evolving or new diseases.

- Expanding marine ranching programs along the coastal zone in order to rebuild fish stocks and contribute to the economy of coastal communities. Consideration on the ecosystem effects of juvenile fish release programs and installations of artificial reefs will be emphasized.

- Conducting research to establish underwater seaweeds forests, consisting of various sea weeds, in order to deal with marine bleaching issues (e.g. bleached coral disrupts the surrounding ecosystem) while contributing to the capture of greenhouse gases.

Conclusion and policy implications

Climate change is an inevitable challenge for Korean capture fisheries and aquaculture production. In this regard, the Korean government has established national policies and strategies under the "Green Growth" framework, which is one of the top priorities of the country. Such plans are expected to contribute to more sustainable and flexible fisheries policy in Korea as well as ensure a stable supply of fish and seafood, particularly given that fisheries are one of the main contributors to the food industry in Korea and a major source of protein for the population.

Research and development will be strengthened to increase the country's adaptive capacity to the effects of climate change, while maximizing new opportunities for growth. In addition, expanding the community-based fisheries management system will provide important non-scientific knowledge for making policies and plans more relevant and enabling policy reform while contributing to climate change adaptation.

Based on the Korean experience and discussions in other national and international fora, the following factors need to be taken into account when developing strategies for adapting fisheries to climate change.

- Inter-disciplinary research - including the biological, social and economic realms - is needed to strengthen the analysis on the potential effects of climate change on local and regional fish stocks as well as the socio-economic consequences for coastal or other communities. As such, the reallocation of research funds may be expected. An exchange of information obtained from monitoring and research on ecosystem effects of climate change is important. In this regard, the development of effective national and international monitoring systems for marine ecosystems and fish stocks is required in a changing climate. It is also important to ensure the appropriate interpretation of research results so that fisheries policy makers and managers can adequately consider all factors in their decision making and management processes.

- Fisheries and coastal infrastructure should be improved to deal with climate change impacts, For example in response to shifting fish populations. The fishing industry will need to consider developing faster, longer-range fishing vessels, installing on-board processing facilities to replace endangered coastal ones or use floating processors when feasible, and find alternative means of transport when coastal roads are flooded and alternate routes are not possible.

- Stakeholder involvement is crucial in developing adaptation strategies as it contributes to addressing the inevitable re-distribution of costs and benefits as fish stocks move and various species becomes more or less abundant. This also serves to enhance buy-in and compliance to policy changes. Local fisher's experience and knowledge will also be beneficial to better designed adaptation strategies.

- Establishment of institutional mechanisms to enhance the adaptation capacity of the fishing industry is required so that they have the flexibility to "follow the fish" – so that can to move within and across national boundaries to deal with stock distribution caused by climate change.

- Preparation of contingency plans for segments of the fisheries sector that might not be able to adapt, particularly for disadvantaged areas and small-scale fishers lacking mobility and other alternatives.

- Integration of fisheries management into the integrated ecosystem and coastal zone management to ensure that fisheries issues are taken into account when dealing with climate change impacts on oceans and coastal areas.

- Realizing the potential of aquaculture production as one element of a climate change adaption strategy.

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Chapter 12

Chinese Taipei: the impact of climate change on coastal fisheries

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This chapter describes the impact of climate change on Chinese Taipei fisheries and introduces how Chinese Taipei addresses the challenges. Accelerating sea surface warming in the waters surround Chinese Taipei since the 1980s has not only diminished winter migratory fish stocks year on year, but also caused such changes as displacement of fishing grounds, species regime shifts and increased the vulnerability of the marine ecosystem. The marine ecosystem and fisheries have to face the problem of the expansion of fish stocks from the south and withdrawal of fish stocks from the north. In addition, the numbers of large fish at high trophic levels have decreased under pressures from several decades of fishing activity while small pelagic fish have shown a relative increase. As the numbers of small pelagic fish show much greater inter-annual fluctuations than those species of larger size or longer lifespan, this is likely to weaken the structure of marine food (fish) pyramid even more. Meanwhile, frequent extreme-weather events and climatic variability during the warming process will damage the Chinese Taipei fishery more. Under such circumstances, traditional fishery management measures will not be able to adapt to the problems caused by climate change. External precautionary and adaptation measures need to be introduced to reduce its impact.

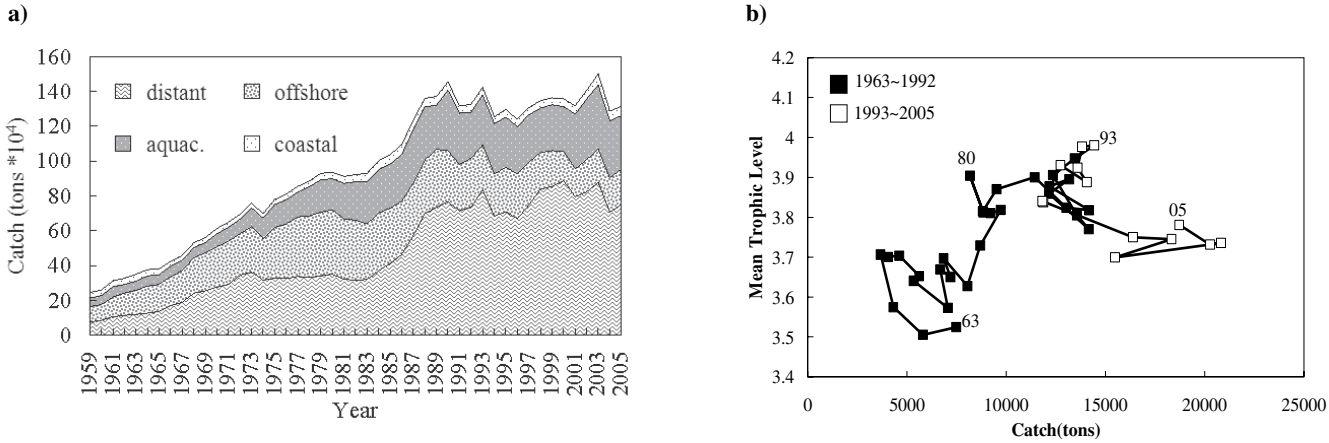
Introduction

Fish stocks around the world are almost all under human fishing pressure and fishing mortality is the major factor causing depletion of fish stocks. According to the Food and Agriculture Organization's (FAO) report, about half of the stocks in the oceans were fully exploited and one-quarter were either overexploited or depleted with no possibilities in the short or medium term of further expansion (Pauly and Christensen, 1995). The FAO capture fisheries data show that the steady decline of mean trophic levels (MTL) of fish communities is a global phenomenon (Tian *et al.*, 2006). All over the world, catch compositions have gone from from high trophic levels, larger size and long lifespan to low trophic levels, smaller size and short lifespan. The global rate of decline in MTL in the three oceans is about 0.1 trophic level per decade.

In addition to the human impacts, another global impact on fish stocks is from climate change. Climate change may affect the seasonality of biological processes and alter marine food webs with unpredictable consequences for fish production. For small pelagic fish stocks, such as anchovy, sardine, pilchard and squid, the effect of climate variability is decisive over that of fishing mortality. The phenomenon of "regime shift" and "global synchrony" in fish society were found in major small pelagic fish stocks over the world (Kawasaki, 1989; IGBP, 2003). The two major factors combined, *i.e.* fishing and climatic impact, determine the trend of fish stock fluctuations. In most cases it is difficult to separate out the impact of human activities from that of the climate. However, no matter how difficult it is to distinguish, the influence of the climate has always been there and will become more decisive as the rate of global warming accelerates.

The Chinese Taipei fishery produces more than 1 million tons annually (Figure 12.1a), and it consists of four components: the coastal, offshore, distant-water and aquaculture fisheries. Like other marine ecosystems, the coastal waters of Chinese Taipei have been overfished for several decades. Any additional threats or even disadvantages to the marine ecosystem brought about by climate change will be fatal to the sustainability of the fishery, which directly supports the livelihoods of more than 320 000 fishermen. This paper provides information about cases of climate change affecting both the coastal and aquaculture fisheries in Chinese Taipei, and discusses possible adaptation strategies.

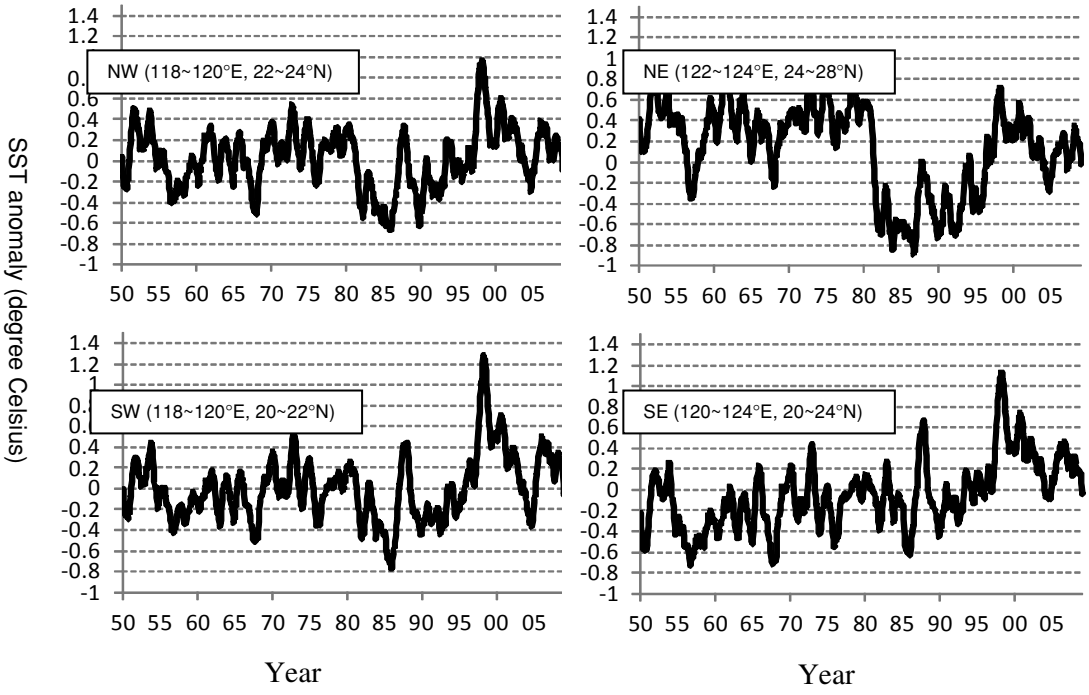
Figure 12.1. Total fishery production (a) and MTL indices of catch from coastal fisheries (b) in Chinese Taipei 1963-2005



Physical change in the coastal environment

The coastal and offshore fishing grounds of Chinese Taipei are located in one of the hotspots of climate change as indicated by the amplitudes of sea surface temperature (SST) warming. The SST anomaly in the four quadrants of waters surrounding Chinese Taipei during the recent half century ranged from 1.6 C to 2.0 C. Except for an abrupt change in the north-eastern waters in 1981, all of them rose in synchrony and the speed of warming seems to accelerate from the mid 1980s (Figure 12.2). The areas with negative anomalies were mainly located in the regions outside the ridge of the continental shelf, while the regions showing higher positive were mainly in the East China Sea. Therefore, the highest rising amplitudes of SST in recent decades were in the north-west continental shelf, followed by southern strait and then the deep sea. The mechanism behind such rises is the diminishing of the China Coastal Current and enhancement of the Kuroshio Current.

Figure 12.2. The rising patterns of 11-month sea surface temperature anomalies (baseline=1970-2000) in the waters surrounding Chinese Taipei



Moreover, behind the rising trend of SST warming the intensity, frequency and seasonality of climate patterns (*e.g. El Niño* events) and extreme weather events (*e.g.* floods, droughts, storms and cold spells) have been altered, which may disrupt fishery and aquaculture. Typhoons are the number one weather disaster in Chinese Taipei. They have occurred on average 3-5 times a year over the last 100 years, but the 10 strongest typhoons have been in the last 10 years. More frequent and intense typhoon-derived floods will increase the vulnerability of aquaculture areas and affect the operation of the coastal fishery.

Impact on fishery production

Both the warming trend and the frequency of extreme events will have an impact on the stability of related marine resources and fisheries as a result. However, as mentioned above, it is difficult to distinguish this impact from that of human activities, unless there is significant evidence from the fishery that climate change is the cause. Table 12.1 summarises a number of cases where there is such evidence that changes were caused by SST warming. They cover 14 species in 5 capture fisheries and 2 species in mariculture (Lee, 2004; Lu *et al.*, 2001).

Table 12.1. Cases of impacts by warming trend of SST

Paired purse seine	1958-2008	Mullet (*Mugil cephalus L.*)	decrease > 90%	northward shift of winter migration
	1981-2008	Pomfret (*Parastromateus niger*)		
Mackerel purse seine	1982-2008	Chub mackerel (*Scomber japonicus*) Jack mackerel (*Trachurus japonicus*) Redtail scad (*Decapterus kurroides*	drop from 60-75% to 25-40%	warm-water species predominate over cold-water species
		Spotted mackerel (*Scomber* Round scad (*Decapterus lajang*)	increase from 25-40% to 60-75%	
Trawl	1982-2008	Anchovy (*Engraulis japonicus*) Anchovy (*Encrasicholina punctifer*) Anchovy (*Encrasicholina heteroloba*)	North: >90% drop to 5-20%, South: 100% replaced by *E. punctifer and E. heteroloba*	same as above
Tuna offshore longline	1977-2008	Skipjack tuna (*Euthynnus pelamis*) Yellowfin tuna (*Thunuus albacares*)	increase 10-20% (relative)	relatively strong recruitment
		Albacore tunas (*Thunnus alalunga*) Bigeye tuna (*Thunnus obesus*)	decrease 10-20% (relative)	relatively weak recruitment
mariculture	1982-2008	Oyster (*Crassostrea gigas*)	decrease > 20% (productivity)	spawning timing disturbed
	1995-2007	Abalone (*Haliotis aqualilis*)	decrease > 90%	water quality affected

The major impact is due to the strengthening of the South China Sea Current and Kuroshio Current and the withdrawal of the China Coastal Current under the SST warming trend. In many coastal fisheries, the catch of warm-water species, such as skipjack and yellowfin tunas (longline), spotted mackerel and round scad (purse seine fisheries), and buccaneer and shorthead anchovy (*Encrasicholina punctifer* and *E. heteroloba*) (trawl fisheries), have gradually replaced cold-water species, such as chub mackerel and jack mackerel and Japanese anchovy (*Engraulis japonicus*). The southern extent of those migratory species overwintering from northern seas, such as mullet and pomfret (paired purse seine fishery), has moved northwards. Those fisheries targeting wintering migratory species, including the paired purse seine and mackerel purse seine fisheries, are struggling to survive and have almost collapsed in recent years.

Fisheries may also suffer from short-term climate variability or extremes. As shown in Table 12.2, the historical *El Niño* and *La Niña* events have resulted in very high inter-annual fluctuation of eel and mullet catch. Such changes were induced by the warm pool movement in the tropical Pacific. Extreme ocean/weather events in 2008 caused disaster to the ecosystem and economic loss in the archipelagic waters of the Peng-Hu Islands.

Table 12.2. Observed impacts by short-term variability or extremes

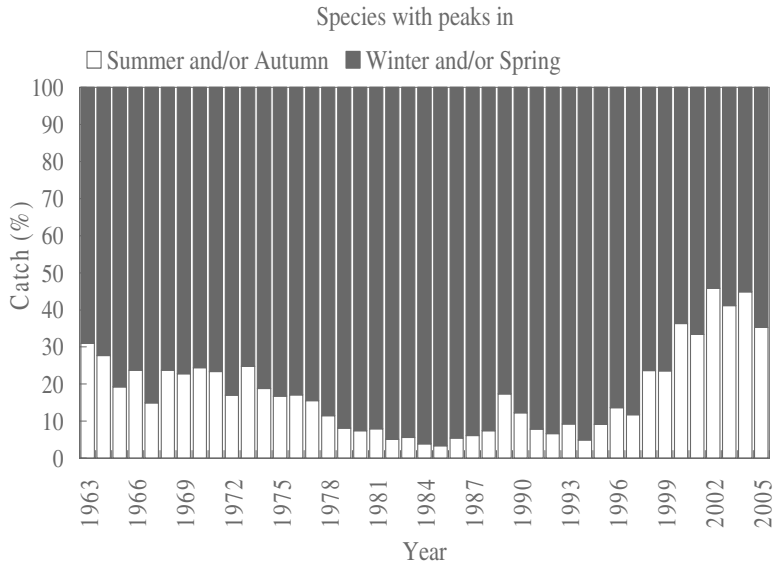
Fishery	Species	Event	Episode	Impact
Eel fry fishery	Japanese eel (*Anguilla japonica*)	*El Niño* (94/95, 97/98, 02/03)	Warm pool moves eastward and Kuroshio current weakened	Catch in 3 *La Niña* years is 10 times higher than in *El Niño* years
		La Niña (95/96, 99/00, 00/01)	Warm pool piles up in west and Kuroshio current strengthened	
Mullet fishery	Mullet (*Mugil cephalus*)	*El Niño* (77/78, 82/83, 86/87)	Kuroshio Branch Current inhibits the China Coastal Current	Caused 30% reduction in catch
Peng-Hu fishery	Multi-species	Severe intrusion of China Coastal Current in 2008	Strong prevailing wind (>6.7m/s) lasted for 3 weeks and average SST dropped to 12 ℃ in Peng-Hu archipelagic waters	Cobia culture collapsed, mass mortality in shallow sea, economic loss of more than TWD 1 billion

Impact on fishery ecosystems

In order to understand the possible impact that climate change has had on the fishery ecosystem, we examined 72 species from the landing database (1963-2007) of coastal fisheries (within 12 nautical miles). As shown in Figure 12.1b, both the MTL indices and the catch of the coastal fisheries increased rapidly from around 1970, peaking in 1993. Since then the MTL started to decline at a rate of 0.01 trophic level a year. Meanwhile, the seasonality of the 72 species showed that the catch ratio of summer/autumn species to winter/spring species has risen significantly since 1993 (Figure 12.3) which implies a regime shift in the seasonality of migratory species.

The trends in MTL indices implies that the resource utilisation of the Chinese Taipei coastal fishery was unbalanced. The phenomenon of "fishing down the marine food webs" seems to become very significant after 1993. The reason behind this was not just fishing pressure, but because of the catch variation of small pelagic fishes in response to climate change. The SST warming in the northern continental area after 1993 coincided with the reversal in the MTL trend. As the inter-annual fluctuations of the small pelagic fishes were much higher than other fish, the structure of the food pyramid of the coastal fisheries was weakened even more.

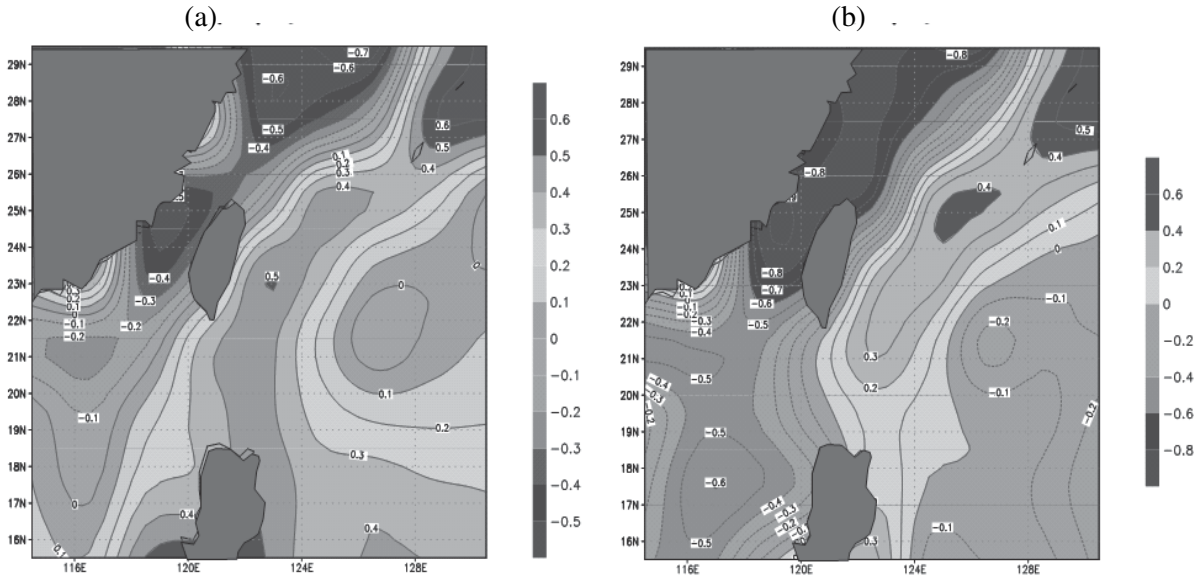
Figure 12.3. Shift in ratio of catches for seasonal fish



Future change under different scenarios

Figure 12.4 shows the correlation coefficients between SST and the total catch of winter and summer migratory species during 1963-2005. There were large areas of negative SST in northern Chinese Taipei, which suggests that species associated with the China Coastal Current during the spring and winter seasons were reduced due to rising SST in these regions. This phenomenon was particularly clear from 1990 onwards when the MTL start to decline.

Figure 12.4. The correlation coefficients between monthly SST and ratio of catch for spring (a) and winter (b) migratory species during 1963~2005



We assessed the future impact of climate change using surface skin temperature predictions provided by the Global Change Research Center (GCRC) of the National Taiwan University, using different models under the Intergovernmental Panel on Climate Change (IPCC) A2 scenarios. Without exception, the ranges of predicted SST warming in all waters surrounding Chinese Taipei were 0.56-2.68 in the years 2030-59 (Table 12.3). Under such conditions, most of the fish species will go on decreasing, especially those which migrate with the China Coastal Current; only warm-water fish species show a partial increase. We estimate that by 2055 this will have led to a 5-50% reduction in catches of currently winter migratory species relative to the levels of 2005, which means a considerable portion of those species will disappear (Lu *et al.*, 2009). Another simulation using FAO data under global warming scenarios also suggests that fishery productivity in the East China Sea in 2055 will decrease more than 50% relative to 2005 levels (Cheung *et al.*, 2009).

Table 12.3. Average sea surface temperatures in the Chinese Taipei waters estimated for the period 2030-2059 by GCRC using different models under the A2 scenarios

Summer (August) **Unit: ℃**						
Model	NE	E	W	SW	NW	ALL
EH4OPYC	1.13-1.15	0.8-0.89	0.56-0.6	0.64-0.82	0.85-1.74	0.99-1.07
CCSRNIES	1.54-1.57	1.33-1.48	2.08-2.68	1.14-1.66	2.01-2.07	1.57-1.75
CCCma	0.81-1.19	0.65-0.78	1.10-1.49	0.87-0.91	NA	0.79-1.62
			Winter (February)			
Model	NE	E	W	SW	NW	ALL
EH4OPYC	1.08-1.12	0.91-1.12	1.11-1.51	0.91-1.06	1.02-1.43	1.05-1.20
CCSRNIES	1.38-1.91	0.93-1.67	1.32-1.86	0.77-1.68	2.03-2.12	1.26-1.84
CCCma	1.08-1.27	0.86-1.10	0.93-1.52	0.92-1.14	NA	0.96-1.20

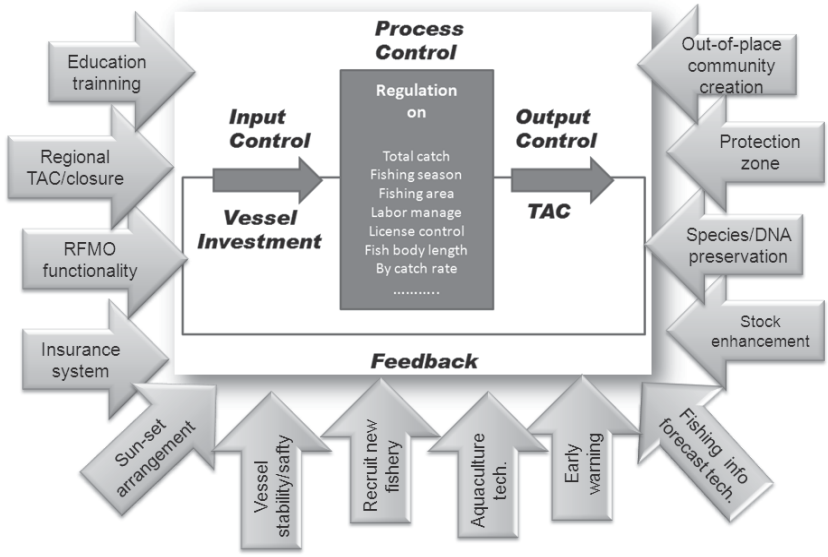
Adaptation strategies and summary

Climate change has been and will continue to be a matter of vital importance to fishery management and policy making. Traditional fishery management is generally operated through controls on inputs, processes and outputs, with the level of control in each step being set by an internal feedback system (Figure 12.5). This system is likely to become invalid because, if the current ocean warming trend continues, the impact from the climate may overwhelm all other internal fishery problems. Both government and fishing communities will have to take action to adapt if they are to reduce the risk of severe suffering.

Figure 12.5 also shows some possible supplementary actions or measures that could be added to the traditional management system. To avoid stock collapses, we may need to

establish a more efficient total allowable catch (TAC) regime and fishing ground closure or control at a regional level, enhancing the function of the Regional Fishery Management Organisations (RFMO). To prevent the extinction of fish stocks, we may need to take actions such as out-of-place community creation, protection zones, species preservation, new aquaculture techniques and stock enhancement. For the efficiency and safety of fishing operations, we may need to improve fishery information/forecasting techniques, vessel stability and insurance system. Others measures like early warning and sunset arrangements are also needed for those fisheries which will have difficulty in surviving at all.

Figure 12.5. Supplement fishery management tools for adapting to climate change



Top priority among these possible adaptations to climate changes, should be protection against weather extremes, because they may cause direct loss of life and property. Adaptating to the problems of changes in fishery production or marine ecosystems will need more comprehensive processes. These may include raising fisher's awareness of the impact of the climate through education and training, changing the ways in which fishery resources are used, adjusting surplus fishing effort, establishing sunset arrangements for severely affected areas (for instance through boat reductions and alternative work), enhancing forecasting techniques for fishing information, managing redistributed straddling and highly migratory fish stocks through RFMOs, and implementing stock enhancement measures. However, there are still very few neighbouring countries or regions with relevant experience or successful case studies. It will be very important to share experiences with interested countries since the lesson of climate impact will be a new one for all concerned.

The Chinese Taipei fishery is not only an indispensable part of the food supply but is also important for the maintenance of people's livelihoods and the security of society. The Chinese Taipei waters, once relatively stable, have commenced a period of rapid temperature fluctuation with amplitudes beyond our earlier estimates. The 6th National Agriculture Meeting, the highest level of consultation on agriculture policy, will be held on 15 June, 2010. The meeting has been entitled "Policy Adaptation of Taiwan Fishery to Climate Impact". The discussion will cover comprehensive fishery issues in regard to

climatic disaster prevention, water resource problems in aquaculture, the preservation of marine biodiversity, fishery resources and fishery structural problems, green energy exploration and greenhouse gas mitigation measures. The outcome of the meeting will become the guidance for our fishery authority to make a proper policy response to this unprecedented challenge.

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Annex 1

Opening Address by Vice-Minister for Food, Agriculture, Forestry and Fisheries of Korea

Distinguished Mr. Greg Schneider, Chair of the OECD Committee for Fisheries,
Mr. Carl-Christian Schmidt, Head of the Fisheries Policies Division of the OECD,
Mr. John Davis, Chair of this workshop,
and respected participants,

Welcome to Busan for the workshop on "The Economics of Adapting Fisheries to Climate Change".

It is my great honor to deliver an Opening Address at the Workshop in this Busan city, the largest port and the hub of Fisheries industry in Korea.

Distinguished participants,

Climate change is becoming more evident and we all understand that addressing climate change is one of the most pressing issues we face. Against this backdrop, the Korean government declared "Low-carbon, Green growth" as Korea's new national vision and has introduced Comprehensive Plan and National Action Plan to Adapt to Climate Change.

At the fisheries level, as sea surface temperature is increasing steadily, Korea has witnessed the impacts of climate change such as altering fisheries stock distribution and emerging sub-tropical fish spices in Korean waters.

To deal with the challenges of climate change, the Ministry for Food, Agriculture, Forestry and Fisheries has implemented strategic plans to adapt fisheries and aquaculture to climate change such as "Comprehensive Marine and Fisheries Policy Strategies for Climate Change". The details will be presented at Country case study of National Strategies to Adapting to Climate Change. In dealing with climate change, there is considerable uncertainty over how climate change will impact fisheries. In addition, the extent to which fisheries are likely to be affected by climate change is quite difficult to determine based on current information.

I hope this workshop will provide us with great ideas on strategies to prepare for the impacts from climate change. To this end, I urge your active participation to yield fruitful results through live exchanges of your experiences and ideas.

Once again, I would like to express my deepest gratitude to all of you for attending this workshop on the Economics of Adapting Fisheries to Climate Change and wish you have a wonderful and pleasant stay in Busan.

Thank you.

Yong-Jae Ha,
Vice-Minister for Food, Agriculture, Forestry and Fisheries of the Republic of Korea

Annex 2

Author biographies

Johann Bell, *Secretariat of the Pacific Community (SPC), Noumea, New Caledonia*

Johann Bell is a Senior Fisheries Scientist with the Strategic Engagement, Policy and Planning Facility at the Secretariat of the Pacific Community (SPC) in New Caledonia. He has been doing and supervising research for the sustainable development of small-scale fisheries and coastal aquaculture in the Pacific and in Asia for 17 years. His recent research interests are in the areas of restocking and stock enhancement of coastal fisheries, planning the use of fish for food security, and climate change and fisheries. Johann is currently leading a comprehensive assessment of the vulnerability of fisheries and aquaculture in the Pacific to climate change. This assessment involves contributions from more than 70 scientists from about 30 institutions.

John Davis, *Institute for Coastal and Oceans Research, University of Victoria, Canada*

John Davis retired from Canada's Department of Fisheries and Oceans in 2008 after 37 years service with the Department with extensive experience in fisheries and habitat management, environmental and policy issues related to sustainable management and conservation of natural resources. As Assistant Deputy Minister of Science, he was responsible for the Department's science programs on a national basis.

Prior to retirement, he was the Special Advisor to the Deputy Minister, on Species at Risk. He served in a number of positions with the Department of Fisheries and Oceans including Director General, Pacific Region, Assistant Deputy Minister of Science, Director General Pacific and Freshwater Fisheries and Director General, Ontario Region.

He holds a Bachelor's Degree in Zoology from the University of Victoria and a Master's and Doctorate degree from the University of British Columbia where he specialized in work with Pacific salmon.

Currently, he is Vice President, Canadian Operations for iDUS Controls Limited, a British Columbia high technology company specializing in intelligent control devices for domestic and commercial water conservation applications.

Susan Hanna, *Department of Agricultural and Resource Economics, Oregon State University, USA*

Susan Hanna is professor of marine economics at Oregon State University, affiliated with the Coastal Oregon Marine Experiment Station and with Oregon Sea Grant. Her research and publications are in the area of marine economics and policy, with an emphasis on fishery management performance, ecosystem-based fishery management, property rights and institutional design. Dr. Hanna has extensive experience as a scientific advisor on marine issues. She worked within the Pacific Fishery Management Council System as a member of its Scientific and Statistical Committee as well as *ad hoc* committees. She served as a scientific advisor to the U.S. Commission on Ocean Policy, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Power and Conservation Council and Oregon Ocean Policy Advisory Council. She was a member of the Ocean Studies Board of the National Research Council (NRC), National Academy of Sciences, and has served on several NRC Committees.

Rögnvaldur Hannesson, *Norwegian School of Economics and Business Administration, Norway*

Rögnvaldur Hannesson was born and raised in Iceland. He holds a Ph.D. degree in economics from the University of Lund, Sweden. His academic career has been in Norway, and since 1983 he has been professor of fisheries economics at the Norwegian School of Economics and Business Administration in Bergen, Norway. He has published four books on fisheries economics and two on petroleum economics and mineral wealth, and about a hundred book chapters and papers in academic journals. He has done occasional work on fisheries economics for the OECD, the FAO, and the World Bank.

Kee-Hyung Hwang, *Blue Economy Research Department, Korea Maritime Institute, Korea*

Kee-Hyung Hwang received his Ph.D. in mineral Economics from Colorado School of Mines, USA, in 1989. He has developed his research career in the field of maritime and fisheries affairs since he joined Korea Ocean Research and Development Institute (KORDI) as senior researcher in 1993. He was mainly involved in the Korea's deep-sea mining program as leader of techno-economic feasibility studies from 1993 to 1996. He has also involved in various research activities related to fisheries management and polices as research fellow at Korea Maritime Institute (KMI) since 1997. He headed Fisheries Policy Research Team from 2003 to 2006, and Fisheries Outlook Center from 2006 to 2008. He served as a technical expert for the Presidential Committee of Agriculture and Fisheries Polices in 2002 and in 2005. Currently he is leading various research projects to support 2012 EXPO Yeosu Korea. He is also an expert adviser for the Organizing Committee for EXPO 2012 Yeosu Korea.

Kirsty Inglis, *Department for Environment, Food and Rural Affairs, United Kingdom*

Kirsty Inglis has been in the United Kingdom's Government Economic Service since 2003 and is currently based in the Marine and Fisheries Economics Unit in the Department for Environment, Food and Rural Affairs (Defra). Focussing on the economics of marine biodiversity, Kirsty's analysis contributes to a range of domestic and international policy areas including the UK's Marine and Coastal Access Act, the designation of Marine Conservation Zones, marine spatial planning and embedding ecosystem services valuation into the policy making process. She leads on the development of pan-European guidance on economic and social analysis in support of the EU's Marine Strategy Framework Directive and is the UK delegate to the OECD's Fisheries Committee. Kirsty has broad research interests which include labour and welfare as well as environmental economics. She has an MA in Economic Policy from McMaster University in Canada, a publication in the Journal of Health Economics and a number of working papers forthcoming.

Il-Jeong Jeong, *Ministry for Food, Agriculture, Forestry and Fisheries, Korea*

Il-Jeong Jeong is Director of the International Fisheries Organization Division in the Korean Ministry for Food, Agriculture, Forestry and Fisheries (MIFAFF). He is a Korean commissioner to ICCAT, CCSBT, WCPFC, IATTC and IOTC. He is currently Chair of Asia-Pacific Fishery Commission. He graduated from Seoul National University and received his PhD degree in Economics from the University of Illinois at Urbana-Champaign in the United States. He participated in the Uruguay Round and DDA agricultural negotiations as a member of Korean delegation. His previous position was a director of Multilateral Agricultural Negotiation Division in the Ministry. While he was working for the Trade and Agriculture Directorate in the OECD from 2005 to 2008, he was a main author of OECD paper "Evaluation of Korean Agricultural policies".

Kieran Kelleher, *The World Bank, United States*

Kieran Kelleher is the Fisheries Team Leader in the World Bank and manager of the World Bank's Global Partnership on Fisheries - PROFISH (*www.worldbank.org/fish*). With a background in biology and business management, he has worked as a fisherman, fish farmer, manager of a fisher cooperative and as a fisheries scientist. He has spent most of his career as economic advisor on fisheries to governments in developing countries. He is the author of global studies on discards, on aquaculture and on fisheries enforcement and co-author of a recent study: "*The Sunken Billions. The Economic Justification for Fisheries Reform*" (www.worldbank.org/sunkenbillions). His wiki page on fisheries and climate change is available at:
http://en.wikipedia.org/wiki/Fisheries_and_climate_change.

Adolf (Adi) Kellermann, *International Council for Exploration of the Sea (ICES), Denmark*

Adi Kellermann has been the Head of Science Programme at the ICES since 2004. Prior to joining the ICES, he worked for the National Park Office in Tonning as Senior Scientist. He received his PhD in Fishery Biology at the Institute for Polar Ecology in 1985. His research interests include ecosystem research, monitoring and assessment, relational data base skills, early life history and ecology of larval fishes, ocean hydrology, fish otolith microstructure and chemistry, SEM techniques, egg and larval fish rearing, fish and plankton surveys and cold water ecology. He has published more than 50 scientific papers.

Daniel (Dan) Lane, *Telfer School of Management, University of Ottawa, Canada*

Daniel Lane is Co-Director of the IDRC-SSHRC International Community-University Research Alliance (ICURA) C-Change project - "Managing Adaptation to Environmental Change in Coastal Communities: Canada and the Caribbean" (2007-2014) and Chair of the Ocean Management Research Network, OMRN (since 2005). Professor Lane's research interests include decision-making processes, simulation modelling, and control of dynamic systems, especially in the area of natural resource management, commercial fishing and aquaculture, and adaptation to climate change. He actively supervises graduate students and is recipient of numerous research grants including the Natural Sciences and Engineering Research Council (NSERC) of Canada Individual Operating and Discovery Grants (since 1986). He has published peer-reviewed papers in Operations Research, OPTIMUM, the Canadian Journal of Fisheries and Aquatic Sciences, the European Journal of Operational Research, INFOR, American Fisheries Society Symposia. He has published major reports for World Fisheries Congress (Brisbane and Vancouver), Fisheries and Oceans (Canada), International Council for the Exploration of

the Sea (ICES), and the OECD Fisheries Committee. He received his PhD at the University of British Columbia in 1986.

Hsueh-Jung Lu, *Department of Environmental Biology and Fisheries Science, Taiwan National University, Chinese Taipei*

Hsueh-Jung Lu received MS and PhD in Fisheries Science from the National Taiwan Ocean University (NTOU) in 1988 and 1995, respectively. After graduation, he served as the Deputy Director of Information Division with the Overseas Fishery Development Council, in charge of fisheries statistics of distant-water tuna and squid during 1995-1999. He is currently an Associate Professor of the Department of Environmental Biology and Fisheries Science, NTOU. His major research interest is fishery oceanographic studies related to mechanism of fishing ground formation, especially under the influence of climatic changes, using hydro-acoustic, geographic information system, and remote sensing methods. For many years, he has been participating in several projects of impact assessment of climatic change on fisheries of Taiwan with finance support from the National Science Council and the Council of Agriculture.

Daniel Lee, *Global Aquaculture Alliance, United Kingdom*

Daniel Lee is the Coordinator for the GAA's BAP (Best Aquaculture Practices) program and also a Research Associate at Bangor University, UK. His spent his early career farming crustaceans, most notably marine shrimp, for research and commercial projects in South America, the Caribbean, Africa and Asia. He gained an international reputation as an aquaculture expert through the publication of the text book *Crustacean Farming, Ranching and Culture* and through his work with the Global Aquaculture Alliance (GAA) and the Aquaculture Certification Council. He has assisted in the development of international standards for responsible aquaculture, with special regard to food safety, traceability and environmental and social issues.

Alastair Macfarlane, *New Zealand Seafood Industry Council, New Zealand*

Alastair Macfarlane has held senior management positions with seafood industry organisations since 1990. He heads up the Seafood Industry Council's Trade and Information Business Unit, with personal responsibility for international fisheries and trade policy issues. He has line management responsibility for information service delivery to the industry and public. He is a member of the Seafood Standards Council, a joint committee between the seafood industry and the New Zealand Food Safety Authority that consults on food safety in the seafood sector. The Seafood Industry Council is owned by commercial stakeholder organisations representing New Zealand's commercial fisheries and aquaculture interests. Alastair Macfarlane is an honours graduate in Economic Geography from Victoria University in Wellington New Zealand.

Edward Miles, *School of Marine Affairs, University of Washington, United States*

Edward Miles is the Bloedel Professor of Marine Studies and Public Affairs, School of Marine Affairs, and Co-Director, Center for Science in the Earth System, Joint Institute for the Study of Atmosphere and Ocean at the University of Washington. He has served as chairman of the Ocean Policy Committee, National Academy of Sciences/National Research Council (1974-79); member of the Executive Board, Law of the Sea Institute, 1972-81 and 1985-89 and President 1989-93; Chairman of the Legal and Institutional Task Group on the Implications of Disposal of High-Level Radioactive Waste into the Seabed and Advisor to the Executive Committee, Seabed Working Group, Nuclear Energy Agency, OCED, 1981-1987; Chairman of the Advisory Committee on International Programs of the National Science Foundation, 1990-92; and member of the

Advisory Committee for the Social, Behavioural, and Economic Sciences, National Science Foundation, 1992-1994. He has also served as consultant to the United Nations, Intergovernmental Oceanographic Commission of UNESCO, Dept. of Fisheries of FAO, and the South Pacific Forum Fisheries Agency. In April 1993 he served as the UN-designated expert on GESAMP, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection and in 1994 he was appointed Lead Author for Marine Policy in WG II-B (Oceans and Large Lakes) of the Intergovernmental Panel on Climate Change 1995, Re-assessment of the Global Climate Change Problem. He is the author of many studies on international organizations, international science and technology policy, marine policy and ocean management, and the regional impacts of climate variability and climate change.

Pavlina Nikolova, *Directorate General for Maritime Affairs and Fisheries (DG-MARE), European Commission, Belgium*

Pavlina Nikolova is an International Relations Officer at the European Commission dealing with international fisheries co-operation and negotiations. She holds a doctoral degree in European policy from the University in Bristol, UK, an MA degree from the Institute for Political Sciences in Strasbourg, France and a BA (Hons) degree in International economics from the University of Varna, Bulgaria. She previously worked as a Director of a regional European information centre, Lecturer in international relations and consultant on international trade and marketing.

Takanori Ohashi, *Policy Planning Department, Fisheries Agency, Japan*

Takanori Ohasi is Deputy-Director of the Fisheries Policy Planning Division at the Fisheries Agency of Japan.

Ian Perry, *Pacific Biological Station, Department of Fisheries and Oceans, Canada*

Ian Perry is a senior research scientist with Fisheries & Oceans Canada at the Pacific Biological Station in Nanaimo, B.C., Canada. His research expertise includes the effects of the environment on larval, juvenile and adult stages of finfish and invertebrates; the structure and function of marine ecosystems; ecosystem-based approaches to the management of marine resources; the human dimensions of marine ecosystem changes; methods for providing scientific advice for new and developing fisheries; and scientific leadership of international and inter-governmental programs on marine ecosystems and global change. He currently heads the Ecosystem Approaches Program at the Pacific Biological Station, and is one of two co-leads for the DFO Strait of Georgia Ecosystem Research Initiative. In addition, he is the Chair of the international Global Ocean Ecosystem Dynamics (GLOBEC) program, whose goal is to understand how global change will affect the abundance, diversity and productivity of marine populations. He is a past Chief Scientist and Chair of the Science Board for the North Pacific Marine Science Organisation (PICES). He is an Adjunct Professor at the Fisheries Centre of the University of British Columbia, and has taught courses on fisheries oceanography at universities in Canada, Chile, and Portugal. He is a past Editor for the scientific journal *Fisheries Oceanography*, is presently an Associate Editor for the journal *Ecology and Society*, and is a member of the Editorial Boards for *Fisheries Oceanography* and *Current Opinion in Environmental Sustainability*.

Graham Pilling, *Centre for Environment, Fisheries and Aquaculture Science, United Kingdom*

Graham Pilling currently leads the 'Seas and Oceans' Group of the Fisheries Division at the Centre for Environment, Fisheries and Aquaculture Science (Cefas), in Lowestoft,

UK. He has over sixteen years experience in the practical assessment and management of marine pelagic and demersal fisheries around the world, in countries from the top ten GDP nations to small island developing states. A key area of recent collaborative work has been examining the implications of future anthropogenic impacts – both climate change and human population increase - on fish stocks, fisheries and ecosystem services around the world. This has included the use of simulations and ecological footprint analyses to examine implications for individual fish stocks such as North Sea cod and specific country groups (small island states), through to global vulnerability analyses to identify specific areas where both marine and freshwater resources and ecosystems important to the poor will be affected.

Jerker Tamelander, *Oceans and Climate Change, Global Marine Programme, International Union for Conservation of Nature (IUCN), Switzerland*

Jerker Tamelander leads activities addressing the impacts of greenhouse gas emissions on oceans, dependent industries and communities. The programme focuses on finding nature-based solutions to climate change, including mitigation through preserving and enhancing natural carbon stocks, and development and implementation of approaches to increasing socio-ecological resilience and adaptive capacity. He also works on spatial planning, development of resilient MPA networks, and addressing Invasive Alien Species (IAS) in the marine environment. Jerker has an MSc in Marine Biology and 15 years of experience from work at the Finnish Institute of Marine Research, the United Nations Environment Programme and IUCN.

Chang-Ik Zhang, *Institute of Fisheries Science, Pukyong National University, Korea*

Chang Ik Zhang received a PhD in fisheries ecology from the University of Washington in 1987 and has been a Professor at Pukyong National University (PKNU) since 1995. He has served the Korean government as Member of The Presidential Commission on Agriculture, Fishery and Rural Policy, and also as a Member of The Presidential Commission on Policy Planning. Since 2005, Dr. Zhang has served as a Member of the Marine Stewardships Council's Technical Advisory Board, and Member of the Korea Academy of Science & Technology. He chaired the Commission for the Conservation of Southern Bluefin Tuna in 2009. He is currently Director of the Institute of Fisheries Sciences of PKNU. His fields of interest are fisheries ecology, population and ecosystem dynamics, and fishery assessment and management. Dr. Zhang is the author of nine books (1991, 1994, 1998, 1999, 2002, 2005 and 2010) in fisheries ecology and management, including a recent book, 'Marine Fisheries Resource Ecology'. He has published more than 110 scientific papers, and given numerous presentations at scientific conferences, many of which have been keynote presentations. He has served on the editorial boards of international journals such as Fisheries Oceanography. He has been Editor-in-chief of the Journal of Korean Society of Fisheries Resources. He is the 1991 winner of the Most Significant Paper Award from the American Fisheries Society, winner of the Best Paper Award from the Korean Cooperation of Science and Technology in 1993, and from the Korean Fisheries Society in 1994. He is deeply involved in the North Pacific Marine Science Organization (PICES) activities, first as a member, and since 1996, as Chairman of the Fishery Science Committee (FIS). He has also served as a member of the Executive Committee of the Climate Change and Carrying Capacity (CCCC) Program Implementation Panel, SCOR Working Group 105 on The Impact of World Fisheries Harvests on the Stability and Diversity of Marine Ecosystems and a member of the Living Marine Resources (LMR) Panel of Global Ocean Observing System (GOOS) of UNESCO/IOC.

Annex 3

List of the workshop participants
(alphabetically by organisation/company)

Coordinating Ministry for Economic Affairs Indonesia	Mr. S. Soetijono Assistant Deputy
	Miss R. Yuli Sri Wilanti Head, Sub Division of Fisheries Policy Preparation
EXPO 2012 Korea	Mr. Sang Heum Baek Deputy Director
	Mr. Kee Young Chang Senior Director
	Mr. Seoung Young Hong Co-Chairman
	Mr. Seungchul Kang Chief Editor
	Mr. Young So Kim Director
	Mr. Jae Hong Lee Vice Secretary General
	Mr. Tae Hoon Lim Deputy Director
	Mr. Bun Do Yoon Director
Fisheries Economic Institute, Korea	Mr. Dong Ryul Chae Research fellow
	Mr. Man Hwa Jung President
Fisheries Infrastructure Promotion Association, Korea	Mr. Ho Chin Shim President
Hokkaido University, Japan	Mrs. Gakushi Ishimura Assistant Professor
Korea Maritime Institute	Ms. Soojin Kim Senior Researcher

Ministry of Fisheries and Aquaculture, Brazil	Mr. Altemir Gregolin Minister
	Mr. Felipe Matoas Secretary, Planning and land Use for Aquaculture
	Mr. Francisco Osvaldo Barbosa Chief, International Advisory Office
Ministry for Food, Agriculture, Forestry and Fisheries, Korea	Mr. Tae Puong Chang Minister
	Mr. Myo In Chang Deputy Director
	Mr. Yun Ki Hyun
	Mr. Young Jae Ha Vice-Minister
	Mr. Dong Hwa Jun Assistant Manager
	Mr. In Gu Kang Director
	Mr. Ki Hwan Kim Deputy Director
	Ms. Se Hee Kim
	Ms. Tal Gi Kim Secretary
	Ms. Soo Jin Kong Assistant Director
	Mr. Do Hyung Koo Deputy Director
	Mr. Cheol Woo Lee Director General
	Mr. Sung Jae Lee Assistant Director
Ministry for Food, Agriculture, Forestry and Fisheries, Korea	Mr. Chi Won Lim Senior Researcher
	Mr. Kwang Suk Oh Director
	Mr. Sun Yong Park Assistant Director

	Mr. Young Gi Park Deputy Director
	Mr. Young Ho Park Deputy Director
	Mr. Jang Woo Seo
	Mr. Jae Hak Soon
National Fisheries Research & Development Institute (NFDRI) **East Sea Fisheries Research Institute, Korea**	Mr. Dae Soo Chang Director
	Mr. Ki Baik Seong Research Scientist
	Mr. In Seong Han Research Scientist
	Mr. In Seong Han Research Scientist
	Mr. Yeong Gong Advisory Researcher
	Mr. Jinhwan Kim
	Mr. Do Hoon KimDirector
	Mr. Sung Yeon Kim Senior Research Scientist
	Mr. Jong Hwa Park Director
	Mr. Sung Woo Park Head of Office
	Ms. Yeing Hye Kim Research Scientist
	Ms. Jin Yi Paek Research Specialist
	Mr. Ju Nam Seo Research Specialist
	Mr. Hyung Kee Cha Senior Researcher
	Mr. Kwang Ho Choi Fisheries Scientist

	Mr. Kang Seok Hwang Fisheries Scientist
	Mr. Seon Jong Hwang Fisheries Scientist
	Mr. Suk Geun Jung Researcher
	Ms. Su Kyung Kang Fisheries Scientist
	Mr. Sang Woo Kim Chief Scientist
	Mr. Young Seop Kim Director
	Mr. Jae Bong Lee Fisheries Oceanographic Scientist
	Mr. Seung Jong Lee Chief Scientist
	Mr. Seok Hyun Youn Research Scientist
National Oceanic and Atmospheric Administration (NOAA), United States	Mr. Gregory Schneider Senior International Trade Specialist
Organisation for Economic Development and Co-operation (OECD), France	Ms. Saba Khwaja Fisheries Policy Analyst
	Mr. SungBum Kim Senior Fisheries Policy Analyst
	Mr. Carl-Christian Schmidt Head, Fisheries Policies Division
Pukyong National University, Korea	Mr. Muhammad Tanvir Hossain Chowdhury Fisheries Officer/Ph.D. Candidate
	Mr. Ahmad Fathoni Master student
	Mr. Dicky Harwanto Researcher
	Mr. Sungbum Hur Professor
	Mr. Su Am Kim Professor

	Dr. Sang-Go Lee Professor
	Ms. Maria Dyah Nur Meinita Ph.D. Candidate
	Mr. Jai Ho Oh Professor
Pukyong National University, Korea	Mr. Yongmin Shin Ph.D. Candidate
	Mr. Hasan Uddowla Ph.D. Candidate
Pusan National University, Korea	Mr. Ikkyo Chung Professor
West Sea Fisheries Supervision Office, Korea	Mr. Kyu Jin Kim Director General
Western and Central Pacific Fisheries Commission, Federated States of Micronesia	Mrs. SungKwoh SOH Science Manager/Interim Executive Director

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The Economics of Adapting Fisheries to Climate Change

Climate change is becoming more evident and, as it increases, will alter the productivity of fisheries and the distribution of fish stocks. From an economic point of view, the changes will have impacts on fisheries and coastal communities in different ways. These expected changes require adaptable and flexible fisheries and aquaculture management policies and governance frameworks. However, the forms of future climate change and the extent of its impact remain uncertain. Fisheries policy makers therefore need to develop strategies and decision-making models in order to adapt to climate change under such uncertainty while taking into account social and economic consequences.

While most work on climate change in the fisheries sector has focused on fisheries science, this book highlights the economic and policy aspects of adapting fisheries to climate change. An outcome of the OECD Workshop on the Economics of Adapting Fisheries to Climate Change, held in June 2010, the book outlines the actions that fisheries policy makers must undertake in the face of climate change. These include: strengthening the global governance system; a broader use of rights-based management systems; ecosystem protection; industry transformation through the ending of environmental harmful subsidies and a focus on demand for sustainably caught seafood; and, in particular, using aquaculture as a key part of the response to climate change.

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