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**Improving Information for Policy Makers**

# Managing Climate Change Risks

**by**

**Roger Jones**

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## FOREWORD

This paper was prepared for an OECD Workshop on the *Benefits of Climate Policy: Improving Information for Policy Makers*, held 12-13 December 2002. The aim of the Workshop and the underlying Project is to outline a conceptual framework to estimate the benefits of climate change policies, and to help organise information on this topic for policy makers. The Workshop covered both adaptation and mitigation policies, and related to different spatial and temporal scales for decision-making. However, particular emphasis was placed on understanding global benefits at different levels of mitigation -- in other words, on the incremental benefit of going from one level of climate change to another. Participants were also asked to identify gaps in existing information and to recommend areas for improvement, including topics requiring further policy-related research and testing. The Workshop brought representatives from governments together with researchers from a range of disciplines to address these issues. Further background on the workshop, its agenda and participants, can be found on the internet at: www.oecd.org/env/cc

The overall Project is overseen by the OECD Working Party on Global and Structural Policy (Environment Policy Committee). The Secretariat would like to thank the governments of Canada, Germany and the United States for providing extra-budgetary financial support for the work.

This paper is issued as an authored "working paper" -- one of a series emerging from the Project. The ideas expressed in the paper are those of the author alone and do not necessarily represent the views of the OECD or its Member Countries.

As a working paper, this document has received only limited peer review. Some authors will be further refining their papers, either to eventually appear in the peer-reviewed academic literature, or to become part of a forthcoming OECD publication on this Project. The objective of placing these papers on the internet at this stage is to widely disseminate the ideas contained in them, with a view toward facilitating the review process.

Any comments on the paper may be sent directly to the author at:

Roger Jones
CSIRO Atmospheric Research, PMB1 Aspendale, Victoria 3195, Australia
roger.jones@csiro.au

Comments or suggestions concerning the broader OECD Project may be sent to the Project Manager : Jan Corfee Morlot at: jan.corfee-morlot@oecd.org

## ACKNOWLEDGEMENTS

This paper is based on a 2,000 word commentary written in August 2002 in response to the article on the uncertainty police in Nature. I apologise for all the extra words but people wanted some basis behind the 2,000 words of assertions. The expanded version was greatly influenced by presentations at the OECD Benefits of Climate Policy Workshop in Paris, December 2002 and the OECD's support in commissioning a fuller version is gratefully acknowledged. The projects that fuelled the several years' research into risk assessment summarised in this paper, were funded by various Australian state governments, the United Nations Development Programme, the Australian Greenhouse Office and CSIRO. The analysis in Section 4.4 was based on provisional analyses by Tom Wigley that I turned around to provide the inverse version. Tom Wigley, Steve Schneider, Jan Corfee-Morlot, Jake Jacoby and Barrie Pittock provided valuable comments.

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**ABSTRACT**

Issues of uncertainty, scale and delay between action and response mean that 'dangerous' climate change is best managed within a risk assessment framework that evolves as new information is gathered. Risk can be broadly defined as the combination of likelihood and consequence; the latter measured as vulnerability to greenhouse-induced climate change. The most robust way to assess climate change damages in a probabilistic framework is as the likelihood of critical threshold exceedance. Because vulnerability is dominated by local factors, global vulnerability is the aggregation of many local impacts being forced beyond their coping ranges. Several case studies, generic sea level rise and temperature, coral bleaching on the Great Barrier Reef and water supply in an Australian catchment, are used to show how local risk assessments can be assessed then expressed as a function of global warming. Impacts treated thus can be aggregated to assess global risks consistent with Article 2 of the UNFCCC. A 'proof of concept' example is then used to show how the stabilisation of greenhouse gases can constrain the likelihood of exceeding critical thresholds at both the both local and global scale. This analysis suggests that even if the costs of reducing greenhouse gas emissions and the benefits of avoiding climate damages can be estimated, the likelihood of being able to meet a cost-benefit target is limited by both physical and socio-economic uncertainties. In terms of managing climate change risks, adaptation will be most effective at reducing vulnerability likely to occur at low levels of warming. Successive efforts to mitigate greenhouse gases will reduce the likelihood of reaching levels of global warming from the top down, with the highest potential temperatures being avoided first, irrespective of contributing scientific uncertainties. This implies that the first cuts in emissions will always produce the largest economic benefits in terms of avoided impacts, the sum of these benefits depending on the sensitivity of the climatic response and the damage function of the respective impacts. The major benefit of the structure presented in this paper is that risk can be translated across local and global scales, linking both adaptation and mitigation within a framework consistent with the aims of the UNFCCC.

## 1. INTRODUCTION

In trying to understand and mitigate the enhanced greenhouse effect, scientists and policy makers are undertaking a global-scale risk assessment (e.g. Beer, 1997 and others). By framing criteria to identify, assess, prioritise and manage risks, the structure of Article 2 of the United Nations Framework Assessment on Climate Change (UNFCCC) is compatible environmental risk assessment frameworks, therefore many of the tools developed to assess and manage environmental risks can be in support of the UNFCCC (Jones, 2001). The requirement to stabilise greenhouse gases at levels sufficient to prevent dangerous anthropogenic climate change sets the criteria for assessment, while maintaining food security, allowing sustainable economic development and allowing ecosystems to adapt naturally set the criteria for management. This task is complicated through issues of uncertainty, complexity, scale and delays between action and response.

Risk is the combination of the likelihood of an event and its consequences. Impact assessments have widely examined the consequences of climate change but have been less able to attached likelihoods to those outcomes. Pervasive uncertainties have limited most assessment to using scenarios that present alternative futures without being able to determine which of those futures may be more likely (e.g. Carter and La Rovere, 2001). However, the use of likelihoods in climate change assessments is emergent. Utilising guidance from Moss and Schneider (2000), the Intergovernmental Panel on Climate Change (IPCC) applied a more structured approach to assessing uncertainty in its Third Assessment Report (2001a–c). Binary true/false statements were given confidence levels based on expert assessment of the evidence that attached words such as *very likely* or *high confidence* to ranges of probability (IPCC, 2001a, p44).

The following conclusions drawn from the Third Assessment Synthesis Report were considered by the Core Writing Team to be robust (IPCC, 2001a). *Projected climate change will have beneficial and adverse environmental and socio-economic effects, but the larger the changes and rate of change in climate, the more adverse effect predominate* (IPCC, 2001a, p 67). These consequences were addressed by IPCC using mean global warming as a common metric (IPCC, 2001a; Smith et al., 2001). Above a few °C relative to 1990, impacts are predominantly adverse, so net primary benefits of mitigation would become positive (IPCC, 2001a). Adaptation is necessary due to climate change that has already occurred and to prevent further climate change that cannot be mitigated. Adaptation is most suited to modest and/or gradual changes in climate (IPCC, 2001a).

This chapter describes methods for risk assessment that quantify the risks of climate change consistent with the above conclusions. These methods have been developed in a series of earlier papers (Jones 2000a&b; New and Hulme, 2000; Jones, 2001; Jones and Page, 2001). The scale of assessment is a key consideration. Most (though not all) impacts are local in nature, so are best addressed through bottom-up methods suited to particular activities and locations. For example, climate hazards, measured as changes in the magnitude and frequency of climate variability and extremes, and their resulting vulnerabilities, need to be assessed at the local scale (Jones et al., 2003). The likelihood of exceeding critical thresholds under well-quantified ranges of change can then be assessed without, then with, adaptation.

Mitigation and adaptation are complementary strategies but largely operate on different scales. Whereas the primary benefits of adaptation are generally local, mitigation will reduce climate change at the global scale. Aggregation of climate damages assessed at the local scale is therefore one of the steps needed to understand global risks. Aggregation can be achieved by expressing local outcomes as a function of global warming. Three case studies are used to demonstrate methods of assessing risk at the local scale. The results are then expressed as a function of mean global warming, allowing comparison and aggregation using a common metric. The studies are: a generic example using global temperature and sea level rise, coral bleaching on the Great Barrier Reef and water supply changes in eastern Australia. This methodology is complementary to global, or ‘top-down’, assessments of impacts such as those reviewed by Smith and Hitz (2003).

A final example is used to show how climate risks can be quantified at the global scale by assessing the likelihood of stabilising the atmospheric concentration of $CO_2$ below a series of equilibrium temperatures. This framework operates on the assumption that because current knowledge of what constitutes dangerous climate change is too uncertain, a number of different levels of warming at equilibrium should be assessed (also allowing the testing of different levels of risk tolerance and applications of the precautionary principle). Bayesian inference can be tested by assessing risk using different input assumptions. Outcomes that occur under a wide range of prior assumptions are likely to be robust. Changing risks can also be assessed under different policy assumptions. Risks can also be updated as new information becomes available.

A robust aspect of the framework is that critical thresholds exceeded at low levels of global warming will be those that can be given high priority for adaptation because they are highly likely to be exceeded. The risk of experiencing severe and adverse consequences (those occurring at a global scale, or widespread local damages aggregated from the bottom up) expressed as a function of global warming, although less likely to occur, provide the impetus for mitigation. The descriptors bottom-up and top-down are used in a number of ways. In this chapter the term bottom-up refers to assessments undertaken at the local scale, and top-down refers to global scale assessments. Bottom-up assessments need to be aggregated to get an overall picture, and top-down assessments need to be disaggregated to understand heterogeneous effects.

# 2. BASIC STRUCTURE OF RISK

Risk is the combination of the likelihood of an event and its consequences (e.g. Beer and Ziolkowski, 1995; USPCC RARM, 1997). Likelihood can be attached to the hazard (i.e. risk equals the likelihood of a hazard and its consequences) or to the consequences (i.e. risk equals the likelihood of exceeding a given level of damage), distinguished as the natural hazards-based approach and the vulnerability-based approach (Jones and Boer, 2003). A hazard can be broadly described as an event with the potential to cause harm. Climate hazards at the local scale include the direct effects of climate and immediate impacts arising from climate events (e.g. secondary climate hazards such as flood and fire). Climate hazards at the global scale include global mean warming, global mean sea level rise and large-scale singularities, such as cessation of thermohaline circulation and collapse of large ice sheets (Schneider, 2003). Vulnerability is the degree to which a system is susceptible to harm and is measured in terms that express a measure of value. This measure may be monetary but can utilise any type of value-based criteria, such as the five numeraires of Schneider (2003) or the somewhat larger set of measures suggested by Jacoby (2003). Global vulnerability is the aggregation of costs from climate risks and the benefits of managing those risks.

If we apply this construction of risk to the IPCC, changing climate hazards are dealt with by Working Group I (WGI; climate) and in part by Working Group II (WGII; impacts), and risk management is dealt with by Working Groups II and III. There are two ways to manage the risks of climate change in a planned manner. Adaptation will reduce the vulnerability to a given climate hazard or hazards, as assessed by WG II; the mitigation of greenhouse gases will reduce the magnitude and frequency of climate hazards, as assessed by WG III.

## 2.1 Uncertainty, complexity and probability

Climate change assessment is dominated by uncertainty, affecting the choice of method and the confidence that can be attached to the results. Uncertainties can be distinguished according to those that may be reduced with improved knowledge and those that remain due to fundamental system uncertainty. Improved knowledge may make forecasting possible, but not if fundamental uncertainties persist. This is likely to be the case under global warming, which is subject to multiple feedbacks resulting from interactions between biophysical and socio-economic systems. Parts of the system are associated with different levels of uncertainty and this uncertainty will reduce at different rates. New knowledge can actually increase quantified ranges of uncertainty as the ‘unknown’ becomes known. All of these factors need to be taken into account in communicating outcomes. In order of decreasing certainty, a result can be expressed as a central prediction, as a central prediction with error bars, as a known probability distribution function (PDF), as a bounded range with no known probability distribution, as a bounded range within a larger range of unknown possibilities, as individual scenarios with plausibility, and as a hypothesis with unknown levels of plausibility.

Both complex behaviour and incomplete knowledge mean that central predictions and well-calibrated probability distributions for climate change are not possible. Outcomes are limited to items lower down the above list, such as ranges of uncertainty, scenarios and hypotheses. Figure 1a illustrates how ranges of uncertainty propagate through an assessment. Figure 1b shows the relationship between individual scenarios and ranges of change that can be constructed from a set of scenarios. It is incumbent on a risk assessment to minimise unquantified uncertainty by utilising as wide a range of uncertainty as possible (Jones, 2000a, b). Note that the range in Figure 1 is not portrayed with a probability distribution. This is consistent with the range of global warming provided by the IPCC (2001b) which has an upper and lower limit but has no PDF attached to it, explicit or implicit.

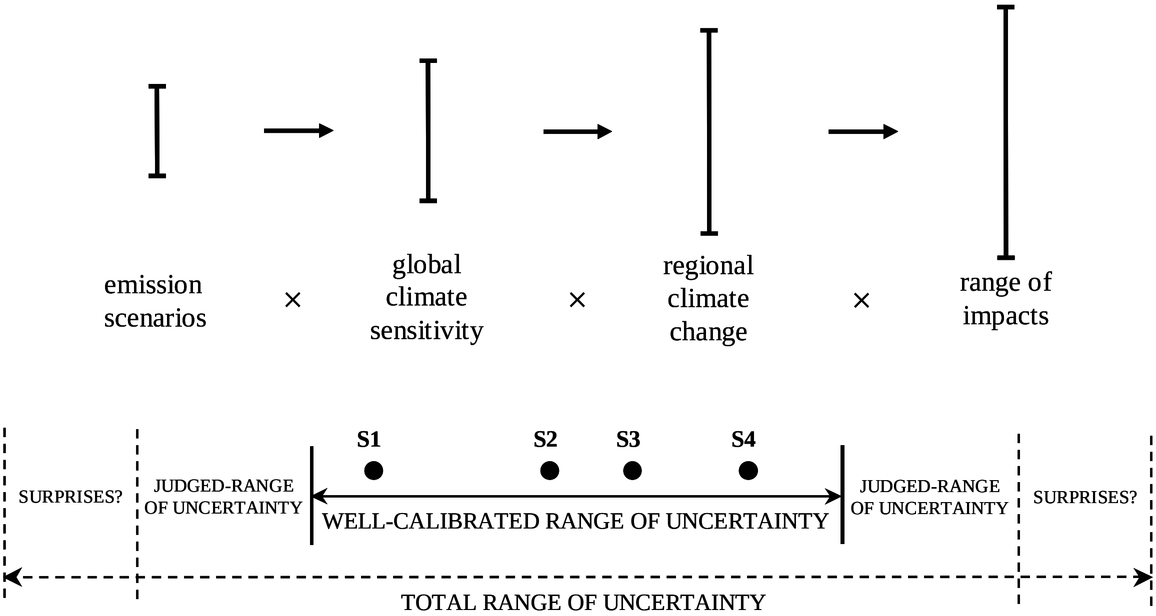


Figure 1. The relationship between (a) ranges of uncertainty cascading through an assessment, and (b) between individual scenarios, S1 to S4, and resultant ranges of uncertainty. These diagrams are sourced from Jones (2000) and Schneider and Kuntz-Duriseti (2002).

Two recent commentaries (Schneider, 2001; Schneider and Moss in Giles, 2002) argue that assessments undertaken by the IPCC should attach probabilities to their conclusions using methods drawing on expert opinion and Bayesian statistics. Their major justification is that if guidance on likelihoods is not given, policymakers will attach their own likelihoods in an ad hoc manner. This is preferable to relying on current scenario-driven approaches, but the nature of the framework used is critical. In this chapter I argue that risk assessment is a more appropriate method to use rather than relying on forecasting methods, e.g. climate forecasting as an outgrowth of weather forecasting. Risk assessment can assess a range of potential outcomes under different policy assumptions, whereas predictive frameworks are much less flexible.

The act of attaching probabilities to outcomes based on complex socio-economic relationships is controversial (Dessai and Hulme, 2003). For example, Grübler and Nakicenovic (2001) argue that because conditional probabilities cannot be attached to the underlying socio-economic processes driving greenhouse gas emission scenarios, probabilities cannot be attached to any outcomes dependent on those scenarios ("good scientific arguments preclude determining 'probabilities' or the likelihood that future events will occur"; Grübler and Nakicenovic (2001)). This implies a serial dependence where probabilities follow the time-dependent sequence of emissions, climate change, impacts and adaptation/mitigation utilised by scenario-based assessments. However, if probabilities do break down at the weakest link in a chain of consequences, the optimal adaptation strategies are those that provide benefits across a wide range of possible outcomes (e.g. Lempert and Schlesinger, 2001).

Grübler and Nakicenovic (2001) go on to say that research into the adverse impacts of climate change (i.e. vulnerability) should be conducted independently of how likely those adverse impacts are to occur. This is possible if vulnerability is assessed independently of climate scenarios, for example the construction of critical thresholds for use in risk assessments (Pittock and Jones, 2000). Critical thresholds can then be assessed for their likelihood of exceedance under ranges of plausible climate change (Jones, 2000a, 2001).

The crucial step is attaching PDFs to ranges of uncertainty. These are not predictions in the conventional sense but encompass a range of uncertainty which contains a single unknown outcome within a range of possibility. Probabilities are constructed by utilising individual scenarios, ranges or probability distribution functions to explore uncertainties. Ranges can be constructed using a set of scenarios (see Figure 1b), using Delphi analysis (formalised methods for gauging expert opinion; e.g., Morgan and Henrion, 1990), expert opinion and model uncertainty. Subjective methods will be required in many cases because objective methods may not be available or may only cover part of the range. Transparency should be maintained at each step so that how the choice of method affects the results is communicated along with the results.

When two or more ranges of uncertainty are combined, the resulting probability distribution will favour the central tendencies of the input PDFs subject to the method of combination (e.g. Jones, 2000b; Schneider, 2001; Wigley and Raper, 2001; Jacoby 2003; Wigley, 2003). Monte Carlo analysis (repeated random sampling) and Bayesian analysis (testing the impact of prior information on the results) are two of the methods commonly used. The need to apply different constructions of probability and likelihood within a Bayesian framework is discussed by Jones (2000b), New and Hulme (2000), Moss and Schneider (2000) and Schneider and Kuntz-Duriseti (2002). Bayesian reasoning can be used to test different input assumptions to determine whether the results are sensitive to those assumptions (e.g. New and Hulme, 2000; Jones and Page, 2001; Dessai, 2003). If they are, then the structure of input uncertainties is important and further research in that area is warranted. If the output is insensitive to input assumptions, then that aspect of the analysis is robust.

Such methods are more flexible and parsimonious than objective methods for 'forecasting' climate change. Multiple runs of different climate models sampling a range of plausible climate sensitivities and feedbacks, and taking into account different natural climate forcings, and land-use change and emission futures have been proposed (Allen and Stainforth, 2002). These schemes have the potential to construct PDFs where the choice of priors has less influence on the results than Bayesian or expert methods (though such an exercise can never be truly 'objective'). However, this would require several orders of magnitude more model runs than assessed by the Climate Model Intercomparison Program: over 2,000 simulations (Allen and Stainforth, 2002). An added difficulty is the choice of greenhouse gas emission scenarios. Would that set of simulations include the SRES non-greenhouse gas policy scenarios, greenhouse gas policy stabilisation scenarios or both?

Forecasting methods have the potential to constrain biophysical uncertainties but it is less clear how they could be used to assess different policy options, unless a different forecast is made for each set of starting assumptions. Forecasts are largely exploratory methods, based on how the future might unfold given a starting set of assumptions. Normative methods are based on a description of how the future might be. For example sustainability is a normative condition, whereas business-as-usual scenarios are exploratory. Because the SRES scenarios are non-greenhouse gas policy scenarios free of explicit measures to mitigate emissions (Nakicenovic and Swart, 2000) they are exploratory, although they contain normative elements not directly related to climate change policies (e.g. specific environmental and economic aims). Stabilisation scenarios designed to explore issues of dangerous climate change are normative.

Methods are needed that can be used to explore both exploratory and normative futures. What happens if no climate change policies are applied? What is the impact of different policy regimes? Policies leading to the stabilisation of greenhouse gases will make non-policy greenhouse gas scenarios redundant, so any forecast of mean global warming or of regional climate change based on so-called non-policy scenarios must be wrong if it is to be effective in mitigating climate change risks. Risk assessment is much more flexible, having the potential to utilise both subjective and objective methods to explore both exploratory and normative futures.

## 2.2 Scale

The dependence of impacts on scale is critical for assessing impacts and adaptation. In most sectors impacts vary widely between locations and groups of people. A major impediment to large scale or top-down impact assessments is that the results from one location cannot be usefully applied to another. Local knowledge is critical. The experiential aspect of adaptation where people have to “learn by doing” means that local stakeholder involvement is critical to both assessment and application (e.g. Jones et al., 2003; Conde and Lonsdale, 2003). Stakeholders are also important in the development and understanding of critical thresholds (Jones, 2001).

Most of the top-down methods assessed by Smith and Hitz (2003) contain a degree of spatial representation to account for differences between regions (e.g. Parry et al., 2001). This heterogeneity is due to both the nature of the climate changes, which are unlikely to be uniform over large areas, and to the distribution of impacts and vulnerability. However, circumstances often dictate that single relationships are utilised widely in global impact models, even though the investigators are aware of widely varying relationships between locations. So assessments in developed countries with good data, e.g. for agriculture in the Europe and the USA, cannot be immediately transferred to Africa or Asia where data is not readily available, because the results will misrepresent those countries’ adaptive capacities. The main benefit of global assessments is that they provide a broad picture of outcomes but may be limited in spatial and temporal detail. In some cases this may significantly constrain estimates of damage costs.

Bottom-up assessments can manage these details much better but need to be aggregated in some way if a global picture is to be obtained. Site specific assessments can also provide local detail that can be used to inform global impact models. For example, transfer relationships based on local information can be used to scale up impact assessments in larger models, but are needed for many regions, not just the few where assessments have been carried out.

A major advantage of local assessments is that scale and complexity can be managed allowing the development of models that can be run with a large number of scenarios, therefore allowing the construction of probability distributions (Jones, 2001). Global impact models are more complex and can usually only be run with a limited number of scenarios. However, the results from local assessments driven with variables critical to a specific activity cannot be readily compared with those from another activity. For example, a crop assessment driven by temperature, rainfall and atmospheric $CO_2$ cannot be easily contrasted with an assessment of storm damage. Expressing the results in terms of global mean warming may allow damages from different activities to be compared (e.g. the impacts expected with 1, 2 and 3°C warming).

## 2.3 Delay, or inertia

The delay between action and response is a key contributor to climate change uncertainty. Although greenhouse gases will mix in the atmosphere within one to two years, the resultant impacts may not manifest for decades to centuries (IPCC, 2001a). Following the stabilisation of greenhouse gases in the atmosphere, warming will continue for some decades at a gradually slowing rate, providing there are no abrupt shifts in the global climate system. Delays in warming the deep ocean mean that sea level rise may continue for centuries. This gradualist model also fails to account for catastrophic changes, or singularities that, while currently being at very low probabilities, become increasingly more likely as warming continues. However, the delay between forcing and response may continue to apply, because under past climates gradual changes in forcing have produced sudden shifts in climate (Schneider, 2003).

Adaptation needs are closely linked to planning horizons. If a current action is likely to impact for up to a century with limited ability to adapt (e.g. the building of fixed infrastructure like bridges and dams) then climate change over that period may need to be anticipated and adapted to. Irreversible impacts that are deemed critical also need to be addressed (see Schneider, 2003). Single activities may contain both short- and long-term planning horizons. Planning horizons will be of different lengths, whereas policy horizons mostly focus on the short to medium term (Jones et al., 2003). This requires outlooks to be long, whereas subsequent actions based on those outlooks can have a limited lifetime, to be re-adjusted as new information becomes available or as a policy sunset clause is exercised.

The pathway to the stabilisation of climate is likely to be a series of shorter-term actions moving towards a longer term goal. Short-term activities, such as crop choice in agriculture, can be useful adaptation options for climate change but are implemented incrementally, so can respond to climate variability on a seasonal basis; the impact of agricultural activity on the landscape and its effects on processes such as salinisation, will require very long-term planning horizons to be exercised. The latter will prove a challenge for shorter-term policy horizons. Areas where incremental adaptations may not be optimal include large infrastructure where the initial design needs to manage changing climate risks over a long time-scale such as bridges and dams.

# 3. ELEMENTS OF CLIMATE RISK ASSESSMENT

This chapter frames risk as the likelihood of exceeding the ability to cope with climate under climate change. At the local scale, the ability to cope is measured using impact and location-specific criteria. At the global scale, the ability to cope is guided by Article 2 of the UNFCCC. The case studies described in this chapter explore methods for linking these scales in order to manage risk through both adaptation and mitigation consistent with the UNFCCC. The starting point begins with risk under current climate, then utilises methods to asses how these risks may change with climate change.

Over time, societies have developed an understanding of climate variability in order to manage climate risk. People have learnt to modify their behaviour and their environment to reduce the harmful impacts of climate hazards and to take advantage of their local climatic conditions. The range of coping mechanisms within a given exposure unit or system that can be described in terms of a range of climate or climate-related phenomena is called the coping range (Hewitt and Burton, 1971; Smit and Pilofosova, 2001). Technological and social developments can be used to expand the coping range. Climate-related outcomes are beneficial within the coping range, display a tolerable level of harm towards the margins and exceed tolerable levels of harm beyond the margins, where a system becomes vulnerable (Jones and Boer, 2003). This limit of tolerable harm is used to define the critical threshold (Pittock and Jones, 2000). In an agricultural system, outcomes may range from bountiful crops in the coping range, to marginal crops at the edge to crop failure beyond the range. Sometimes, the relationship is clear, as in cyclone damage or flood failure; sometimes it is indistinct, where the outcomes are contingent on socio-economic influences with varying groups showing different levels of vulnerability (Smit and Pilofosova, 2001).

In most climate-related systems, the further one moves beyond the coping range, the greater the vulnerability will be. Adaptation will expand the coping range and mitigation may limit the likelihood of that range being exceeded under climate change.

The coping range is most easily defined for an activity, group and/or sector, although sectoral and national coping ranges have been proposed (Yohe and Tol, 2002). Critical thresholds for these coping ranges will be context specific and can be expressed using a wide range of measures. A global coping range is implied by the structure of Article 2 of the UNFCCC where 'dangerous' climate change forms a global critical threshold. However, this threshold is difficult to define and will be interpreted variously according to different levels of risk perception, risk tolerance and the criteria used to measure damages and benefits.

## 3.1 Global scale

The IPCC Third Assessment Report concluded that as global warming increases, the number of activities damaged by climate change will increase, as will the damage suffered by individual activities (Smith et al., 2001). This allows the magnitude of global warming to be linked with the severity of consequences (IPCC, 2001a; Parry et al., 2001; Swart et al., 2002). If impacts can be expressed as a function of the increase in global mean temperature, then it is possible to integrate a large number of impacts. At low levels of warming there may be many positive and fewer negative impacts, but those negative impacts will affect the poor disproportionately. At high levels of warming the impacts will be more negative and more widespread (Smith et al., 2001). The likelihood of reaching dangerous climate change is therefore low at low levels of global warming, increasing at ever higher levels, although the decision of what is dangerous is a policy-related rather than scientific question (Azar and Rodhe, 1997).

In terms of exceeding given levels of global warming, the likelihood of exceeding the lower limit of the potential range of warming will always be higher than the likelihood of exceeding the upper limit. For example, if we assume that the range of 1.4°C to 5.8°C (IPCC, 2001b) forms the limits of the well-calibrated range of possible global warming by 2100, the lower limit of 1.4°C is highly likely to be exceeded and the upper limit is highly unlikely to be exceeded. This outcome holds even though the objective probability distribution of global warming remains unknown and will hold for all subjective distributions. Therefore, a cumulative probability distribution function (CDF) from low to high levels of warming that measures the likelihood of exceeding a given level of warming is more robust in terms of assessing risk than a peaked probability distribution assessing the "most likely" value of global warming.

Under this structure, the adverse consequences of climate change increase with global warming, while the likelihood of reaching successively higher levels of damages decreases. However, the product of probability × consequence remains unknown. For damage functions that increase slowly, risk may diminish as probabilities reduce; for damage functions that increase steeply, risk may increase non-linearly and peak towards the upper limit of the warming range; for damage functions that are step-like, especially global-scale singularities such as ice-sheet collapse, risk may extremely high at very low probabilities occurrence (e.g. for sake of argument, a 5% likelihood of a 10% decrease in global Gross Domestic Product would be non-trivial).

### 3.2 Local scale

At the local scale, damages will increase as climate takes a system beyond its coping range. Most damages will occur in response to altered variability and extremes. For example, increases in the rate and magnitude of coral bleaching, inundation of low coasts during storm surges, fire frequency and drought and floods may exceed rates that allow system recovery. For each system and location, this relationship needs to be understood under past, present and future conditions. The consequences of climate change for a particular activity can be assessed using a critical threshold marking the tolerable limit of harm (Parry et al., 1996), or as a continuous relationship that can be partitioned according to given levels of success or failure (Jones and Boer, 2003).

The coping range can be used as a conceptual model to operationalise and communicate risk. The climatic stimuli and their responses for a particular locale, activity or social grouping can be used to construct a coping range if sufficient information is available (e.g., Smit and Pilifosova, 2001). Changes in climate hazards may lead to critical thresholds being exceeded more frequently (Pittock and Jones, 2000). Ideally a critical threshold marks a known level of vulnerability, broadly defined as the outcome of climate-related hazards in terms of cost or any other value-based measure (Jones and Boer, 2003). Society will also change over time, altering its capacity to cope with climate hazards. It is therefore possible to compare changing hazards with current capacity or to alter the coping capacity of society in line with projected socio-economic change at some time in the future (Jones and Mearns, 2003). This can be in the form of an anticipated change, for example as the result of policy or planned development, or a desired change, for example a future sustainable state. An example of how the ability to cope can totally alter the response to climate-driven hazards is provided by Tol (2003) who describes how economic development in an emissions scenario can negate changed exposure to malaria vectors caused by the accompanying projected climate change. Changes in climate hazards can be modified by mitigation and the width of the coping range modified by adaptation. Both will alter projected risks.

# 4. APPLICATION OF RISK ANALYSIS

The following sections show how to formulate both local and global scale risk assessments in a manner consistent with Article 2 of the UNFCCC. Cumulative probability distribution functions are created to assess the likelihood of exceeding critical thresholds (the point at which harm exceeds levels of tolerance): 1) using generic examples of global warming and sea level rise, 2) an example of local coral bleaching 3) an example using regional water supply and 4) assessing the likelihood of being able to stabilise atmospheric $CO_2$ below a given global average temperature at equilibrium.

Risk analysis can be applied to climate change impacts in two ways, depending on whether the starting point focuses on the climate hazard or on the socio-economic outcome. The first method assesses the likelihood of a given hazard then of the ensuing consequences. This is the approach usually used in natural hazards research and is consistent with the standard approach to impact assessment as described by Carter et al. (1994) with the addition of probabilistic methods as described by Jones (2001). It can be applied to simple and complex climate hazards and to secondary hazards closely aligned with climate, such as fire and flood, where climate can be closely aligned with outcomes. It is largely an exploratory method. The second method focuses on the outcomes, setting criteria based on possible desirable or undesirable future states, such as critical thresholds, and then analysing the likelihood of exceeding those criteria. These criteria can be based on current or plausible future levels of adaptation. This is largely a normative method, where thresholds can measure a level of criticality that is to be avoided, or a set of desirable future conditions. Both methods are applied in the following sections.

## 4.1 Global sea level and temperature rise

The following example shows how probabilities of exceedance can be applied to thresholds for warming and sea level rise set based on global average values. The use of global values for location-specific thresholds is a low-precision method best used when regional climate scenarios or quantitative links between climate and impacts are not available. It can also be used to estimate the exceedance of ‘global’ critical thresholds, but these are subject to the same limitations of global damage functions as discussed earlier.

Two critical thresholds for warming of 1.0°C and 2.5°C are compared. Of those two thresholds, a global average warming of 1.0°C is much more likely to be exceeded. For example, coral reefs that bleach above a warming threshold of 1.0°C face a far greater risk than those that will not bleach below 2.5°C. (In other words, it is more likely that a 1ºC threshold will be exceeded than a 2.5ºC threshold when looking across all possible climate outcomes.) The most southern permafrost zones in Europe, Asia and North America will experience seasonal melting at lower temperature rises than those further north. Alpine ecosystems close to their marginal limits will be more severely affected than those at higher altitudes. The same principle holds for sea level rise. For example, we intuitively know that the lowest areas of coast are the most likely to be inundated, irrespective of the level ultimately reached. Applying the IPCC (2001b) range of sea level rise of 0.09 to 0.88 m at 2100, a section of coast vulnerable to a rise of 0.25 m is much likelier to be affected than a section vulnerable to a rise of 0.75 m. This principle extends to all activities where critical thresholds or other risk-based criteria can be characterised as a function of mean global warming or of sea level rise.

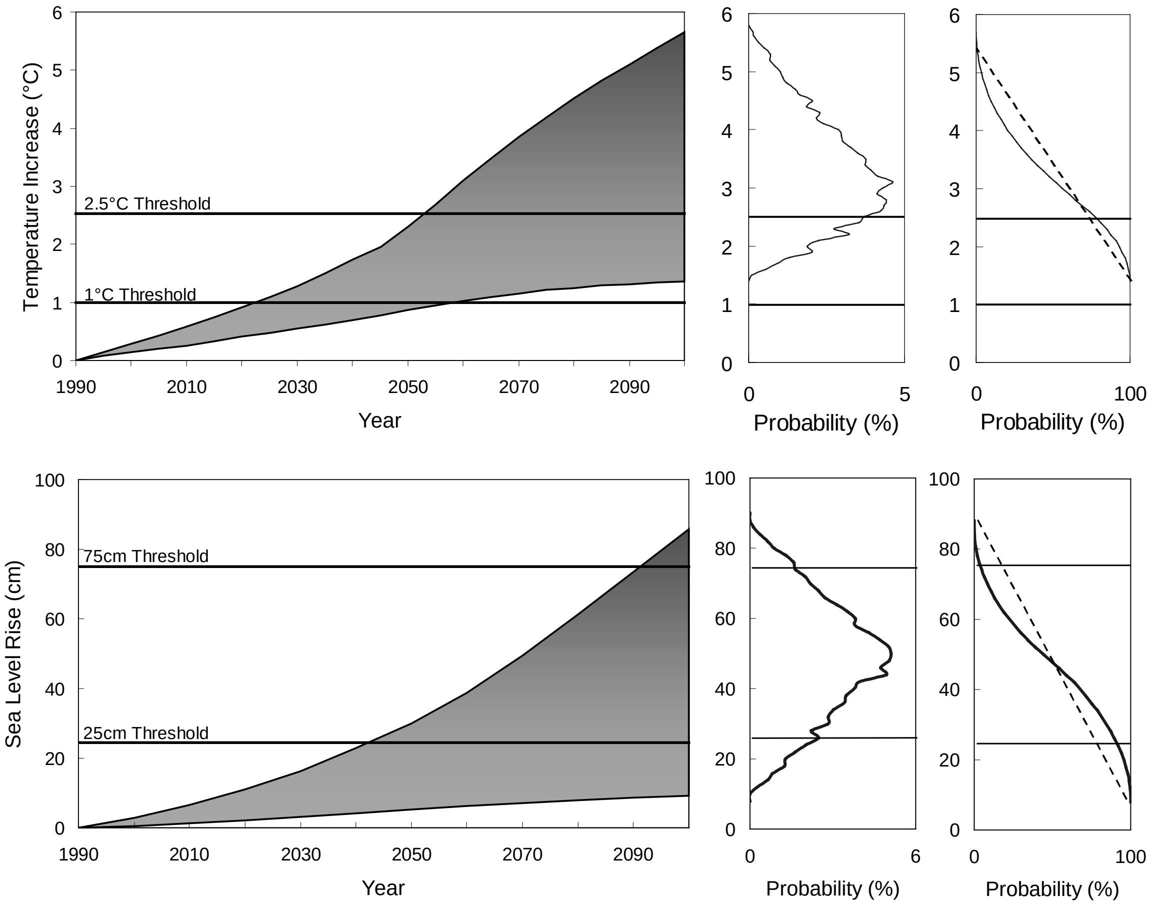


Figure 2. Relating threshold exceedance to the likelihood of climate change. The left-hand panels show ranges of temperature increase (upper charts) and sea level rise (lower charts) 1990–2100, showing a 1°C and 2.5°C warming threshold and a 0.25 m and 0.75 m sea level rise threshold, respectively. The centre panels illustrate the 'most likely' outcomes for temperature and sea level rise in 2100 based on prior assumptions of input uncertainties. These probability distributions each combine two ranges of uncertainty, randomly sampled and multiplied in a manner consistent with Schneider (2001; see text). The right-hand panels show the same probability distributions recast as likelihood of threshold exceedance (cumulative probability). The dashed line represents a uniform probability distribution (all points are equally likely; not shown in centre panels). These probabilities show that even though the likelihood of predicting a particular outcome in terms of climate is very low, the probability of calculating threshold exceedance is much less sensitive to input assumptions and is unidirectional, proceeding from the bottom up.

Figure 2 shows how these thresholds can be related to probability distributions of global warming and sea level rise. On the upper and lower left are ranges for temperature and sea level rise from the IPCC TAR (2001b). The central panels show PDFs for 2100 constructed by multiplying two randomly sampled ranges of component uncertainties for both temperature and sea level rise. Temperature was constructed from the range of radiative forcing in Wm-2 for the SRES scenarios and the range of climate sensitivity (1.5 to 4.5°C at 2×$CO_2$), both sampled using a uniform distribution. The ranges for sea level rise are also produced from two sources: the range of thermal expansion as one range of input uncertainty and the other sources of uncertainty as the other, again sampled using uniform distributions. The right-hand panels show the PDFs recast as CDFs. The PDFs in the central panels act are framed as conditional predictions while the CDFs in the right-hand panels illustrate the probability of exceeding a given level of damage.

It is difficult to associate each pair of thresholds in the central panels with its relevant PDF. In fact, the lower temperature threshold of 1°C falls outside the range of probabilities, but common sense tells us by 2100 this critical threshold will be exceeded under all outcomes. This would also be the case if a uniform PDF was applied in the central panels (not shown), but in terms of assessing the most likely warming and sea level rise, the two PDFs produce markedly different results. The CDFs in the right-hand panels of Figure 2 show the likelihood of threshold exceedance. The lower thresholds for temperature and sea level rise both are much more likely to be exceeded than the upper thresholds. Therefore, the locations associated with that lower threshold face a much greater risk than those locations associated with the upper threshold, allowing outcomes to be prioritised for the purposes of risk management. Probabilities of exceedance associated with the CDF are also much more robust to changes in input assumptions. For example, in Figure 2 the uniform CDF (all points in the range of global warming and sea level rise being equally likely) shows similar probabilities of exceedance to the non-uniform CDF. However, if we were relying on uniform and non-uniform PDFs to predict the most likely sea level rise or global warming, the difference between the two is substantial.

### 4.2 Local coral bleaching

This example deals with the risk of thermal bleaching of corals at a single location. Risk assessments at the local scale require estimates of local changes in key climate variables and locally relevant criteria such as critical thresholds for bleaching and mortality. The site used is Magnetic Island on the Great Barrier Reef, Australia. After assessing the risk at the local scale, this risk is then framed as a function of global warming.

Projected rises in sea surface temperature are likely to increase the frequency and severity of coral bleaching under greenhouse warming (Hoegh-Guldberg, 1999). Coral thermal bleaching occurs when local sea surface temperature rises above a threshold described by a duration–temperature relationship constructed from observed bleaching events (Berkelmans, 2001). If the number of days over the Austral summer (December–March) exceeds a given temperature, then corals are expected to bleach. Thermal bleaching curves have been constructed for several locations on the Great Barrier Reef including Magnetic Island (Berkelmans, 2001). Using these curves and artificially-generated daily sea surface temperatures (SST) based on observed data, a model was created that calculates the annual risk of bleaching under climate change. The relationship between local warming and bleaching frequency was created by perturbing a daily record of SST with incremental changes in summer SST obtained from eight climate models (Done et al., 2003).

The vulnerability of corals is related to the frequency and degree of mortality and the duration of subsequent recovery, rather than bleaching itself (Done et al., 2003). Observations of bleaching events and coral relocations suggest that mortality shows a similar relationship to days above threshold as does bleaching. For example, Acropora, an important reef genus, suffers significant mortality at 0.5°C to 1.0°C above the bleaching threshold (Berkelmans, pers. comm. 2002). This example therefore looks at the bleaching threshold itself and a succession of thresholds at 0.5°C intervals above the bleaching threshold. As each successively hotter threshold is breached, both coral mortality and the subsequent recovery time will be increased.

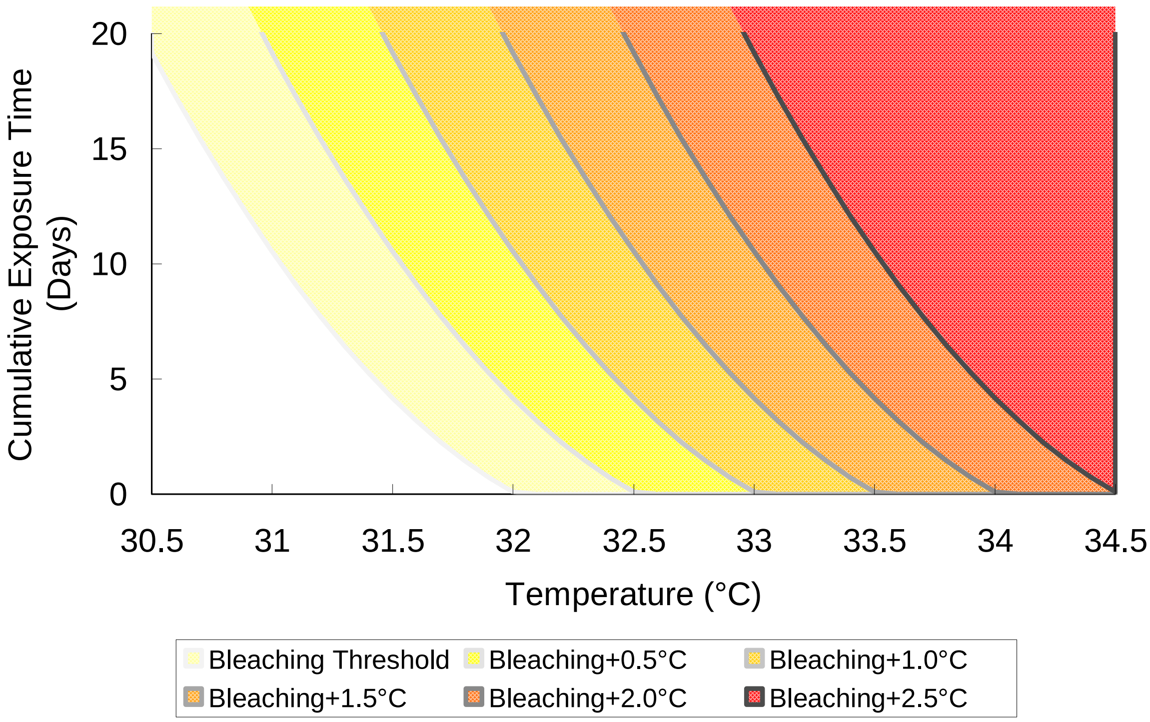


Figure 3. Bleaching and mortality curves (bleaching curves stepped up in increments of 0.5ºC) for Magnetic Island. The most severe observed events have exceeded the bleaching+0.5°C threshold. As successively more severe events occur, the recovery time will be longer. Events reaching temperatures on the right-hand side of the graph are likely to have a recovery time of decades.

Figure 3 shows the structure of the bleaching and mortality curves for Magnetic Island with the bleaching curve on the far left and a succession of curves at 0.5ºC increments up to bleaching+2.5ºC. The most severe observed bleaching events on the Great Barrier Reef exceeded the bleaching+0.5ºC threshold in 1998 and 2002 (the latter event was used to validate the model). Although significant mortality was observed in some hot-spots, recovery has been widespread. Many bleached corals recovered and fast-growing species are recolonising heavily affected areas – positive signs of a resilient ecosystem (Done, pers. comm., 2002). However, as one moves to the right of Figure 3, the numbers and species of coral affected will increase, as will aesthetic and ecological recovery times. Sustained higher temperatures will kill both fast-growing (sensitive) and slow-growing (tolerant) species. The fast-growing species are generally more sensitive to temperature, so if the slow-growing species are being killed in some years, the fast-growing species are likely to be affected in most years. The recovery period from a bleaching+2.5ºC event is uncertain, but is likely to be decades.

The next step is to estimate the frequency of bleaching events at current and increased levels of SST. Figure 4 is a bleaching-temperature response surface showing the annual likelihood of threshold exceedance for all thresholds from bleaching to bleaching+2.5ºC. The current risk of bleaching at Magnetic Island is about 40% and the risk of exceeding bleaching+0.5ºC is about 25%. This estimate is consistent with recent events; during the period 1990–2002 these probabilities were 30% and 15% respectively. Figure 4 can be read in two directions. If read from the vertical axis across to the right then down, the chart links temperature increase to a given bleaching frequency. Read from the horizontal axis up then left, the chart shows the annual probabilities of exceedance for a given level of warming.

CDFs for local increases in SST were then created and superimposed on the response surface in Figure 4. Two component ranges of uncertainty contributed to these CDFs: local increase in SST provided by eight climate models, calculated as change per degree of global warming, multiplied by ranges of global warming for 2030 and 3070 from the IPCC TAR (2001b). The CDF was constructed by randomly sampling and multiplying these two uncertainties assuming a uniform probability distribution of the components. The range of local warming for Magnetic Island on the Great Barrier Reef for the summer period is 0.66°C to 1.07°C per degree of global warming; ranges of global warming are 0.54°C to 1.24°C in 2030 and 1.17°C to 3.77°C in 2070. Uncertainty analysis showed that global warming contributes to 60% of the range of uncertainty in local SST change and local warming contributes about 40%. Using a non-linear PDF for global warming taken from Wigley and Raper (2001) did not significantly change the results.

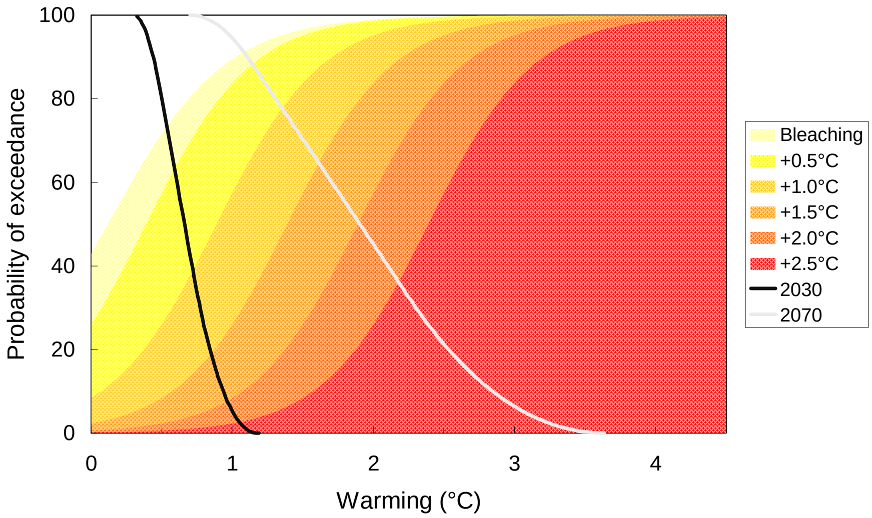


Figure 4. Response surface for warming and annual bleaching risk for Magnetic Island with probability distributions of average summer warming in 2030 and 2070 superimposed. The response curves for bleaching to bleaching+2.5ºC thresholds are expressed as the annual risk of bleaching on the vertical axis. The warming curves are expressed as the likelihood of exceeding a given mean summer warming by 2030 or 2070. Warming is measured from a 1990 baseline, the bleaching baseline is 1990–2002.

The vulnerability of coral depends on the severity and frequency of bleaching. If the recovery time between bleaching events is too brief, then the reef ecosystem will degrade, initially altering the composition of the coral community. With higher frequencies of severe bleaching, the environment will ultimately become unsuitable for coral growth (Done et al., 2003). The level of damage that constitutes a critical threshold for coral is highly uncertain and needs to be explored.

During the 1990s there was sufficient recovery time between bleaching events (Done et al., 2003), but increasing the annual frequency of exceeding the bleaching+0.5ºC threshold to 50% (equivalent to a 1998 or 2002 bleaching every second year) would place coral ecosystems under severe stress. From Figure 4, by 2030 this frequency would be exceeded by over half of the projected range of warming. By 2070 the entire range of projected warming would exceed the bleaching+0.5ºC threshold of every second year. Also by 2070, 95% of all outcomes exceed a 1ºC warming and half of the possible outcomes exceed the bleaching+2.0ºC threshold more frequently than one in every two years. Although spatial differences in bleaching thresholds suggest that thermal adaptation does occur, we do not know what adaptation rates may be, and adaptation has not yet been observed in response to past bleaching events. However, at an arbitrary rate of 0.05ºC per decade, a cushion of 0.15ºC and 0.3ºC would be provided by 2030 and 2070 respectively. This is only a small part of the total range of warming but would reduce both the lower and upper limits slightly.

The next step is to estimate the consequences of coral bleaching as a function of global warming. Figure 5 shows the relationship between global warming and bleaching risk for Magnetic Island. On the left side is a chart showing global mean warming based on the SRES marker scenarios from 1990 to 2100 with the range of local warming for Magnetic Island SSTs superimposed. The Magnetic Island SSTs show the minimum (most likely to be exceeded), 50th percentile and maximum (least likely to be exceeded) warming levels. On the right hand side, the consequences of that warming are shown as annual risk of a succession of bleaching thresholds.

Outcomes in Figure 5 are based on exceeding a succession of bleaching and bleaching/mortality thresholds one year in every two. By 2025, temperatures are likely to be causing bleaching at unprecedented levels (the bleaching+1.0°C threshold being exceeded in 50% of years), resulting in unprecedented levels of damage. At a global warming of 2.5ºC the bleaching+2.5ºC threshold will be exceeded in 50% of years, at 4.5 ºC bleaching+2.5ºC threshold will be exceeded every year. Using a spatial model of bleaching risk based on the 1998 and 2002 bleaching events on the Great Barrier Reef, Berkelmans et al. (submitted) estimate that 82% of the GBR would bleach with a warming event equivalent to a bleaching+1.5ºC event, 97% of the GBR would bleach during a bleaching+2.5ºC event and 100% of the GBR during a bleaching+3.5ºC event. Although not shown on Figure 4, a bleaching+3.5ºC event possible affecting 100% of the Great Barrier Reef has a 1 in 100 possibility with a local increase in SST of about 2ºC, increasing to 50% of frequency years with a local warming of 3.5ºC. From Figure 5, these latter two outcomes would become possible from 2040 and 2060 respectively.

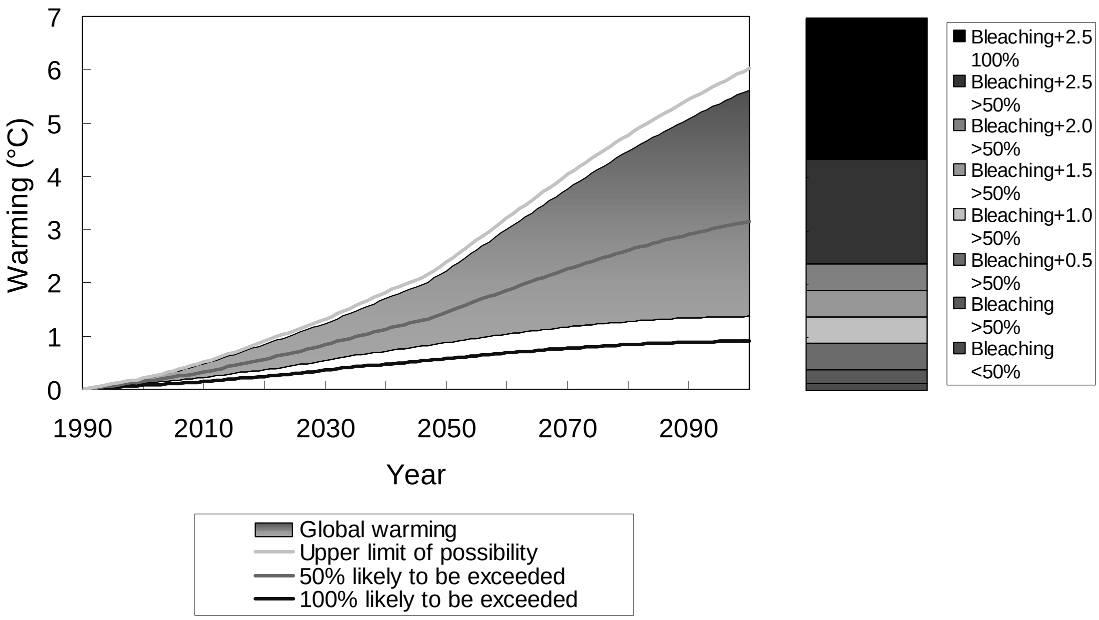


Figure 5. Global warming based on the range of SRES marker scenarios and climate sensitivity consistent with IPCC (2001) with super-imposed local warming ranges of SST for Magnetic Island, Great Barrier Reef, on the left. On the right is the range of consequences portrayed as thresholds based on exceeding the 50% levels (one year in every two) of a succession of bleaching and bleaching/mortality thresholds (and 100% of the bleaching+2.5°C threshold).

Figure 5 shows bleaching risk at single site expressed as a function of global warming. The following information is needed to expand this to a global risk assessment for coral reefs: 1) a better understanding of critical thresholds related to levels of ecosystem vulnerability, including concepts of resilience and recovery, 2) better developed spatial models of bleaching risk, 3) a larger number of site-based models of bleaching risk, 4) an understanding of other stresses contributing to bleaching or ecosystem resilience including freshwater, turbidity, over-exploitation and nutrient pollution. This can then be used to ask questions like “What level of climate change looks dangerous for coral reefs?” and “How do the risks faced by coral reefs compare with risks faced by other areas of concern?”

## 4.3 Catchment Water Supply

Impacts where rainfall is a major driver will have a large uncertainty when presented as a function of global warming because of uncertainties surrounding the direction and magnitude of rainfall change. Despite this, hydrological risks are far too important to be ignored. This next example describes water supply risks in an Australian catchment, the Macquarie River in eastern New South Wales (Jones and Page, 2001). Regional changes to potential evaporation (Ep) and precipitation (P) were used to perturb historical daily records of P and Ep from the period 1890–1996 which served as input into a river management model. The historical time series was separated into a drought-dominated (dry) period (1890–1947) and a flood-dominated (wet) period (1948–1996) allowing different modes of decadal rainfall variability to be assessed along with greenhouse-induced rainfall change. Three outputs were considered for risk assessment: storage in the Burrendong Dam (the major water storage), environmental flows to the Macquarie Marshes (nesting events for the breeding of colonial waterbirds), and proportion of bulk irrigation allocations met over time.

A transfer function summarising the results of individual models runs was created to investigate probability distributions using Monte Carlo sampling. Fifty-six simulations using a range of scenarios exploring the IPCC (2001b) range of global warming, and regional changes in P and Ep from nine climate models were analysed. The results were then used to create the following transfer function:

$$\delta\text{flow} = a \times ( \text{atan} ( \delta\text{Ep} / \delta\text{P} ) - b )$$

where atan is the inverse tan function, δEp and δP are in mm $yr^{-1}$, δflow is mean annual flow in gigalitres (GL) $yr^{-1}$ for water storage and environmental flow and percent of a capped allocation for irrigation, and a and b are constants. The results have an $r^2$ value of 0.98 and standard error in mean annual flow ranging from 1 to 2%, allowing this simple function to substitute for the more complex river management model for the purposes of risk and uncertainty analysis.

Three ranges of input uncertainty contributed to the analysis: global warming, and regional δP and δEp expressed as percentage change per degree of global warming. Monte Carlo methods were used to sample the IPCC (2001b) ranges of global warming for 2030 and 2070. These were then used to scale a range of change per °C of global warming on a quarterly basis for P. Ep was then sampled using a relationship between P and Ep established from climate model output. Finally, quarterly changes for P and Ep were totalled to determine annual δP and δEp which was then applied to the above transfer function. The following assumptions were applied to the analysis:

- The range of global warming in 2030 was 0.55–1.27°C with a uniform distribution. The range of change in 2070 was 1.16–3.02°C (Note these ranges are slightly different to those above – they were undertaken with earlier, provisional data preceding IPCC (2001b)).
- Changes in P were taken from the full range of change for each quarter from the sample of nine climate models. The annual range of change in P was about ±4% per degree of global warming.
- Changes in P for each quarter were assumed to be independent of each other (dependence between seasonal changes could not be found).
- The difference between samples in any consecutive quarter could not exceed the largest difference observed in the sample of nine climate models.
- δEp was partially dependent on δP (δEp = 5.75 – 0.53δP, standard error = 2.00, randomly sampled using a Gaussian distribution, units in percent change).

Figure 6a shows the results for 2030 that project the most likely outcomes in terms of change to mean annual supply. Although there is an increased flood risk with constant and increased flows, the drier outcomes are considered worse in terms of lost productivity and environmental services. The driest and wettest extremes are less likely than the central outcomes where the line is steepest. The extremes of the range are about +10% to -30% in 2030 and about +25% to -60% in 2070, but the most likely outcomes range from about 0% to -15% in 2030 and -0% to -35% in 2070.

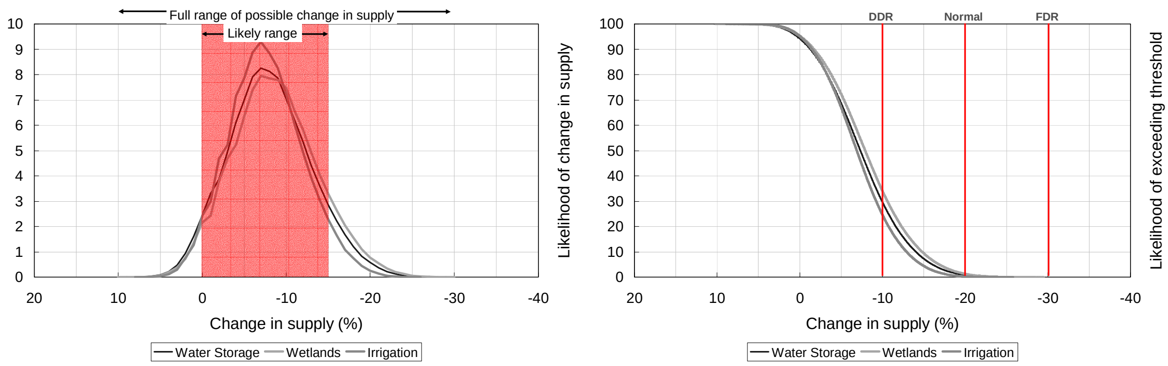


Figure 6. (a) Probability distribution for changes to mean annual Burrendong Dam storage, Macquarie Marsh inflows and irrigation allocations based on Monte Carlo sampling of input ranges of global warming, δP and δEp in 2030. (b) Cumulative probability distribution showing likelihood of exceeding critical threshold in drought-dominate, normal and flood-dominated rainfall regime.

To assess vulnerability, two critical thresholds for the system were considered:

1. Bird breeding events in the Macquarie Marshes, taken as 10 consecutive years of inflows below 350 GL.
2. Irrigation allocations falling below a level of 50% for five consecutive years.

Both thresholds are a measure of accumulated stress rather than a single extreme event. From the sample of initial runs described above, both thresholds were exceeded if mean annual flow declined by >10% in a drought-dominated climate, >20% in a normal climate and >30% in a flood-dominated climate. Their probability of being exceeded by 2030 is shown in Figure 6b. If climate is in a drought-dominated regime, there is a 30% probability of the two thresholds being exceeded, but the likelihoods are small if rainfall is close to normal or in a flood-dominated regime. The probabilities of critical threshold exceedance in 2070 are much higher (Jones and Page, 2001)

Uncertainty analysis was carried out to understand how each of the component uncertainties contributed to the range of outcomes. Three ranges of input uncertainty (global warming and local changes in P and Ep) were assessed by keeping each input constant within a Monte Carlo assessment while allowing the others free play, (e.g., Visser et al., 2000; Wigley, 2003). Global warming was held at 0.91°C in 2030 and 2.09°C in 2070. δP was taken as the average of the nine models in percent change per °C global warming for each quarter. δEp was linearly regressed from δP, omitting the sampling of a standard deviation. In both 2030 and 2070, δP provides almost two-thirds of the total uncertainty, global warming about 25% and δEp just over 10%.

The contribution of input probability distributions to the results was explored through Bayesian analysis (e.g. New and Hulme, 2000). The input PDFs of δP, δEp and global warming were investigated as were different sampling strategies. In terms of cumulative probability distributions, the results did not change markedly (usually <10% for the original distribution; Jones and Page, 2001). The ‘most likely’ parts of the ranges were largely unaffected by increasing the ranges of input uncertainty, even though the breadth of the range increased.

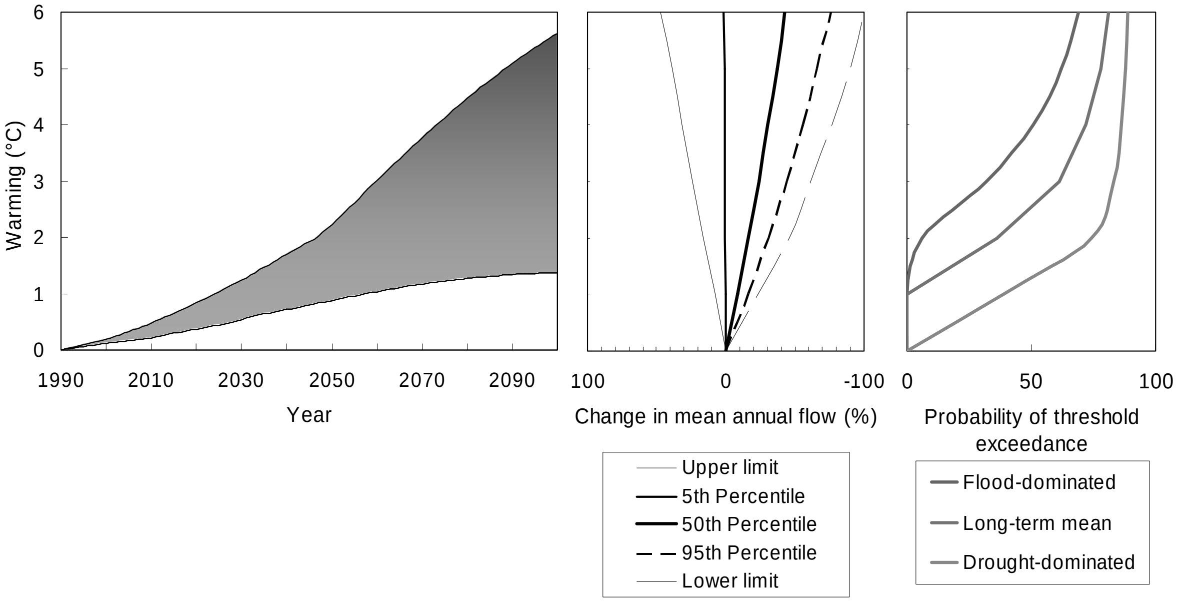


Figure 7. Change to annual water storage and supply for the Macquarie River shown as a function of global warming. The central panel shows the range of change in flow using the upper and lower limits, 5th and 95th percentile and the 50th percentile. The likeliest 90% of outcomes lies within the 5th to 95th percentiles extending from neutral to strongly negative. The right-hand panel shows the likelihood of exceeding critical thresholds as a function of decadal rainfall regime and global mean warming.

The results were converted to express changes in mean annual water storage as a function of global warming. This was undertaken by making incremental changes in global warming (in the range 1°C to 6°C at 1°C intervals) and holding that level constant while sampling the full ranges of δP and δEp in a manner similar to the uncertainty analysis carried out above. The results are shown in Figure 7, where the central panel shows the total range of uncertainty as a function of global mean warming (left-hand panel). The right-hand panel shows critical threshold exceedance as a function of decadal rainfall variability and global warming.

The range of uncertainty for mean annual flow increases markedly with global warming although the most likely 90% of outcomes form a substantially smaller range (the area lying within the 5th and 95th percentiles in the central panel of Figure 7). The likelihood of crossing the two critical thresholds also increased with global warming. With a warming of 2°C there is approximately a one in three chance of exceeding the critical thresholds if decadal rainfall variability is close to the long-term mean; this is less likely if rainfall variability is in a flood-dominated regime and more likely if rainfall is in a drought-dominated regime.

The largest uncertainty is the direction and magnitude of rainfall change which, if known, would reduce total uncertainty enormously. Climate models indicate that once a direction of rainfall change is established, the magnitude increases with global warming (at least until stabilisation; Cai et al., 2003), therefore the identification of rainfall change is critical for impacts dependent on the volume of precipitation. Once the direction of rainfall change is established, drought and/or floods will intensify over time, requiring adaptation commensurate with the magnitude of global warming. The regions where small changes in climate are likely to breach a critical threshold are those that face the greatest risk.

Decadal rainfall variability complicates matters, and may delay the attribution of rainfall change for some decades (Hulme et al., 1999). In the study region, decadal variability can vary rainfall by as much as ±20% from the long-term mean. Without understanding the dynamics of such changes, diagnosing the magnitude and direction of rainfall change under global warming will be extremely difficult. Therefore, the large uncertainties affecting the results will remain significant until the direction of rainfall change is established and decadal rainfall variability is better understood. However, much of the vulnerability within the catchment is due to over-allocation of resources. This vulnerability can be significantly reduced by adaptation consistent with carrying out the National Water Reform process, securing adequate environmental flows and increasing the efficiency of irrigation water use.

Globally, aggregating information from different water supply systems is a difficult task. Populations exposed to water stress is the major criterion used by Arnell et al. (2002) in a global assessment using model output from a single GCM forced by two stabilization profiles. However, few large assessments have involved inputs from more than one climate model, and the results are highly dependent on rainfall changes which are very model specific. The technique used here has been to explore uncertainty using a very simple model constructed from a more complex system specific model. To demonstrate a wider utility, similar methods need to be applied in a larger number of river basins around the world.

### 4.4 Greenhouse gas stabilisation

This section looks at managing climate risks by stabilising greenhouse gases at a level that aims to avoid ‘dangerous’ climate change consistent with the UNFCCC. Based on a series of input assumptions, the conditional probabilities of meeting joint equilibrium temperature and stabilisation targets are explored. Note that this section is exploratory, serving to provide example only. In a genuine risk assessment, a wide range of underlying assumptions should be explored.

The previous examples illustrate analytic frameworks that, by expressing local climate risks as a function of global warming, can be placed within a global context. Although these risks increase appreciably with global warming, the critical thresholds that occur at the lowest levels of warming will have the highest probability of exceedance. Damages occurring at low levels of global warming display the greatest need for adaptation. However, where adaptation is not feasible, where serious and irreversible outcomes are possible, or where aggregated damages from a large number of impacts become significant, stabilisation of greenhouse gases at safe levels will be required.

The SRES scenarios are non greenhouse-gas-policy scenarios that have no specific allowance for mitigation of greenhouse gases (Swart et al., 2002), although some do have normative environmental elements. One robust aspect of risk management through mitigation is that if reductions in greenhouse gases are sustained over time the potential range of global mean warming will reduce from the top down. The warmest outcomes become progressively less likely while the lowest probabilities of exceedance remain largely unchanged (unless stabilisation leads to the reduction of the lower limit of warming compared to that produced by the B1 scenario). Probabilities can be used to explore how mitigation can be used to manage risk by stabilising greenhouse gas emissions at different levels and thus limit warming.

Monte Carlo sampling of the input uncertainties of the temperature at stabilisation, measured as the change in temperature since 1990, was explored using the relationship:

$$T_{stab} = -0.7 + \partial T_{2\times} \times \mathrm{Ln}(CO_{2\,stab} / 278) / \mathrm{Ln}(2) + \partial Q_{non\text{-}CO2} / (3.71 \times \partial T_{2\times})$$

Where -0.7 allows for warming already experienced, $T_{stab}$ is the temperature at stabilisation, $\partial T_{2\times}$ is temperature sensitivity, $CO_{2stab}$ is the atmospheric concentration of $CO_2$ in ppm and $\partial Q_{non\text{-}CO2}$ is the radiative forcing of non-$CO_2$ elements (greenhouse gases and aerosols) in $Wm^{-2}$. The ranges of change were 354 ppm to 1000 ppm for $CO_{2stab}$, -0.5 $Wm^{-2}$ to 3.5 $Wm^{-2}$ $\partial Q_{non\text{-}CO2}$ and 1.5°C to 4.5°C $\partial T_{2\times}$. The range of $CO_2$ stabilisation extends from the concentration in 1990 to 1,000 ppm; the range of non-$CO_2$ forcing is 1.5 $Wm^{-2}$, close to the average of all SRES scenarios to 2100, with uncertainty bounds of ±2

$Wm^{-2}$; the climate sensitivity has been unchanged since 1PCC (1990) and the forcing relationships can be found in Appendix 2 of IPCC (1997). Each of these ranges was sampled independently assuming a uniform probability across the range, for a total of about 65,000 samples.

The impacts of using prior assumptions within such an exercise were discussed earlier.

Figure 8 shows two constructions of probability for temperature at stabilisation: the peaked and cumulative distributions as a function of increasing temperature. Figure 8a shows that (according to the input assumptions) the most likely outcome is close to 3°C but that warming at stabilisation ranges from <1°C to >11°C. Figure 8b presents the same distribution as a cumulative probability function, showing that the 50th percentile is about 4°C. Therefore, based on this example, if policy makers decided that it was desirable to remain below a stabilisation level of 1,000 ppm $CO_2$ in the atmosphere, there would be a 50% probability stabilising below 4°C and 50% probability of being above. Limits of 1.5°C and 6°C are also shown. These limits are used to explore ‘what if’ questions about establishing the level of dangerous climate change, shown in Figure 9.

Having information on risk as a function of global warming on a global or a local basis allows us to ask the question: “What is the level of greenhouse gas stabilisation needed to stay below critical outcomes?” The probability distribution in Figure 8 can be partitioned to provide guidance on this question. Assuming that it is not possible to identify the level of dangerous climate change a priori then the likelihood of reaching different levels can be investigated by relating global warming to an aggregate of local criteria, or to global criteria. At this stage, given the limited information linking global warming to levels of damage or to damage functions, it seems prudent to investigate the likelihood of reaching a wide range of targets. The probability of exceeding different levels of global warming was investigated as a function of stabilised atmospheric $CO_2$. The likelihood of stabilising between 1.5°C and 6°C was also assessed.

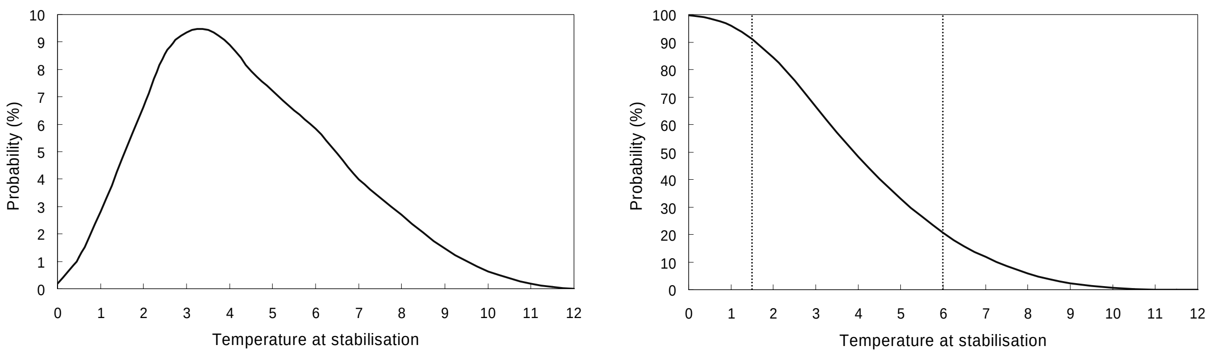


Figure 8 (a) Probability distribution function for the global average temperature at stabilisation. (b) Cumulative probability of temperature of stabilisation as a function of being below a given temperature.

Figure 9 shows the likelihood of reaching different levels of warming at equilibrium. The curves each represent the range of temperatures between 1.5°C and 6°C in increments of 0.5°C. The vertical axis indicates the likelihood of being below a given temperature. The three horizontal dashed lines denote a 2 in 3, 50/50 and 1 in 3 probability of being below a given temperature and concentration, denoted as the point where a temperature curve crosses each line.

For example, if we wish to investigate whether stabilisation below 2°C is possible, then we have a 50/50 chance of being below that level at about 440 ppm $CO_2$. If we wish to stabilise below 3.5°C, there is 2 in 3 chance of success by stabilising at 500 ppm $CO_2$. At 650 ppm this falls to a 40% chance of being below 3.5°C. Conversely, if we wish to stabilise $CO_2$ at 750 ppm, then we have a 1 in 3 chance of being below 4°C, a 50/50 chance of being below 5°C and a 2 in 3 chance of being below 6°C.

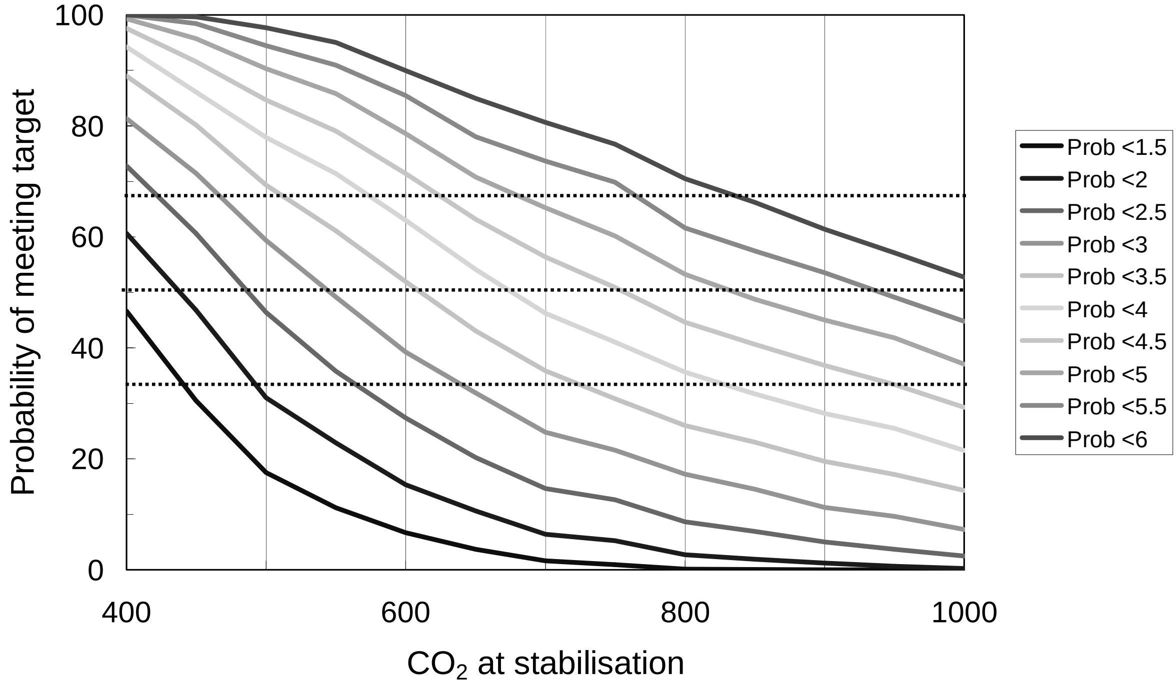


Figure 9. Likelihood of meeting designated temperature targets and given levels of global warming, based on the probability distribution shown in Figure 8. Three horizontal dotted lines of likelihood, a 2 in 3, 50/50 and 1 in 3 chance of stabilising below a series of equilibrium temperatures ranging from 1.5°C to 6°C at a given level of $CO_2$ stabilisation, are shown.

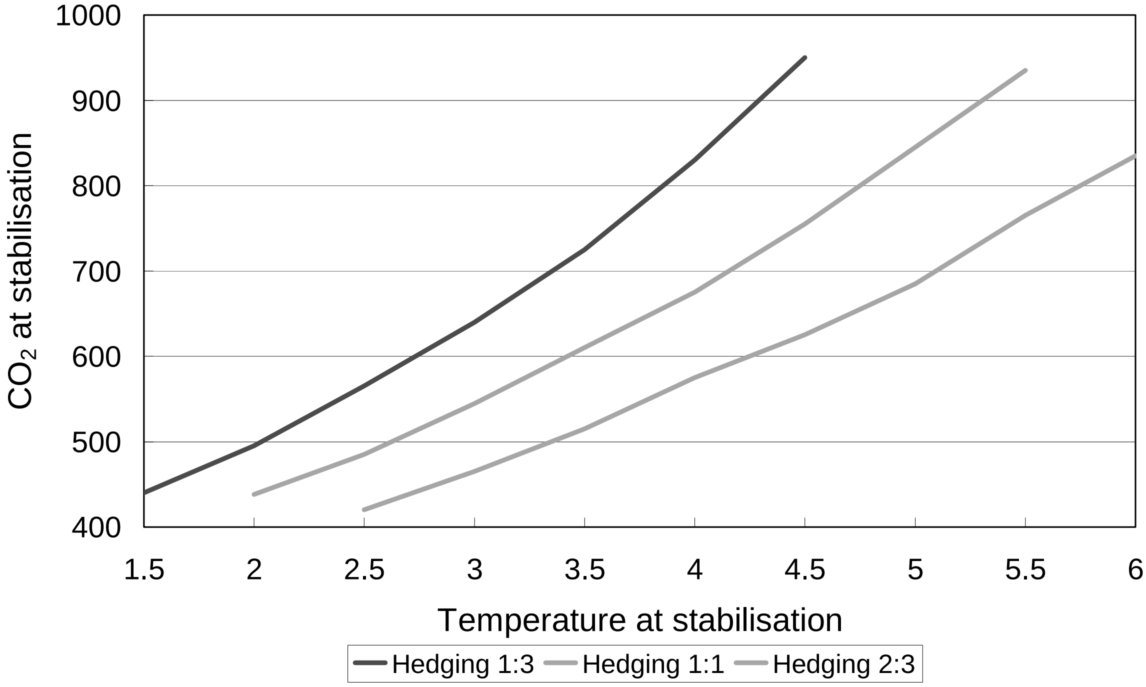


Figure 10. Lines of likelihood, hedging a 1 in 3, even probability and 2 in 3 change of stabilising below a given temperature at different levels of $CO_2$ stabilisation derived from Figure 9.

Alternatively, we may be interested in the levels of risk hedging. For example, Figure 10 summarises results from Figure 9 in terms of hedging risk at 1 in 3, 50/50 and 2 in 3 probabilities. For example, to have a 2 in 3 chance of being below an equilibrium temperature of 3°C, stabilisation at about 450 ppm would be required. At 5°C with the same level of hedging 700 ppm would suffice. What levels of hedging would policymakers prefer to utilise if they wish to stabilising emission in order to avoid damages? This is an interesting area of policy research yet to be explored.

The axes in Figure 10 can also be viewed in terms of increasing costs of mitigation down the vertical axis and increasing cost of damages along the horizontal axis. A reasonable cost-benefit outcome would occur in the zone where the costs on both axes are similar, or where net benefits outweigh costs. However, if we superimpose the lines of hedging in Figure 10 on this structure it becomes clear that a neutral or positive cost-benefit outcome would only have a limited probability of occurring. Even if the socio-economic outcomes could be controlled through risk management, the scientific uncertainties may remain sufficiently large to limit the likelihood of being able to reach a positive cost-benefit outcome. Utilising uncertainty analysis as detailed here and in Wigley (2003) would help to constrain such uncertainties.

This analysis is very much at odds with models that optimise damages in order to assess costs. By taking risk into account, the likelihood of reaching a balanced outcome is limited, whereas models that optimise costs always reach a balanced outcome. The requirement within the UNFCCC to use the precautionary principle in managing climate uncertainties suggests that explicitly dealing with risk is the more appropriate approach. Therefore, this example shows that the probability of being able to meet a 'balanced' outcome on the basis of cost-benefit needs to be factored into cost-benefit analyses. If non-monetary damages can also be attached to different levels of stabilisation, then the costs and ancillary benefits of mitigation can be weighed up with the costs and benefits (ancillary and non-monetary) of adaptation within a probabilistic framework.

This task would require the aggregation of local benefits developed through bottom-up assessments that build on those described here, and through increasingly sophisticated models that can assess damages at the global scale. This is an area that requires considerable further work.

# 5. DISCUSSION AND CONCLUSIONS

## 5.1 Managing risk across scale

This chapter describes risk assessment methods structured around the objectives of Article 2 in the UNFCCC that aim to manage the uncertainty, scale and delays between implementation and response under climate change. Two of the key linkages concern aspects of scale:

- the scale of the assessment in the form of top-down and bottom-up methods and
- the scale of the prescribed risk management options of adaptation and mitigation.

Risk is explored through assessing climate–society relationships at these different scales. Relationships between climate hazards and coping strategies are largely specific to activities, communities and locations. However, some risks, such as the risk of large ice-sheet collapse and the cessation of deep ocean-water formation, are global in scale. If global warming moves a system beyond its coping range, the number and magnitude of hazards will increase making that system vulnerable. The critical threshold is located where the level of vulnerability exceeds a tolerable limit. Therefore, many of the damages of climate change are scale-specific ranging from local to global scale, but occurring mainly on smaller scales.

Adaptation modifies the coping range of a system by expanding its breadth, whereas the mitigation of greenhouse gases modifies the climate hazards themselves. Although adaptation and mitigation cannot be directly mapped onto top-down and bottom-up methods, adaptation is better suited to bottom-up methods of assessment, and mitigation, because it acts directly on the magnitude of climate change, is better suited to top-down methods. Although the impact of mitigation on climate is best measured at the global scale, mitigation can be implemented across a range of scales (e.g. industry, enterprise and regional scales). The ancillary benefits of mitigation will also accrue at these scales while benefits of reduced damages will occur on impact-relevant scales. Therefore linkages between different scales are needed (bottom-up and top-down) as well as within a single scale of assessment.

Likelihoods of reaching or exceeding specific outcomes are assessed by sampling and combining the ranges of uncertainty contributing to those outcomes. The two case studies of coral bleaching and water supply show this in terms of key input variables and thresholds specific to each situation.

Coral bleaching was assessed in terms of local sea surface temperature, with the hazard measured as degree days above a series of bleaching and mortality thresholds. Although the coping range for coral under thermal beaching is uncertain, recent bleaching events indicate that is close to its limits in many locations. The analysis in Section 4.2 shows that severe impacts will occur on the Great Barrier Reef under modest increases in local warming (c. ~2 °C). Further work needs to determine critical thresholds for coral based on both biophysical and social criteria, for example the ecology and aesthetics of reef systems as proposed by Done et al. (2003) or in terms of its impacts on tourism (Hoegh-Guldberg and Hoegh-Guldberg, 2003).

The results from the catchment water supply assessment were presented in two ways: as 'most likely' outcomes in terms of water supply, and in terms of critical threshold exceedance. These thresholds were subject to changes in both mean rainfall and decadal rainfall variability imposed on interannual rainfall variability. If rainfall is in a drought-dominated regime, then a further decrease of streamflow of 10% would exceed the catchment-wide coping range in terms of irrigation supply and environmental flow. These thresholds would be -20% in a normal climate and -30% in a flood-dominated climate.

Both case studies presented their results in terms of a locally specific coping range. This structure minimises the input uncertainties providing information for risk assessment at the scale most suitable for assessing adaptation needs. Because both impact assessments were couched in impact-specific terms, they had no common metric that could be used for aggregation. Converting their results to a factor of global warming increases their uncertainty, because global warming comprises only 60% and 25% of the joint ranges of input uncertainty for the coral bleaching and water supply cases respectively. However, this procedure allows different local assessments to be compared and their results to be aggregated to larger scales.

This task will be made easier if common measures specific to each type of impact are developed to allow results to be aggregated at the global scale. For example, a common level of frequency and/or severity above a given bleaching threshold could be used to assess potential damages to coral reefs worldwide, allowing the global proportion of coral reefs under threat to be assessed. For water resources, water quality and supply under stress at the catchment scale and aggregated to number of people (as in Arnell, 1999), or areas of wetlands, may provide suitable global measures. However, assessing the likelihoods of water-related impacts will be more complex to manage because of the number of climatic and non-climatic drivers. The relative risks between different activities, sectors and regions could also be assessed to determine which faced the greatest risks or benefits under climate change.

The structure of the coping range can also be applied to global scale risks on a conceptual level, using the UNFCCC as a guide. Climate change threatens to global mean temperature beyond levels previously experienced by humans, by human systems and by many other species. Dangerous climate change forms a threshold which cannot be predicted a priori and which is likely to be defined in policy terms rather than objectively through scientific means. However, research can contribute to its definition through an understanding of risk under successively higher levels of global warming. This position will evolve over time as new information emerges.

### 5.2 Managing risk over time

Sections 4.1, 4.2 and 4.3 provide information on the changing probabilities of exceeding thresholds attached to individual activities over the course of this century. However, Section 4.4 on global risks deals with stabilising climate at an indeterminate time in the future, rather than assessing evolving risks over time. To be effective, risk management needs to act on robust information as it becomes available at the same time as risk assessment strives to understand the remaining uncertainties. The role of policy is crucial in deciding when and how to act. Near-term action in mitigation and adaptation would reduce risks (IPCC, 2001a) but the framework for how this should be decided has not yet been established.

The preceding case studies showed that the critical thresholds exceeded under low levels of global warming were likely to be exceeded earlier rather than later, and under a greater range of emission scenarios. The thresholds dealt with here were static, but thresholds based on rates of change, such as those associated with forest migration (Leemans and Eickhout, 2003) can also be used. Activities with critical thresholds that are sensitive to low levels of climate change are often also subject to significant risks under current climate – in such cases adaptation will yield both short and longer-term benefits. Likelihoods of critical threshold exceedance under climate change can then be used to prioritise the need for adaptation.

Activities likely to be affected within their planning horizons would then receive a high priority for adaptation. Adaptation measures would then be prioritised according to their feasibility and net and ancillary benefits. If autonomous and planned adaptation cannot sufficiently reduce the risk of critical outcomes, mitigation will become the primary mechanism of risk management.

Adaptation does not alter the frequency and magnitude of primary climate hazards, but increases the ability of an activity to cope with climate change. This will either delay critical threshold exceedance or if adequately integrated with mitigation may allow the rate of climate change to slow and stabilise before a given critical threshold is exceeded. Secondary climate hazards such as flooding or fire are influenced by human activities so can be partially modified by adaptation in addition to mitigation.

We have assessed adaptation in two probabilistic impact assessments: milk loss under heat stress (Jones and Hennessy, 2000) and wheat production (Howden and Jones, 2001). In both cases, the net benefits of currently practised adaptations increased with global warming even though those benefits did not keep up with increasing loss rates in all cases, showing that eventually, losses can outstrip benefits under larger climate changes. For activities where damages increase with global warming, adaptation will become more difficult and expensive with increasing climate changes. More activities will also require adaptation. This suggests that the ability to adapt is limited and is best suited to modest changes in climate (e.g. IPCC, 2001a).

If we accept the range of scientifically-based uncertainties as quantified by the IPCC (IPCC, 2001b), greenhouse gas mitigation will reduce the level of radiative forcing in the atmosphere independently of those scientific uncertainties. Policy-directed mitigation will reduce the risks of climate damages below those that would otherwise have occurred. For example, the range of warming from the non-policy SRES scenarios at 2100 is 1.4–5.8°C, whereas the range of warming from stabilisation scenarios with targets ranging from 450 ppm to 1,000 ppm $CO_2$ has been estimated to be about 1.2–3.6°C at 2100 by the IPCC (2001a). This implies that successive efforts to mitigate greenhouse gases will reduce the likelihood of reaching levels of global warming from the top down, with the highest potential temperatures being avoided first. Successive mitigation efforts will produce a progressively cooler range of global warming. This would suggest that the avoided economic costs associated with the adverse impacts of climate change (IPCC, 2001a, para 9.27) are highest with the first cuts, becoming successively smaller as mitigation efforts continue. The sum of these avoided costs will depend on the sensitivity of the climatic response and the cumulative damage function of climate impacts.

The structure of risk showing a number of robust outcomes is shown in Figure 11. The range of mean global warming under the SRES scenarios is shown in the left-hand graph, while likelihood and consequences are shown on the right-hand side. The lower shaded zone on the warming graph shows where adaptations are most optimal, covering the lesser increases in warming and are linked to the joint benefits of managing both current and future climate risks. The upper shaded zone shows where the delayed benefits of mitigation act from the top down, reducing the likelihood of the lower probability but higher consequences risks. The table on the right-hand side shows the probability and consequences of exceeding a given level of warming. The probability-consequence construct on the right is intended to match the range of warming at any given time, expanding from ~1°C in 2020, to ~3 °C in 2055 to ~6°C in 2100. Critical thresholds situated below the range are almost certain to be exceeded and those above the range extremely unlikely to be reached. Targeted adaptation will allow the most vulnerable systems to cope with limited amounts of warming while mitigation will reduce the probability of extreme levels of warming occurring (bearing in mid that the highest warmings would require both high emissions and a high climate sensitivity). This is another example of the top-down, bottom-up complementarity of adaptation and mitigation.

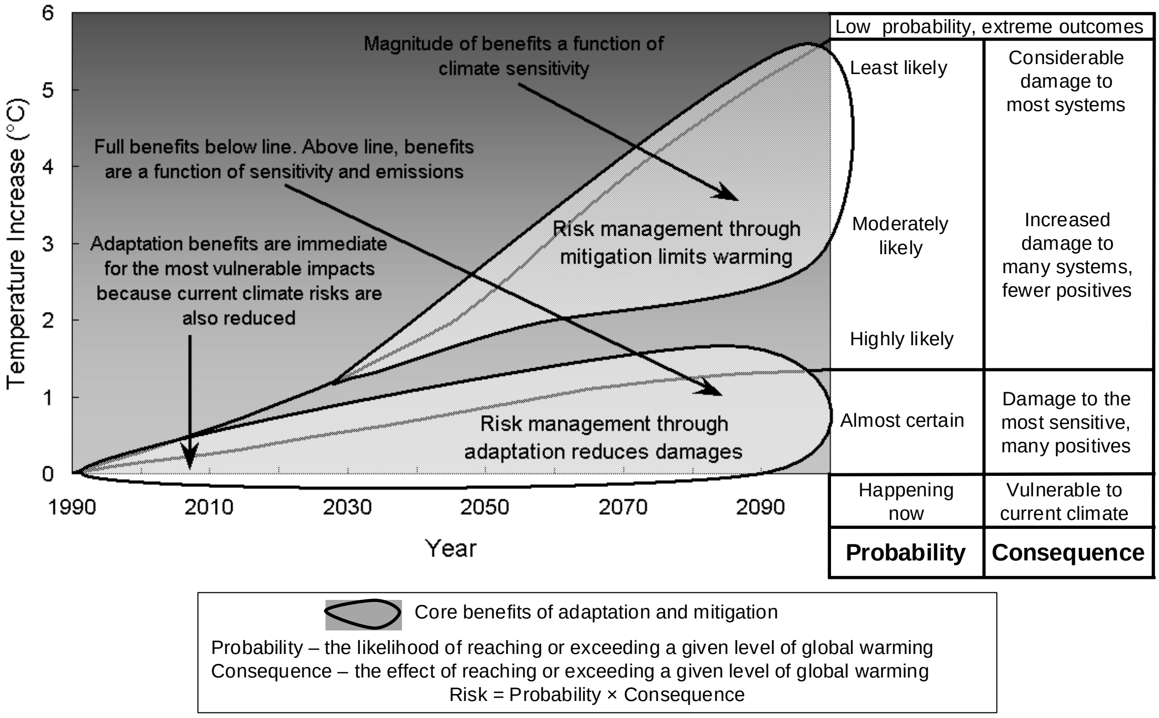


Figure 11. Synthesis of risk assessment approach to global warming. The left part of the figure shows global warming based on the six SRES greenhouse gas emission marker scenarios with the zones of maximum benefit for adaptation and mitigation. The right side shows likelihood based on threshold exceedance as a function of global warming and the consequences of global warming reaching that particular level based on the conclusions of IPCC WG II. Risk is a function of probability and consequence.

## 5.3 Conclusion

In this chapter I argue that probabilities can be attached to climate change assessments and that this is best carried out using a risk assessment framework. One reason for preferring risk assessment over prediction-based methods is scientists and policymakers do not share a clear picture as to how climate change risks should be weighed up against policy risks. This is a difficult area for the IPCC who endeavour to be policy-relevant without being policy-prescriptive.

Policy risks include the risk of doing too little, the risk of doing too much, the risk of moving ahead without sufficient information and the risk of delaying and suffering irreversible change. The certainty surrounding climate change is too large and the system too complex to manage a command and control situation, where climate change is forecast, a target is chosen and then policymakers act to meet that target. Some of the existing uncertainties may take years to narrow down to a sufficient level and some may be irreducible. Although this chapter concentrated on the risks of climate change, these need to be weighed up with policy risks such as those listed above. Risk assessment offers a flexibility and robustness that forecasting does not. Critical levels of impact can be assessed independently without having to predict vulnerability under specific climate scenarios. The likelihood of exceeding these critical thresholds can then be assessed under different policy regimes. It is in this context that the benefits of climate policy can be assessed.

A number of insights can be gained by moving from assessments based a limited number of scenarios to those dealing with ranges of uncertainty:

1. Ranges of quantified uncertainties can be utilised to identify the activities facing the greatest risk under climate change rather than relying on single, unrelated scenarios.
2. The assessment of critical thresholds allows vulnerability assessment to be conducted independently of its likelihood of occurrence, fulfilling the conditions of Grübler and Nakicenovic (2001).
3. Dangerous levels of anthropogenic greenhouse gases do not need to be predicted before the prioritisation of adaptation and mitigation options can begin. Adaptation and mitigation to manage the activities identified as most at risk can proceed while ongoing risk assessments at the local and global scale are pursued.
4. Bayesian methods of constructing priors for different ranges of uncertainty can be used to determine which are robust and which are subject to input uncertainties.
5. The sustained mitigation of greenhouse gases will reduce the likelihood of the highest potential warming occurring, irrespective of the ultimate value of climate sensitivity. While the magnitude of net benefits will be a function of climate sensitivity, the earliest mitigation efforts will always yield the largest economic benefits in terms of damage reduction (unless delayed mitigation is cheaper than accrued damages from that delay). Short-term ancillary benefits of mitigation, such as reduced pollution or reduced energy costs, will ensure both short- and long-term returns.
6. Global assessments based on the optimisation of cost-benefit outcomes may only have a limited probability of being achieved.

The framework presented in this chapter is consistent with Article 2 of the United Nations Framework Convention on Climate Change and can be used to investigate the risks of climate change using both top-down and bottom-up methods. By expressing the outcomes of individual assessments as a function of global warming, it is possible to aggregate across scale for a single activity using common thresholds and between activities expressing the outcomes as a function of global warming. A risk assessment framework provides better management of uncertainty than does linear assessments of climate change. It allows the prioritisation of adaptation and mitigation options according to the greatest need and can be refined as new information becomes available. It also provides a synthesis consistent with the aims of the UNFCCC that can unite the interests of the IPCC Working Groups I, II and III in preparing for the Fourth Assessment Report.

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