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Improving Information for Policy Makers

Adaptation benefits and costs – measurement and policy issues

by

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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.

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1. INTRODUCTION

This paper has three main objectives. The first to comment on the way in which adaptation to climate change is treated in the lead paper prepared for this workshop by Smith and Hitz (2002) and to summarise what I see as the main technical issues in evaluating the contribution of adaptation to avoiding climate change damages. The second is to show how these issues can be incorporated into a conceptual framework for characterizing adaptation in regional and multi-regional sectoral assessments of climate. The final objective is to show how this framework might be operationalised using a hypothetical example from a river basin.

But before I do this, I want to briefly address an important issue raised by Smith and Hitz (2002) in this paper, which is: who needs information about the "global benefits" of mitigation and adaptation and why do they need it?

It is well known that adaptation benefits and costs, as well as mitigation costs, are local in nature. We also know that, while the global marginal benefits of reducing a ton of GHGs in the atmosphere is the same, no matter where mitigation takes place, the local climate effects and local marginal benefits will be different. The artif cial distinction between the charge of the World Bank with national environmental benefits and the GEF with global environmental benefits aside, why are we in such a rush to sum up these benefits?

It is important to look at both sides of the issue regarding who needs information about the global benefits of reducing climate change damages. First, as a skeptic, my conclusion is that under the current system of global climate governance, decision makers in the UNFCCC "system" do not need information about the global benefits of reducing GHGs or offsetting climate damages to make decisions. However, questions about the distribution of climate change damages do raise issues that help us to understand the current instability of global climate governance.

Let me expand a little on this in two directions. First, all of the Kyoto mechanisms are either strictly regulatory-based or mitigation cost-based in the interests of making the regulatory scheme more cost-effective. To comply, the Parties only need to know their own quotas and, if the markets created under emissions trading, Joint Implementation and the Clean Development Mechanism are efficient, their own marginal mitigation costs. The marginal benefits of emissions reductions are irrelevant to compliance decisions.

Second, two pieces of information are emerging that have interesting burden sharing implications that helps to bring into focus issues about the distribution of global damages and benefits that are at the heart of many UNFCCC debates. The first is that marginal emissions reductions costs are probably lower in many non-Annex I than Annex I countries (IPCC 2001a). The second is that climate change damages may be more severe in non-Annex I countries than in Annex I countries (Mendelsohn et al. 2000; Rosenzweig and Parry et al. 1999; Sohngen et al. 2001) and in some sectors developed countries that are located relatively closer to the poles may experience small benefits from climate change (Mendelsohn et al. 1994; Adams et al 1999).

For an economist, these two pieces of information have interesting implications for the stability of the current system of global climate governance. If, as an analytical exercise, one chooses to maximize the global benefits of emissions reductions, then two important first-order conditions that flow from this are: 1) the sum of the marginal damages avoided in each region (i.e., global damages)should be equal in all regions that undertake mitigation and 2) the marginal cost of mitigation in these regions also should be equal. If the regions that are damaged the most by climate at the margin also have the lowest mitigation costs, this thrusts the economic burden of mitigation on them and gives rise to the need to implement schemes for the "winners" in the Annex I countries to compensate them under the "polluter pays" principle. Furthermore, if adaptation is viewed as a substitute for environmental inputs in production, the least damaged nations will concentrate more on adaptation than mitigation, even when the technological externality created by the stock of GHG emissions in the atmos phere is internalised through such mechanisms as side payments and carbon taxes. An equally troublesome issue regards entitlements to the benefits of emissions reductions in sectors and countries where the marginal benefits of reducing GHG emissions may be negative (meaning that the marginal impacts of climate are beneficial).

On the positive side, there are many good reasons why everyone involved in mitigation and adaptation decisions at the global, regional and national levels need more information about the marginal benefits and costs of avoiding climate change damages.

But before I discuss these, I want to briefly make a simple point about the institutional distinction between the global benefits of mitigation versus the local benefits of adaptation. Adaptation is a substitute for mitigation, albeit far from perfect. If a farmer can limit the effects of reduced soil moisture on yields through different management practices and input substitution, these actions displace the effects of mitigation actions on global climate. As such, local adaptation and global mitigation are linked and so are their benefits and costs. More adaptation locally means less mitigation globally.

While better information about the marginal benefits of mitigation and adaptation at the global level does not play a direct role in the implementation of the Kyoto mechanisms, it is important in the longer term for the Parties to the UNFCCC both to address the issue of burden sharing and to allow them to re-think how adaptation can be integrated into the existing, mitigation-heavy UNFCCC. In this regard, the general question of how effective and costly adaptation is as a substitute for mitigation is very important. However, information about the distribution of these benefits across sectors, regions and nations may be more important than global totals to address these issues.

Domestic policy makers in climate-sensitive sectors have more limited needs for global information than for national information (except when it comes to taking a position on burden sharing). Those in countries with lowlevels of GHG emissions want to know the benefits and costs of adaptation in their countries and the costs of mitigation that may be imposed on them (both by regulation and by participating voluntarily in the Kyoto mechanisms) by international treaties and conventions. Those in countries with high levels of emissions want to know the benefits and costs of both mitigation and adaptation in their countries, since reducing national emissions may also have some substantial national benefits (as well as costs, obviously). The same is even truer for domestic planners. Energy planners are focused narrowly on the costs of reducing emissions at home and in the markets that develop as a result of the Kyoto mechanisms. Planners in climate-sensitive sectors are interested in the local benefits and costs of adaptation related to specific options and projects.

Thus, I would argue that research about the global benefits of adaptation and mitigation should work from the national sectoral level up, not from the global level down, and that once data, tools and methods for doing this are in place, *and are implemented systematically*, we can indeed produce global estimates that will be helpful in clarifying burden sharing issues, even if they stir up a lot of trouble. We should not be in a rush to create global estimates, which I have argued have limited short-term policy value, until we get things right at the national and sectoral levels. We are a long way from being able to do this, particularly in developing countries, where adapting to the damages of climate changes created by developed countries is at the core of the current instability of the UNFCCC and Kyoto Protocols.

2. WHAT IS ADAPTATION?

The paper by Smith and Hitz (2002) directly and indirectly draws attention to the general lack of consensus that exists about how to include the accomplishments and costs of adaptation in estimates of the damages due to climate change and the benefits of reducing GHG emissions. This confusion stems from a broader lack of conceptual agreement about what adaptation to climate change is, which is reflected both in a number of the studies where adaptation is treated, and in the discussion by Smith and Hitz.

For example, in Smith and Hitz's discussion covering the agricultural sector two types of adaptation are mentioned. The first involves changes in management practices, such as shifting planting dates, increasing fertilizer use, introduction of new plant varieties and installation of irrigation systems to offset the effects of reduced precipitation and higher temperatures on yields. These adaptations were introduced into the studies by Rosenzweig et al. (1995) and by Parry et al. (1999), exogenously, by manipulating the input data/parameters to the relevant crop yield models. But they were not introduced into the study by Darwin et al. (1995) by, for example, adjusting the returns to land consistent with these adjustments. These adjustments represent adaptation to climate change, however, they were "forced" into the modeling framework exogenously, rather than being an endogenously determined outcome of farm level decisions and market forces. Further, the adaptations that were introduced, in an experimental way, by Rosenzweig et al. (1995) and by Parry et al. (1999) were not "homogenous", involving a mix both of short- and long-run and autonomous and strategic measures that, very arguably, should be treated differently.

A second type of adaptation (directly related to the last point) that Smith and Hitz address in their paper relates to the equilibrium adjustments that occur in the global sectoral trade model used by Rosenzweig et al. and by Parry et al. and the general equilibrium model used by Darwin et al. Partial and general equilibrium models are also employed in some of the studies examined for other sectors: sea level rise (Darwin and Tol, 2001) and forestry (Sohngen et al., 2001 and Perez-Garcia et al.[1] 1997 and 2002). All of these studies share in common the feature that when crop yields change exogenously, the market prices of goods and services in the directly affected sectors (in both partial and general equilibrium models) and in other sectors linked to them through the inter-industry flow of goods and services (in general equilibrium models) also change. These price changes, in turn, have the potential to influence a wide variety of investment, production and consumption decisions in the climate-sensitive sectors, as well as those linked to them in the various models.

So, do these types of adjustments to "market forces" represent adaptation, or not?

Smith and Hitz refer to these adjustments as "adaptations of a sort" in their review of the Rosenzweig et al. and Parry et al. studies, but then in explaining how the general equilibrium features of Darwin's model take into account adjustments in crop and livestock mixes the authors drop all reference to the term adaptation. The issue is not even raised by Smith and Hitz in connection with sea level rise or forestry, where both partial and general equilibrium models are used to estimate climate damages. But, as I

[1] Discussion of these studies was omitted from the paper by Smith and Hitz (2002), due to lack of information about the climate scenarios used in them.

will try to show later, I believe these adjustments should "count" as a part of the adaptation process and the major questions are:

- how to measure their effects and how to value their contribution to the marginal benefits of adapting to climate change.

A third type of adaptation is presented in the discussion by Smith and Hitz regarding sea-level rise. This type of adaptation involves both autonomous and strategic investments by the public sector in infrastructure such as, in the case of these studies, sea walls and dykes. These investments represent a form of adaptation because they directly avoid climate damages. But what about investments, other than sea walls, dykes and water supply reservoirs, that have a less visibly direct relationship to preventing climate change damages? One can give a few, more obvious examples: new investments in agricultural and timber land to "follow" climate-induced changes in NPP over time and space[2], investments in agricultural machinery and fertilizer production capacity in response to climate-induced changes in substitution possibilities and investments in agricultural storage capacity to smooth out climate-induced price fluctuations for agricultural commodities. I have purposely chosen investments that are rather immediately linked to climate variability and climate change. More generally the relationship between a wide range of fixed and quasi-fixed factors in weather and climate sensitive natural resource sectors, the constraints they impose on short-run adaptation measures, and the effects of investment on the scope of adaptation decisions has not been discussed enough in the literature on adaptation.

Another type of adaptation to climate change I want to address in the context of the paper by Smith and Hitz focuses on the relationship between economic development and adaptation to climate change and involves more generally the relationship between "no regrets" actions taken by individuals and governments and adaptation. In the context of adaptation, a no regrets action is one that is taken for reasons other than avoiding climate change damages, but which nevertheless "softens" the impacts of climate change as they occur. In their paper, Smith and Hitz indicate that exogenous assumptions about economic development in a number of the studies had a fairly substantial effect on many of the damage/benefit estimates. As they pointed out, economic development often reduces national vulnerability to climate change and in their concluding remarks they emphasise the importance of "proactive" adaptation measures that can be taken today to reduce regional vulnerability to climate change. I would make the point a little differently, and more strongly, by saying that there are potentially many actions, particularly in developing countries, that can be taken today for reasons that are more directly related to a broad variety of other developmental goals (including reduced vulnerability to existing climate variability) that also are potentially effective in reducing the vulnerability of nations and regions to climate change.

Related to the issue of what properly constitutes adaptation is the question of how we account for the benefits and costs of adaptation and how we relate these to the damages caused by climate change. This was the topic of an earlier study by Callaway et al. (1999). In that study, my colleagues and I made two points that are relevant to the paper by Smith and Hitz (2002). The first point was that, while a number of studies had estimated the economic value of climate change damages, none of these had separated out the benefits of adaptation or related these benefits, consistently, to the damages caused by climate change, with and without adaptation. I think this still as true in 2002 as it was in 1999.

The second relevant point was that measures of the value of resources used to avoid climate change damages should be counted as the real resource costs of adaptation and not as the benefits of adaptation. The Smith and Hitz paper reviewed the sea level rise study by Darwin and Tol (2001) in which the authors demonstrate the second point very forcefully. Unfortunately because Darwin and Tol were

[2] Changes in species distributions (i.e., locations) were introduced exogenously, not endogenously by Sohngen et al. (2001).

using different models and methods to estimate the real resource costs of protective measures against sea level rise, on the one hand, and the value of the damages due to sea-level rise, on the other, they were not able to effectively parse out the damages avoided by these protective measures and relate this to the value of the residual (i.e., after protection) damages due to sea-level rise.

Finally, I want to look at the issue of “market integration” and where it lies in relationship to adaptation. All of the studies reviewed by Smith and Hitz in the agricultural sector employ methodologies that link domestic production in various regions to world food markets. The study by Darwin et al. (1995) and a related study by Rosenzweig et al. (1993) directly focus on the role of world food markets in filtering the damages that would occur if there were no trade (i.e., autarky). None of these studies explicitly model the comparison between autarky and free trade, but Rosenzweig et al. (1993) does show that domestic market adjustments (which unfortunately are not clarified very well in the paper) and trade liberalization significantly offset climate change damages when measured in terms of cereal production and nutrition.

In a related study, Winters et al. (1998) used a computable general equilibrium approach to estimate the macro-economic impacts of climate change on developing countries (Asia, Latin America and Africa) in conjunction with the same climate change scenarios and a subset of the yield data from Rosenzweig and Parry (1994). This study confirmed the importance of adaptation in reducing the damages of climate change in all three regions as measured by percent changes in agricultural production, GDP, and a number of other indicators. However, differences in the avoided damages between the three regions could be explained by the extent to which agricultural production was concentrated in households, the degree of integration in domestic food markets and by the degree of integration of the domestic farm sector into global food markets. The authors conclude that policies to reduce climate change damages in developing countries should focus on intensification of agricultural production and integration in the international market in Africa and the intensification of production of export crops in Latin America and Asia. In other words, they stress a renewal of traditional agricultural development practices focusing on infrastructure development and modernization in concert with current “softer” development policies to develop human and social capital resources.

The study by Winters et al. (1998) helps to focus my earlier remarks on no-regrets adaptation measures, since the policies advocated in this study are development policies, primarily, but which have secondary benefits. The study also helps to focus attention on the issue of adaptation capacity, an issue that is not raised directly in any of the studies reviewed by Smith and Hitz (2002). And it also helps to illustrate that it is difficult to draw the line between the difference in an investment in adaptation measures and an investment that strengthens adaptation capacity. Perhaps there is no need to make this distinction. But what is important, at some point, is to be able to link and measure something we call adaptation capacity to the ability of individuals and organizations to adapt to climate change through specific measures. The most immediate measures that come to mind are related to the ease with which inputs and outputs can be substituted for one another in consumption and production, as in Winters et al. (1998), along with measures of resource scarcity and mobility. Some of this can be incorporated into multi-market sectoral models through demand and supply functions (properly derived), but ultimately only through models that characterise inter-industry structure, as well, such as used by Darwin et al. (1995).

Having said this, I would like to go on in the remainder of the paper to show how it is possible to:

- Combine various types of adaptation – behavioral adjustments, partial and general equilibrium price adjustments, and investments in infrastructure into a unified adaptation framework that includes autonomous and strategic adaptation, as well as adaptation that has a “no regrets” component;

- Link adaptation to climate variability to climate change; and

- Do this in a framework that is general enough to apply to a large range of objectives, not just economic efficiency, but – when it is appropriate – uses a consistent welfare accounting system to isolate the benefits and costs of adaptation.

- Do this in an explicit type of modeling framework that can be applied at the national sectoral and project levels, that has some relevance to planning under risk.

3. A FRAMEWORK FOR ESTIMATING THE BENEFITS AND COSTS OF ADAPTATION

In this section of the paper I outline an earlier framework developed by Callaway et al. (1999) to characterise adaptation benefits and costs. I indicate the shortcomings of the framework in terms of the issues I raised at the end of the last section and then go on to illustrate one way the framework can be modified to address these issue. This section contains a "made-up" numerical example to illustrate how the framework can be applied both to the planning and assessment of adaptation options and projects, including a discussion of "no regrets options" in the context of Smith and Hitz's concept of "proactive adaptation".

3.1 The original framework

In an earlier paper, Callaway et al. (1999) outlined a conceptual framework for estimating the benefits and costs of adaptation that can be applied at almost any scale. This framework was largely based on earlier work by Fankhauser (1997). Since writing the earlier paper, I have made a number of modifications to this framework and that is what I want to present here.

To present the framework, it is necessary to define adaptation to climate change. I use this term to include, broadly, any adjustments that that individuals, singly and collectively (in whatever organizational framework), make *autonomously* or policy makers undertake *strategically* to avoid (or benefit from) the direct and indirect effects of climate change. Individuals and organisations can do this *autonomously* in the sense that economic, social and political institutions with which they interact provide incentives for them to adjust "automatically" to climate change, without political intervention. Or, they can adapt *strategically* through decisions made by governments. Stated in this way, the line between autonomous and strategic adaptation is not easy to draw in all cases, since, conceptually, governments do not usually operate outside the underlying incentive systems that have developed to guide behaviour. In the case of a market economy, this distinction is fairly easy to make based on differences between the private objectives of individuals, firms and factor owners and the social objectives of governments and the divergence of these objectives due to market failures. In this type of politically economy, private decision makers respond to whatever incentives they face, whether these are market or public policy driven. As such, private decision makers can be expected to respond autonomously to strategic climate change policies, but would not take the same actions on their own, except for altruistic reasons. Maybe this distinction holds true for all societies, but I would not use it generally, since there may well be workable incentive systems in some societies where private and collective welfare are better aligned than in market or socialist economies in developed countries.

It is important to note that this distinction applies broadly to all of the different types of adaptation discussed in the paper by Smith and Hitz (2002), namely: autonomous short-run adjustments in the behaviour of individuals and firms, autonomous market adjustments to climate change that indirectly affect human and organizational behaviour, and both autonomous and strategic long-run adjustments in technology, infrastructure and institutions. I only say this because, even though strategic adaptation will often take the form of long-run adjustments, there is no theoretical reason to limit the types of adjustment that can occur autonomously or strategically.

The core ideas in the conceptual framework developed, first, by Fankhauser and touched up a bit by Callaway et al. (2002) can be explained with the use of Table 1[3]. It should be noted that this framework was originally developed in the context of a market economy. Table 1 characterises four different, general adaptation cases. The columns indicate the climate, either C_0, the existing climate or C_1, the altered climate, to which individuals and organisations are adapted, while the rows indicate whether society is adapted to the existing climate, A_0, or the altered climate, A_1.

The idea was that individual and organisational behaviour is "optimally" adapted to an existing climate regime (C_0) through behaviour that can be broadly characterised as A_0. When the climate changes from C_0 to C_1, there is associated with the new climate, a new behavioural optimum, characterised by A_1.

Table 1. Alternative Adaptation Scenarios for Estimating Adaptation Costs and Benefits

Adaptation Type	Existing Climate (C_0)	Altered Climate (C_1)
Adaptation to existing climate (A_0)	Existing climate. Society is adapted to existing climate: (C_0, A_0), or Base Case	Altered climate. Society is adapted to existing climate: (C_1, A_0).
Adaptation to altered climate (A_1)	Existing climate. Society is adapted to altered climate: (C_0, A_1).	Altered climate. Society is adapted to altered climate: (C_1, A_1).

Source: Modified from Fankhauser (1997)

The top left box describes a situation in which society is adapted to the existing climate, C_0, through adaptive behaviour A_0. This is sometimes referred to as the Base Case. The lower right box represents a situation where society is adapted to a change in climate from C_0 to C_1. that has changed over time through behaviour A_1. The top right box describes a situation in which society behaves as if the climate was not changing, and is adapted to the existing climate, but not the altered climate. The bottom left box represents a case in which society decides to behave as if the climate had changed, when in fact the climate has not changed. Note that if the null hypothesis is that the current climate does not change, H_0: $C_0 = C_1$, then accepting the null hypothesis when it is false, and not adjusting to climate change that does occur (top right box), is associated with making a Type II error. Rejecting H_0 when it is true, by adjusting to climate change that does not occur (bottom left box), represents a Type I error.

In the paper by Callaway et al. (1999) the following definitions were adapted from Fankhauser (1997) to define the various benefits and costs associated with climate change and adaptation:

- *Climate change damages* - the net cost to society of climate change, if climate changes and adaptation does not takes place.
- *Adaptation benefits* - the value of the climate change damages avoided by adaptation actions.
- *Adaptation costs* - the value of the resources society uses to adapt to climate change.
- *Net adaptation benefits* - the value of adaptation benefits minus adaptation costs

[3] It should be noted that this framework was originally developed in the context of a market economy, but in this paper I will refer more generally to behaviour in any kind of political economy.

- *Imposed cost of climate change* - the net cost to society of climate change taking into account that adaptation occurs. This is the difference between climate change damages and net adaptation benefits.

If we let W(C, A) represent net social welfare, however measured, then the imposed cost of climate change is calculated as the difference between net welfare in the lower right scenario in Table 1, or W(C_1, A_1), minus net welfare in the top left scenario, W(C_0, A_0). However, this is not the correct comparison to be used for measuring the costs and benefits of adaptation. To do this one must compare the costs and benefits of actions that are taken in the top right box with those in the bottom right box, or between the following two states: (i) when climate changes, but society is adapted to the existing climate (C_1, A_0), and (ii) when climate changes and society adapts to the altered climate (C_1, A_1). Thus, Climate Change Damages = W(C_1, A_0) – W(C_0, A_0); the Imposed Cost of Climate Change = W(C_1, A_1) – W(C_0, A_0); and the Net Benefits of Climate Change = W(C_1, A_1) – W(C_1, A_0).

Callaway et al. (1999) illustrated these welfare measures in the market for a single good produced in a climate sensitive industry. This is shown in Figure 1, below. The effects of climate change are illustrated by shifts in the supply curve for the good S(A, C). D indicates the demand curve for the good. Often the demand for a good or an input is influenced by weather and climate, but showing these changes complicates the graphic analysis. Therefore D does not respond to climate change in this figure and the others like it in this paper. In this diagram, areas A+B equal the loss in consumer and producer surplus associated with *climate change damages*. *The imposed cost of climate change* is represented by loss of consumer and producer surplus indicated by area B, and the area A represents the positive *net benefits of adaptation*.

Figure 1 indicates welfare losses. However one can use the same conceptual approach to characterise the physical damages of climate change in terms of climate change damages and the residual damages of climate change. In the same way, the difference between the two, which are the net adaptation benefits can be characterised in terms of the physical climate change damages avoided by adaptation measures. And the inputs used to "create" and implement adaptation measures can in some sense be treated as the physical analogue to the real resource costs of adaptation, although not all inputs, such as information, are easy to characterise in physical terms, even if they have a real cost. The point is that this framework could be applied using many different damage metrics.

In passing we should note that this framework answers the objections raised by Darwin and Tol (2001) about the use of opportunity cost measures to capture the benefits of adaptation. In our framework (Callaway et al. 1999), adaptation costs is *not* a measure of avoided climate change damages, it is strictly a measure (monetary or physical) of the real resources used to avoid climate change damages.

A number of problems with this framework were presented in Callaway et al. (1999) and others have emerged in my mind since it was published. Most notable among these are:

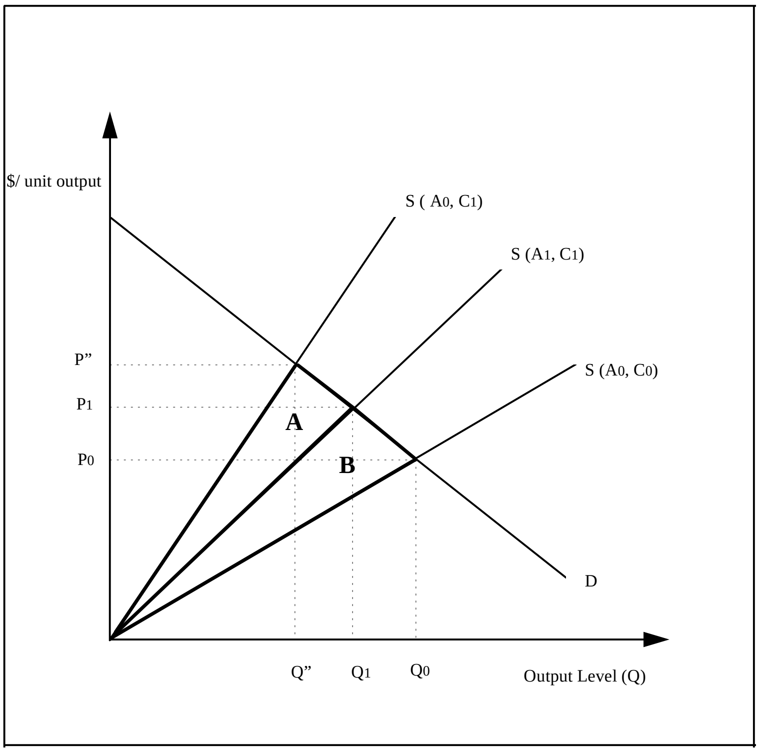
- The link between adaptation to climate variability and climate change was missing, making the framework both deterministic and incomplete.

- The counterfactual scenario, (C_1, A_0), as stated, could not be observed, and did not make empirical sense, either.

- More generally, the framework did not relate this process of adaptation to planning under uncertainty, both through planning models and how this process could be integrated into assessment models at the sectoral and project levels.

- The framework did not distinguish between short- and long-run adjustments to climate change and variability.

Figure 1. Illustration of adaptation in a goods market (old framework)



3.2 Modifications to the framework

This section of the paper follows up on these problems and shows how the framework can be modified to address them.

3.2.1 Linking climate variability to climate change

In fact, all of the problems with the earlier framework are closely related and the key to resolving these problems lies in making the counterfactual scenario (C_1, A_0), believable. This involves two steps:

- first, by linking the framework in a more detailed way to the way in which individuals and organisations engaged in climate and weather-sensitive activities respond to climate variability and

- second, by linking this to a more general paradigm for planning under uncertainty.

In the earlier adaptation framework paper (Callaway et al. 1999) and the even earlier work by Fankhauser (1997), the counterfactual scenario in which producers did not adjust their input use to the new climate was necessary to isolate the adjustment that individuals and organisations made to climate change. In support of this construct, we know there are historical examples of places that were settled due to lack of sufficient information about the true climate and then abandoned when random (perhaps even "persistent") periods of above-average rainfall eventually gave way to the dominant, drier climate pattern. We also know that no matter how much information we have about climate and climate variability, "we don't need to be smart get out of the rain". Thus, experience and common sense tell us that, while it is indeed possible to be poorly-adapted to the "true" climate without sufficient information, one does not need a lot of information to make some adjustments to climate variability while other adjustments require a little more information and, thus, take longer.

To better relate adjustments to climate variability with those to climate change I go back to Smit (1993,) and Carter (1993) and Smit et al. (1996, 2000) who suggested that farmers are always "optimally" adjusted to climate variability, given the information available to all of them formally and informally, but that at any given time they also face constraints imposed by past decisions to adjust to climate variability. This does not mean that they can always guess the weather with precision but it does mean two other important things: a) given their knowledge about the joint distribution of meteorological variables, individuals and organisations build a certain amount of flexibility into their activities in order to be able to cope with the weather variability they and others have faced in the past, and b) this flexibility may enable individuals in regions with a great deal of weather variability to better cope with climate change than those living in regions where there is very little weather variability*, even if they do not have information that the climate has in fact changed.*

The point Smit (1993) and Smit et al. (1996, 2000) make about the importance of information in adapting to weather variability helps us to link the strongly counter-factual adjustment case used for measuring adaptation benefits to the actual behaviour of individuals under uncertainty, both in terms of their adjustment to climate variability and climate change.

When people, singly or collectively, make short- or long-term decisions that are weather or climate sensitive, they take the information available to them from the joint distribution of weather and/or climate variables into account, both in planning and implementation. The type of information that is relevant to them – weather or climate – depends on the time horizon associated with a specific action and the flexibility they have in adjusting their behaviour. These time horizons vary widely. For example, information about the weather next week is crucial at harvest time for farmers, as is the day's wind speed and wave height for a coastal fisherman. On the other hand, when individuals make investment decisions they usually take a long-term perspective, because investment expenditures in land and capital goods and other tangible assets are long-lived and often "lumpy" and it is costly to replace them once the investment decision is made. An investment decision to plant a particular type of forest species for harvest requires a planning horizon that spans the rotation length for the species and the products for which it will be harvested. The useful life of a water supply reservoir for irrigation water may be 50 years or more. Thus, investment decisions are more likely made on the basis of climate, as opposed to weather information.

The flexibility that individuals and organisations have to adjust to climate variability is partly related to the above distinction between the short- and long-run, but it also is related to environmental and technological features that characterise the structure of production activities in the household, in firms and organisations, generally. When a crop is damaged by hail, for example, the damaged plants cannot be resurrected back to life. In the same way, once an ear of corn has tasselled, there is no substitute for sunlight and persistent rains after this occurs will mean low yields. There is little the farmer can do about this, except cut his economic losses and hope for better weather in the next crop season.

To link adaptation to climate variability to adaptation to climate change, I want to formally define what I mean by weather, climate and climate variability. To understand these differences, we need, first, to characterise the joint distribution of

k =1,…, K meteorological variables (M) as:

$$M = M_1,...,M_K \overset{d}{=} \Phi_M(\upsilon_M, \sigma_M^2, \Omega_M, \Theta_M), \qquad \text{EQ.1}$$

where υ_M, σ_M^2, and Ω_M are, respectively, the means and variances of the partial distributions of the individual random variables in M, Ω_M is the variance-covariance matrix of M, and Θ_M represents a vector of the higher order moments of the distribution of M. In this framework, climate is characterised by the distribution parameters of M, while the observed (or predicted) weather is characterised by the observed (or predicted) values of the various meteorological variables that comprise the joint distribution of M. For example at time t this would be: M_{1t}, M_{2t}, … , M_{Kt}. Climate variability, which is a part of climate, is characterised by the variances of the partial distributions of meteorological variables, the covariances between the meteorological variables and the higher-order moments of the partial and joint distributions of the meteorological variables, such as skewness and kurtosis.

Now, to show how decision-makers in the private and public sectors deal with the randomness of climate and climate variability in their capacity as resource planners or managers we introduce the idea of the production function. The production function in a climate-sensitive sector, industry, or even more broadly "an activity" is a way to characterise the relationship between the outputs of an activity and the inputs used to "create" that output, including meteorological variables. Here, I will use a very simple form of a production function, where there is just one output:

$$Q_{st} = f(X_{st}, K_{st}, M_{st}), \qquad \text{EQ.2}$$

where the subscripts s and t represent, respectively, the state of nature (or climate) and t represents time. Q stands for the single output and X and K are, respectively, vectors of variable inputs (X) and fixed or quasi-fixed factors (K), while M is a vector of random meteorological variables, as characterised in EQ.1 above. Note that a single value for any of these meteorological variables, M_{ist}, is a weather value, for example the observed or predicted precipitation in a particular month.

This is a simple production function, but the concept itself is general enough. It is not only applicable in traditional production activities, such as in the agriculture, forestry, fisheries and energy sectors, but can also be used to characterise the relationship between the services provided by a wide variety of household and commercial activities. For example, the concept is broad enough to characterise the role of land and sea level rise to the output commercial enterprises that are located in low-lying coastal areas. The concept of the production function is also broad enough to apply, not only to activities that are associated with the production of goods and services that are sold in markets, but also to household production and the production of "non-market" goods and services that are not sold in markets (Freeman 1994). Perhaps the most important example of non-market production in the climate change arena is the production of ecosystem services (Toman 1997).

Throughout this paper, I will assume that the climate and the weather are exogenous: the planner/manager cannot change the climate. This assumption is restrictive for making global decisions, as well as in countries that emit sizeable fractions of global GHG emissions. In these cases, emissions and climate are either completely or partially under the control of decision makers. However, only a handful of nations produce a sizeable enough fraction of global GHG emissions to significantly influence their own climates and weather. Moreover, at the sectoral and activity levels, where most adaptation occurs, decision makers have no control over the climate or weather they face. Thus, from here on, it must be understood that the analysis contained in this paper is based on the notion of "partially optimal" adaptation, taking the level of GHG mitigation as exogenous.

To show how the climate and weather influence production and how changes in climate and weather affect the decisions of planners and managers in climate sensitive sectors and industries, I introduce the idea of ex-ante, ex-post planning. The problem that confronts planners is how to select the amounts of quasi-fixed factors that are optimal for the climate they face. This is a long-run decision since, once the investment in quasi-fixed factors is made, they become fixed factors. The problem of managers is a short-run problem: how to adjust their variable inputs to cope with the weather, given that the amounts of the fixed factors have already been determined[4]. An ex-ante, ex-post planning problem combines both types of decisions and this approach is commonly used in planning new electrical generating capacity, where a given amount of capacity must be able to cope with weather-driven peak demands.

3.2.2 Making the framework stochastic

The ex-ante, ex-post approach to planning is amenable both to autonomous adaptation and to strategic adaptation planning decisions. The ex-ante part of the model makes sense from the perspective of either type of adaptation decision since there is no restriction on the objectives to be followed or the constraints imposed. The ex-post part of the model takes into account autonomous adaptation that occurs in response to the ex-ante decision regarding investment in quasi-fixed factors. Again, there is no reason why the autonomous adaptation that is characterised in ex-post decisions should be economic, or market driven. Autonomous adaptation is simply a general term used to describe how people respond on their own to political, social and economic incentive systems and rules, regardless of the objectives of this system. Nor does this approach necessarily involve the use of mathematical models. A farmer in a developing country, whose only objective is to feed his family, has to plan on the number of large animals he needs for food and to perform work under a variable climate and has to live with these decisions through good times and bad (up to a point). For the purposes of this paper, I will use a mathematical model to illustrate the principle of ex-ante, ex-post planning in a mathematical framework, but that is only in order to be concise. And, since the approach is general, I will illustrate it through a non-economic model[5] of output maximisation for a climate, s, over $\tau = 1, \ldots, T$ random trials of weather observations (or predictions) for that climate. The problem involves selecting the values of X and K that will:

$$\text{Maximise: } Z = \sum_{\tau}^{T} pr(\tau) f(X_{s\tau}, K_s, M_{s\tau}) \qquad \text{EQ.3.1}$$

Subject to:

$$M_{s\tau} = D(M_s, \tau) \qquad \text{for all } \tau = 1, \ldots, T \qquad \text{EQ.3.2}$$

where $pr(\tau)$ is the probability of occurrence of each τ and $D(M_s, \tau)$ is shorthand for the climate distribution function that generates the random weather values for $M_{s\tau}$ over T random trials. In this model Z in EQ.3.1 is the expected value of output that is optimal over all T trials, while EQ.3.2 defines the values of the weather variables that are generated in each trial.

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4 For a variety of reasons, it is often too costly or physically difficult to adjust quasi-factors to unplanned events.

5 Elsewhere, Callaway and Ringius (2002) have shown how this approach can be applied to the problem of a household farmer whose objective is to meet the nutritional needs of his family.

Note that in this model the quasi-fixed factors, represented by the vector K_s, do not change over the trials, τ. Thus the optimal values of the quasi-fixed factors, K_s^*, are optimal generally for the climate and only the values of the variables inputs, $X_{s\tau}^*$ can be adjusted individually when the weather changes in each trial, τ. However, both the long-run adjustment in the quasi-fixed factors and the short-run adjustment of the variable inputs, with the quasi-fixed factors held constant (as fixed factors) are determined simultaneously in this model over all the random weather trials. In real life, this will not be the case. The quasi-fixed factors will be determined, ex-ante, and the variable inputs will be adjusted, ex-post, given the fixed factors. But if the observed climate parameters used in the model are the same as the true climate parameters and the number of random (or repeated random) trails is large, this type of approach mimics this iterative process, as well[6]

We can write the ex-ante (long-run) solution equation for the vector of quasi-fixed factors as:

$$K_s^* = k_s^*(M_s) . \qquad \text{EQ.4}$$

The ex-post (short-run) solution equation for the vector of variable inputs can, with a little re-arranging be written as:

$$X_{s\tau}^* = x_s^*(\overline{K}_s^*, M_s) = x_s^*[k_s^*(M_s), M_s)] = x_s^*(M_s) \ . \qquad \text{EQ.5}$$

The bar over K in EQ.5 is used to show that once the optimal amounts of the quasi-factors have been determined in the long-run, they are fixed over the individual weather events. By substituting these solution equations into the production function, we get the solution equation for the ex-post (short-run) solution equation for output:

$$Q_{s\tau}^* = q_s^*[x_s^*(\overline{K}_s^*, M_s), \overline{K}_s^*, M_{s\tau}] = q_s^*[x_s^*(M_s), k_s^*(M_s), M_{s\tau}] = q_s^*(M_s, M_{s\tau}) . \qquad \text{EQ.6}$$

The ex-ante, ex-post planning approach can also be used to characterise the process of adaptation to climate change, both in the long-and short-run, by showing what happens when climate changes permanently, for example from M_0 to M_1.

3.2.3 Linking the counterfactual case and damage/benefit definition to adjustments to climate variability and climate change

How decision makers will react to this climate change depends on two factors:

- whether or not climate changes can be detected or predicted with enough reliability that decision makers are willing to act (i.e., make investment decisions) on the new information, and
- how much flexibility exists, both in economic terms (i.e., short-run vs. long-run), and physical/environmental terms to adjust the variable inputs and quasi-fixed factors. Presumably the amount of flexibility is a function of pre-existing adaptation to current climate variability and the "overlap" between climate change existing climate variability.

[6] The above formulation assumes that weather is random, for illustrative purpose. However, the weather generating mechanisms in the model can be also be designed to mimic deterministic (time dependant) and partially-deterministic weather generating processes, if that is the case.

If the information from either type of source is reliable, then decision makers will adjust the capital stock and institutional arrangements under their control consistent with the results of planning models that characterise this climate change. One can call this process "full adjustment"[7] and it represents the fullest kind of adaptation that can occur with reliable information about climate change. The change in a short-run value of the output variable[8] associated with this process of full adjustment can be written as:

$$Q^*_{0\tau} = f\left(X^*_{0\tau}, K^*_0, M_{0\tau}\right) \longrightarrow Q^*_{1\tau} = f\left(X^*_{1\tau}, K^*_1, M_{1\tau}\right) \qquad \text{EQ.8}$$

where

$$Q^*_{0\tau} = f\left(X^*_{0\tau}, K^*_0, M_{0\tau}\right) = q^*_s[x^*_0(\overline{K}^*_0, M_0), \overline{K}^*_0, M_{0\tau}] \text{ and}$$

$$Q^*_{1\tau} = f\left(X^*_{1\tau}, K^*_1, M_{1\tau}\right) = q^*_s[x^*_1(\overline{K}^*_1, M_1), \overline{K}^*_1, M_{1\tau}]$$

In the earlier framework I helped to develop, we looked at the transition between these two sets of optimal adjustments in terms of just two partial steps, with the counterfactual case of no adjustment to climate change, lying in between full adjustment process shown in EQ.8. Now, it can be seen that by linking adjustment to climate variability to adjustment to climate change the transitional process becomes both more complicated and, I think, more realistic.

If climate change is not detected or the information about predicted changes is too unreliable for planning purpose, this puts decision makers effectively in a short-run situation where the quasi-fixed factors are fixed *and* they respond to changes in weather by varying their variable inputs. The change in the value of output in these circumstances can be decomposed into three parts.

1. *Pure effect of climate change (a purely physical response, with no human adjustment possible):*

$$Q^*_{0\tau} = f\left(X^*_{0\tau}, K^*_0, M_{0\tau}\right) \longrightarrow Q'_{1\tau} = f\left(X^*_{0\tau}, K^*_0, M_{1\tau}\right). \qquad \text{EQ.9}$$

where $Q'_{1\tau} = f\left(X^*_{0\tau}, K^*_0, M_{1\tau}\right) = q'_s[x'_0(\overline{K}^*_0, M_0), \overline{K}^*_0, M_{1\tau}]$.

This part of the adjustment involves what I have elsewhere (Callaway and Ringius 2002) termed "the pure climate effect", in which the output responds *only* to the change in the weather (under the new climate). The quasi-fixed factors are not adjusted in this case because the climate change has not been detected or forecast with sufficient reliability to allow re-planning. The variable inputs, in theory at least, could be adjusted to cope with the observed changes in weather, but in this partial change case they are not adjusted to cope with climate change, due to the restrictive nature of the production technology or just the sheer inability to alter the effects of "nature". Such cases are easy to observe in the dealings of farmers and water managers in a wide variety of settings. Can this pure effect be modelled? I will deal with this question later on, in connection with measuring the benefits of partially adjusting to climate change.

[7] If a known non-stationary process generates climate, then these "full adjustments" will be gradual and perhaps discontinuous over time, but the process of adjustment can nevertheless be referred to as a full adjustment process.

[8] We can also show similar paths for the optimal expected value of the objective function.

2. *Partial adjustment to climate change (limited adjustment to perceived climate variability):*

$$Q_1^{'} = f\left(X_0^*, K_0^*, M_{1\tau}\right) \longrightarrow Q_{1\tau}^{''} = f\left(X_{1\tau}^{''}, K_0^*, M_{1\tau}\right) \qquad \text{EQ.10}$$

where $Q_{1\tau}^{''} = f\left(X_{1\tau}^{''}, K_0^*, M_{1\tau}\right) = q_s^{''}[x_0^{''}(\overline{K}_0^*, M_1), \overline{K}_0^*, M_{1\tau}]$.

The next part involves adjusting the variable input to be optimal for the change in weather (under the new climate), holding the fixed factors at their optimal values under the old climate. Callaway and Ringius (2002) have termed this as a "partial adjustment" to climate change. The adjustment is considered partial because the quasi-fixed factors are not fully adjusted to climate change and this also limits the adjustment of the variable inputs. However, since decision makers experience the change in weather, they are still able to make some adjustment, even if the quasi-fixed factors are not adjusted. This type of adjustment can also be observed in many different settings, and what is important about it, is that decisions makers do not need to have reliable information about climate change to make these adjustments. Rather, they are responding to perceived climate variability.

3. *Full adjustment to climate change (adjustment to climate change given reliable – not perfect – information about climate change):*

$$Q_{1\tau}^{''} = f\left(X_{1\tau}^{''}, K_0^*, M_{1\tau}\right) \longrightarrow Q_{1\tau}^* = f\left(X_{1\tau}^*, K_1^*, M_{1\tau}\right) \qquad \text{EQ.11}$$

The final part of the change occurs when climate change is detected or predicted with enough reliability for planners to act on it. In this partial change, the quasi-fixed factors are adjusted optimally for the new climate and decision-makers adjust their variable inputs accordingly as the weather changes.

3.2.4 Measuring climate change damages and benefits of adaptation

Corresponding to these three types of adjustment (or non-adjustment), there are also comparable measures of damages and benefits that are consistent with the definitions in the earlier framework. Since the objective function of the problem, used here, is measured in terms of yields, the damages associated with climate change and the benefits of avoiding climate change damages are also measured in terms of yield changes. However, as I indicated earlier the same approach could be used to measure welfare changes in monetary or other terms.

1. *Maximum climate change damages:*

$$Z\left(X_{0\tau}^*, K_0^*, M_{1\tau}\right) - Z\left(X_{0\tau}^*, K_0^*, M_{0\tau}\right) \qquad \text{EQ.12}$$

The "pure effect of climate change" is difficult to model, except at the level of an individual economic activity and while, it can be observed in relevant cases, it can also be used as somewhat theoretical construct to define the highest possible damages that can be caused by climate change. This can be thought of as a pure measure of vulnerability to climate change, without taking into account any form of human adjustment to climate change. Presumably, this can be altered in the long-run by adopting production functions that allow meteorological inputs to play a less important role in the production function of an activity. For example, the production function of green-house crops would be less sensitive to changes in the natural environment than field crops. Of course, this is an extreme example. Nonetheless, it illustrates the point.

2. *Imposed cost of climate change with partial adjustment:*

$$Z\left(X_{1\tau}^{''}, K_0^{*}, M_{1\tau}\right) \; - \; Z\left(X_{0\tau}^{*}, K_0^{*}, M_{0\tau}\right) \qquad \text{EQ.13}$$

This expression measures the changes in physical or monetised climate change damages, taking into account the partial adjustments that are made in response to climate variability, but not climate change. It has an advantage over our (Callaway et al., 1999) previous definition of the imposed cost of climate change in that the first term is derived directly from an observable adjustment that individuals and organisations make to climate variability when they do not have reliable enough information to detect or plan on the climate changing. More importantly, being able to measure this adjustment allows us to decompose the imposed cost of climate change into two parts: one due to partial adjustment and one due to full adjustment (next definition). Conceptually, this expression represents the residual damages that are left over after partial adjustment, that is: without explicitly planning for climate change and acting on these plans.

3. *Imposed cost of climate change = Climate change damages with both partial and full adjustment:*

$$Z\left(X_{1\tau}^{*}, K_1^{*}, M_{1\tau}\right) \; - \; Z\left(X_{0\tau}^{*}, K_0^{*}, M_{0\tau}\right) \qquad \text{EQ.14}$$

This expression represents the damages from climate change after both partial and full adjustment are taken into account, using and acting on available information about climate change.

4. *Net benefits of partially adjusting to climate variability:*

$$Z\left(X_{1\tau}^{''}, K_0^{*}, M_{1\tau}\right) \; - \; Z\left(X_0^{*}, K_0^{*}, M_{1\tau}\right) \qquad \text{EQ.15}$$

This net benefit measure is derived directly from EQ.10. Conceptually, it is the physical or monetised value of the damages avoided associated with moving from the "worst case" in which no human adjustment occurs, either to climate variability or climate change, to one in which partial adjustment to perceived climate variability takes place (in the absence of reliable information about climate change).

This raises the question of whether it is possible to simulate the pure effect of climate change in existing models and so measure the net benefits associated with this adjustment. My answer is that it may be quite possible in the context of physical models, for example the crop yield models used by Parry et al. (1999) and Rosenzweig et al. (1995), where it would be possible to evaluate these models using meteorological data from a climate change scenario and holding the application of managed inputs at the values prevailing for the existing climate. In fact this is what both sets of authors did to simulate climate change, initially, and then they "imposed" adaptation scenarios on top of this, by varying management. Of course, this raises the larger issue of whether models that do not explicitly link human and physical behaviour through the production function in a systematic optimisation framework (directly or indirectly) can produce optimal or conditional allocations of fixed factors or variable inputs. It would appear that in the models used in both these studies, changes in management were introduced exogenously and so the market adjustments depicted in the trade model were conditional. I believe the Farm model, developed by Darwin et al, avoids this problem.

At any rate, I am not sure that it is possible in many cases to depict these benefits in operational models used at the sectoral or national level to estimate climate change damages and the benefits of avoiding these damages. Consequently, the pure effect of climate change still remains a somewhat theoretical construct. Thus, in many cases, both the maximum climate change damages in EQ.12 and the net benefits of partially adjusting to climate change may be difficult to measure in larger scale models. This means that generally, while it may be possible to create partial adjustment scenarios using existing approaches and models, the measurement of adaptation benefits per se will be limited to the change from partial adjustment to full adjustment.

5. Net benefits of fully adapting to climate change:

$$Z\left(X^{*}_{1\tau}, K^{*}_{1}, M_{1\tau}\right) - Z\left(X^{''}_{1\tau}, K^{*}_{0}, M_{1\tau}\right) \qquad \text{EQ.16}$$

This expression is derived directly from EQ.11. It represents the damages avoided, once partial adjustment to climate variability has taken place, as a result of fully adjusting the quasi-fixed factors used in the production function to expected changes in climate.

Figure 2 illustrates the changes made in the framework. It characterises the damage and benefit measures in the market for a good in the same way as Figure 1, in terms of the maximisation of consumer and producer surplus in a market, for the sake of consistency. If we think of the vertical axis as measuring marginal output, instead of output price, the diagram fits either case, conceptually, leaving out other exogenous variables that influence production. Of course the marginal and optimal output would be different under the two different objectives.

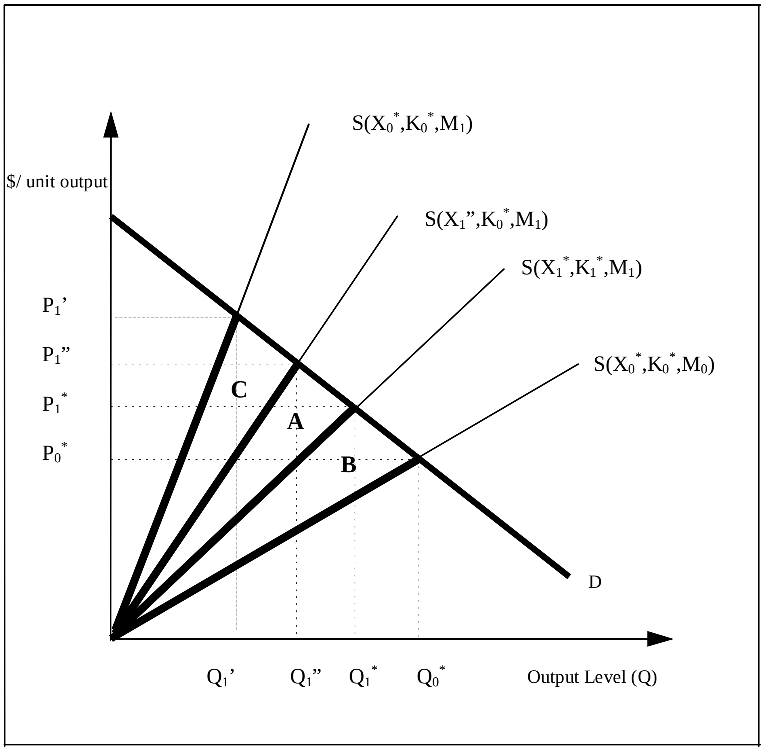
But now that changes in quasi-fixed factors have been added to the analysis, I need to add a word of caution. Typically, when long-run adjustments in market supply take place, they are in response to demand shifts. However, this case is somewhat different because the point I am trying to make is that, even without increases in demand, detection or anticipation of climate change by producers may create incentives to adjust quasi-fixed factors. This and later figures isolate that effect without consideration of normal long-run adjustments to demand increases. Taking both factors into account is, of course, important in determining the effect that climate change and adjustment to it will have on the long-run supply curve of an industry, but a complete graphic analysis of both the effects of climate change and demand growth on producer supply adjustments would obscure the main point I am trying to make[9]. It is important to add that demand growth and anticipation or detection of climate change may well interact in real life. That is in cases where fixed or quasi-fixed factors are “lumpy”, the anticipation or detection of climate change may not change the marginal benefits of adaptation sufficiently to justify long-run adjustments. However, increased demand for a good may alter that picture in the long-run and make it profitable to adjust to both influences.

In Figure 2, a fourth supply curve has been added to reflect the pure effect of climate change. Net welfare will always be lower in this case than in the others, because it is more highly constrained. The welfare loss represented by the areas C+A+B is equal to *the maximum climate change damages*. The welfare gain from partial adjustment, represented by a shift to the next lowest supply curve, and measured by the area C, represents *the net benefits of partially adjusting to climate change* when these changes are treated as existing climate variability. Therefore, the welfare loss characterised by the area, A+B, which is left after partial adjustment to climate variability takes place, is equal to *the imposed cost of climate change with partial adjustment*. The welfare gain from full adjustment, alone, involving a shift from the partial adjustment supply curve to the full adjustment supply curve, just lower down, and measured by the area A,

[9] The long-run supply curve for a constant-cost industry is perfectly elastic (horizontal). However, if both increases in demand and climate change impacts are time-dependent, then the long-run supply curve of an industry that adjusts to those impacts will slope upward, as in the increasing-cost industry case, assuming climate change impacts shift the short-run supply curve to the left, as shown in Figures 1 and 2.

represents *the net benefits of fully adapting to climate change*, once the quasi fixed factors have been adjusted using information about climate change. Thus the area B represents *the imposed cost of climate change*, once all adjustments have taken place.

Figure 2. Illustration of adaptation in a goods market (new framework)



Now to see how these concepts can be applied to planning under uncertainty and the assessment of the benefits and costs of adaptation options at the sectoral level and projects at the local level, I want to introduce a "made up" example of ex-ante, ex-post planning.

4. AN EXAMPLE

This example involves the use of an ex-ante, ex-post planning model to determine the optimal capacity of a small reservoir under ex-ante uncertainty about climate. The model can be used in two different ways: either as an ex-ante planning model, or as an assessment model, used ex-ante or ex-post to estimate climate change damages, the imposed cost of climate change and the benefits (or costs) associated with adapting (or not adapting) to climate change.

The basin model is not as complicated as those that Brian Hurd and I developed (Hurd et al. 1999) for the EPRI study, *The Impacts of Climate Change on the US Economy* (Medelsohn and Neumann 1999). It consists of a single runoff source that discharges through a potential reservoir site. Immediately downstream there is an aggregate diversion point for irrigated agriculture and below that another aggregate diversion point for municipal use. The river then discharges into the sea. The demand for water, by both aggregate uses, is modelled seasonally, over four water seasons, with the use of inverse water demand functions, where the marginal returns to water are a function of consumptive use. Initially, there is no reservoir and, by law, at least 75% of the annual runoff must go to agricultural use.

Planners want to select among four options, based on the discounted net present value of the benefits of:

1. Doing nothing and leaving the situation unchanged (i.e., the status quo).

2. Adopting markets to allocate water, seasonally, between agricultural and municipal uses.

3. Building an optimally sized reservoir.

4. Building an optimally sized reservoir and adopting water markets.

In this hypothetical river basin, there are two prevailing types of climate patterns: one in which runoff occurs in the late winter and early spring and another in which runoff is reduced by about 10% and occurs in late fall and early winter. Each of these climate states is characterised in the model by seasonal runoff distributions. In the model these distributions are "mixed" using probability combinations pr(state 1, state 2), where p(state 1) + p(state 2) = 1. (Just two climate states are used in the example, but this was done only to keep the keep the analysis simple). We solved this model for a range of probability combinations, but only show the results for a selected number of them.

The model developed to look at this problem is a "price-endogenous spatial equilibrium model, patterned after those developed in Hurd et al. (1999), with two important differences. First it is stochastic in that seasonal runoff is generated randomly according to distribution functions for the two states of nature. Second, the model jointly optimises reservoir capacity, water storage, allocation and consumption simultaneously under the two states of nature, based on the expected net present value of the willingness of users to pay for water less operational costs, less the capital cost associated with reservoir capacity. Thus, the reservoir capacity depends, ex-ante both on climate variability associated with each climate state plus the probability of occurrence of each of these states. Once the optimal reservoir storage capacity is determined, ex-ante, the management of the reservoir is also constrained ex-post, by capacity and the resulting values for the endogenous variables in all periods depend on the fixed reservoir capacity. However, both long-run and short-run decisions are explicitly modelled with perfect foresight[10], but with risk. The model can be expressed as:

Maximize the expected value of: EQ.17

$$Z = \sum_{\tau}^{\Lambda}(1/\Lambda)*\{\sum_{s}^{S}pr_s * \sum_{t}^{T}\sum_{j}^{J}\sum_{i}^{N}(1+\sigma)^{-t}[\Theta_{sij}*(c_{sij}W_{si\tau jt}) - .5*\Psi_{sij}*(c_{sij}W_{si\tau jt})^2 - p_{si}*W_{si\tau jt}]\} - (\gamma * K + .5*\delta * K^2)$$

Subject to:

Reservoir Storage Balance: EQ.18

$$S_{s\tau\tau jt} - S_{sjt} + REL_{s\tau jt} = RO_{s\tau jt} \overset{d}{=} \Phi_{sj}(\upsilon_{sj}, \sigma_{sj}^2, \Omega_{sj}, \Theta_{sj}) \quad \text{for all s, } \tau\text{, j and t}$$

Diversion Balance for Agriculture: EQ.19

$$W_{s,ag,\tau jt} + F_{s,ag,\tau jt} = REL_{s\tau jt} \quad \text{for all s, } \tau\text{, j and t}$$

Diversion Balance for Municipal: EQ.20

$$r_{s,ag,\tau jt}W_{s,ag,\tau jt} + F_{s,ag,\tau jt} = W_{s,muni,\tau jt} + F_{s,muni,\tau jt} \quad \text{for all s, } \tau\text{, j and t}$$

Flow to Sea Balance: EQ.21

$$r_{s,muni,\tau jt}W_{s,muni,\tau jt} + F_{s,muni,\tau jt} = OUT_{s\tau jt} \quad \text{for all s, } \tau\text{, j and t}$$

Reservoir Capacity Constraints: EQ.22

$$S_{s\tau jt} = 0 \quad \text{for all s,j and t}$$

$$S_{s\tau jt} \le K \quad \text{for all s, } \tau\text{, j and t}$$

No Market Constraint: EQ.23

$$\sum_{j}^{J} W_{s,ag,\tau jt} = .75 * REL_{s\tau jt} \quad \text{for all s, } \tau \text{ and t}$$

Initial and Terminal Condition: EQ.24

$$S_{s,0,0} = S_{sJT} \quad \text{for all } \tau$$

Where:

Indexes (sets):

[10] One could also introduce adaptive expectations about runoff into the model, but I have not done this.

τ = 1,…, Λ: trial periods

s = 1, …, S: states of nature

t = 1, …, T: years

j = 1, …, J: water seasons

i = 1, …, N: activities (agriculture, municipal)

Endogenous Variables:

Z = Expected net present value of the sum of producer and consumer surplus

less capital costs

W = Water diversion

S = Reservoir storage

K = Reservoir storage capacity

REL = Reservoir releases

F = F low in river remaining after diversion

OUT = Outflows to sea

Parameters and Exogenous Variables:

pr_s = The probability of occurrence of state s: pr(winter+spring runoff, fall+winter runoff)

σ = Opportunity cost of capital

Θ = Intercept of inverse water demand function

Ψ = Slope of inverse water demand function

γ = Intercept of storage cost function

δ = Slope of storage cost function

p = Variable cost of delivering water

c = Consumptive use fraction of diverted water

r = Return flow fraction of diverted water

RO = Runoff into the reservoir

And W, S, K, REL, F, OUT ≥ 0.

The objective function, Z, (EQ.17) represents the expected net present value of consumers and producers surplus associated with the operation of the reservoir and the delivery and consumption of water minus the capital cost of constructing the reservoir. The reservoir balances (EQ.18) maintain the intertemporal continuity between storage, releases, and runoff into the reservoir. Seasonal runoff is random and varies by water season and the climate state. Water is released from the reservoir and flows downstream to satisfy agricultural water demands and municipal water demands that are farther downstream. The two diversion balances (EQ.19 and 20) take into account that water, which is not diverted from the river, remains in the channel and then is combined with the return flows from use, before reaching the next diversion activity. The flow to sea balance (EQ.21) adds the water in the river channel that is not diverted by municipal water users and combines it with the return flow from municipal uses to account for the flow that reaches the sea.

The last two sets of constraints are used to formulate different problems (or cases) to look at institutional changes in water allocation rules and the interaction between these rules and storage capacity. There are two reservoir capacity constraints (EQ.22). One restricts water storage in each period to the capacity of the reservoir, for cases where reservoir storage is assumed. The other sets storage to zero in each period for cases where no reservoir is assumed and run-of-river conditions prevail. The No market constraint (EQ.24) requires that 75% of all the water released in each year be allocated to agricultural diversions[11]. The single initial-terminal constraint (EQ.24) requires that terminal storage and initial storage values are equal. These are determined endogenously, along with the values for seasonal diversions, seasonal reservoir, seasonal reservoir releases, seasonal in stream flows at each diversion, seasonal outflows to the sea and reservoir storage capacity.

The results from this model are preliminary. Also, to keep the example focused on the benefits and costs of adaptation, I only show the welfare and reservoir storage capacity estimates for the various cases. This is somewhat regrettable, because changes in seasonal reservoir storage and water allocation to users differ quite a lot under the different climate probability combinations and institutional rules.

The methodology used to address this planning problem was as follows. First, GAMS (1998) was used to solve the planning problem and obtain optimal values for the endogenous variables over a number of probability combinations, pr(1, 0), …, pr(0, 1) for each of the four project options. This set of runs simulated optimal adjustment to climate change, since the storage capacity was allowed to adjust freely. This information was used to calculate the development benefits of the four project options, assuming the climate did not change, and the value of the imposed cost of climate change after partial and full adjustment for each option, including doing nothing.

Partial adjustment solutions were also obtained for each of the probability combinations and option cases. These simulations were conducted by taking the value of optimal reservoir capacity for options 3 and 4[12] for a given climate probability combination and holding it constant in all the runs for the remaining probability combinations in which the climate and runoff were different. This set of runs was designed, in a planning capacity mode, to simulate a situation in which planners did not have reliable enough information about climate change to use in their planning and wanted to explore the expected benefits and costs of each option under different climates. From an assessment perspective, it represents a situation in which water managers and users are only partially adjusted to climate change through their adaptation to existing climate variability.

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[11] Note that consumptive use is less than the amount of water diverted, due to evaporative losses and return flows. Also total diversions in a year do not necessarily equal total releases due to the presence of return flows.

[12] There is no partial adjustment solution for the status quo or option 2, since no reservoir is built in these two cases.

Table 2 shows the welfare, project benefit and capacity results of the first set of runs, for the probability combinations pr(1, 0), pr(.9, .1), pr(.25, .75) and pr(0,1) and their associated values of expected annual runoff. For each option, the value of net welfare falls as climate shifts, over the indicated probability combinations, from pr(1, 0) to pr(0, 1). Under any single expected climate, the net benefits of option 4 (instituting water markets and building a reservoir) dominate all other options. But note that the difference between the net benefits of option 4 and option 2 (instituting water markets, only) under the climate pr(1, 0) is quite small, but increases fairly dramatically as the probability of winter and spring runoff falls and the probability of fall and winter runoff increases. As this occurs, the importance of reservoir storage capacity in both options 3 (building a reservoir, only) and 4 in adjusting to climate change becomes more and more important relative to water markets. This can be seen, not only by comparing the net benefits of these three options relative to optimal storage capacity increases across the various probability combinations, but also by noting that when we compare the optimal storage capacity estimates for options 3 and 4, water markets become a poorer and poorer substitute for reservoir capacity as the climate shifts from pr(1, 0) in the direction of pr(0, 1).

Table 2. Expected Net Welfare and Optimal Reservoir Capacity for Project Options Under Alternative States of Natire – Full Adjustment

Project Options	States of Nature Probability Combinations			
	Pr(1, 0)	Pr(.9, .1)	Pr(.25, .75)	Pr(0, 1)
	Expected Annual Runoff x 10^3 m^3			
	9210	9100	8380	8100
	Expected Net Welfare x $\$10^6$			
1. Status quo	85.557	82.330	61.351	53.282
2. Market only	118.119	112.965	79.467	66.582
3. Dam only	96.313	93.983	79.612	74.476
4. Market + dam	119.389	116.663	106.454	102.945
	Project Net Benefits in Relation to Status Quo x $\$10^6$			
2. Market only	32.562	30.636	18.116	13.300
3. Dam only	10.756	11.653	18.261	21.194
4. Market + dam	33.831	34.334	45.104	49.663
	Optimal Capacity (10^3 m^3)			
1. Status quo	---	---	---	---
2. Market only	---	---	---	---
3. Dam only	3732	3946	5143	5740
4. Market + dam	775	2531	4514	4754

Tables 3 and 4 show the expected net welfare results of the partial adjustment runs for options 3 and 4, in which capacity is fixed at its optimal value as indicated in the first column of the table and the climate probability combinations are varied over the rows. The diagonal values in both tables are just the optimal expected net welfare values from Table 2.

Table 3. Expected Net Welfare for Project Option 3 (Dam only) Holding Reservoir Capacity Fixed and Varying Climate – Partial Adjustment

Reservoir Capacity	States of Nature Probability Combinations			
	Pr(1, 0)	Pr(.9, .1)	Pr(.25, .75)	Pr(0, 1)
	Expected Net Welfare x $\$10^6$			
Pr(1, 0): 3732	*96.313*	93.962	78.678	72.800
Pr(,9, .1): 3946	96.292	*93.983*	78.976	73.204
Pr(.25, .75): 5143	95.347	93.249	*79.612*	74.367
Pr(0, 1): 5740	94.647	92.630	79.518	*74.476*

The results in these two tables can be used in a variety ways. First, each off-diagonal row entry represents the maximum expected net welfare that can be achieved when the reservoir capacity is fixed at the level in column 1. Each off-diagonal column entry, on the other hand, shows how changes in reservoir capacity affect expected net welfare given the climate probability combinations for that column. All the off diagonal elements in any given row or column are smaller in value than the diagonal element for that row or column, indicating partial adjustment. This is due, mathematically, to the LeChatelier principle. Conceptually, it shows that when the long-run reservoir capacity is not adjusted as climate changes, the resulting short-run behaviour of water managers and users is also not optimal for the altered climate.

Table 4. Expected Net Welfare for Project Option 4 (Dam + Water Markets) Holding Reservoir Capacity Fixed and Varying Climate – Partial Adjustment

Reservoir Capacity	States of Nature Probability Combinations			
	Pr(1, 0)	Pr(.9, .1)	Pr(.25, .75)	Pr(0, 1)
	Expected Net Welfare x $\$10^6$			
Pr(1, 0): 775	*119.389*	115.465	89.960	80.150
Pr(.9, .1): 2531	118.697	*116.663*	103.444	98.360
Pr(.25, .75): 4514	117.102	115.682	*106.454*	102.905
Pr(0, 1): 4754	116.856	115.465	106.423	*102.945*

The information in these two tables can be used to calculate the loss in expected net welfare as a result of making either a Type I or Type II error regarding climate change. An example from option 3 can be used to illustrate this. Suppose we currently experience a climate characterised by pr(.9, .1) and our best information is the climate change will be like pr(.25, .75). The null hypothesis is that climate will not change. If we accept the null hypothesis (no climate change) and do not build a bigger reservoir, and climate does change as we expected, then the cost of making this Type II error will depend on how the climate changes. Let us say it does change, as expected, as in pr(.25, .75). If we had correctly predicted the climate change and built the optimally sized reservoir, expected net welfare would equal $79.612 million . But since we did not build the bigger reservoir and are in state of partial adjustment, the maximum welfare that can be achieved under the changed climate is $78.976 million. The difference between these values, or $636,000, is the expected cost of making a Type II error in this particular case. Now let’s say we reject the null hypothesis and increased the size of the reservoir, consistent with our expectations and the climate did not change. In that case the expected cost of making this Type I error will be $93.983 – $93.249 million, or $734,000.[13]

In an adaptation assessment framework, the information in the last three tables can be used to the damages due to climate change and the benefits of adjusting to climate change, both partially and fully. Unfortunately, it was not possible to estimate the *maximum climate change damages* in this example or the *net benefits of partially adapting to climate variability*. The pure effect of climate change could not be simulated using the model here because the water demand functions were not derived, explicitly, from production functions[14]. These estimates are contained in Tables 5 (option 3) and 6 (option 4). In constructing these tables, I have taken the liberty to show only the partial results for climate that is changing in just one direction, reflecting an increase in the joint probabilities that runoff will occur earlier in the water year rather than later, in other words: the probability of late winter and early spring runoff decreases, while the probability of late fall and early winter runoff increases.

The rows in Tables 5 and 6 present the estimates of expected for the different damage-benefit categories by the four ex-ante probability combinations. The columns in the two tables represent the expected ex-post values for the different probability combinations. Thus, if planners assumed the subjective probability combination Pr(1,0) in designing the project, but the probability combination that actually occurred (the true probability combination) was Pr(.9,1), then the expected value of climate change damages would be 2.351 million dollars, whereas this would increase to 17.635 million dollars if the true probability combination was Pr(.25, .75), and would increase still further to 23.514 million dollars if the true probability combination was Pr(0, 1).

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[13] This information can be used in a Bayesian framework to estimate the value of additional information about climate change, as sampling occurs. But I do not want to go into this in depth in this paper, except to indicate that the conceptual framework presented here is consistent with Bayesian decision-making and can be taken further in that direction.

[14] An effort was made to simulate this by holding water use constant and existing reservoir capacity constant, but it resulted in many infeasible solutions. These infeasibilities are, of course, instructive of the strain water users and managers would face if they could not adapt to climate variability, which they can.

Table 5. Estimates of Climate Change Damages, Imposed Cost of Climate Change and Net Benefits of Adaptation for Project Option 3

Damage-Benefit Categories For the Different Probability Combinations	States of Nature Probability Combinations		
	Pr(.9, .1)	Pr(.25, .75)	Pr(0, 1)
Pr(1, 0)	Expected Welfare Estimates x $10^6		
Climate change damages[1]	-2.351	-17.635	-23.514
Imposed cost of climate change[2]	-2.331	-16.701	-21.838
Net benefits of adaptation[3]	0.208	0.934	1.676
Pr(.9, .1)			
Climate change damages		-15.007	-20.778
Imposed cost of climate change		-14.371	-19.507
Net benefits of adaptation		0.636	1.271
Pr(.25, .75)			
Climate change damages			-5.245
Imposed cost of climate change			-5.137
Net benefits of adaptation			0.108

[1] With partial adjustment
[2] With both partial and full adjustment
[3] Due to full adjustment

These two tables contain a lot of information relating to vulnerability and adaptation. Going back to the previous discussion about Type I and Type II errors, one of the most important conceptual points about these two tables is that climate change damages that are avoided by full adjustment (i.e., the *net benefits of adaptation*) are also the cost associated with making a Type II error in this example. At the end of the paper I will try to draw this all together in some suggestions about how the various measures in these tables might be conceptually related to vulnerability and adaptive capacity. But for now, I will make only a few points.

First, the adaptation benefits associated with the various changes in climate tend to be much larger in absolute and relative terms for option 4 than for option 3. What this suggests is a strong interaction between water markets and reservoir storage in adjusting to climate change. The net adaptation benefits of being able to adjust storage capacity in the presence of water markets is substantially greater than the net benefits of adjusting storage capacity when there are no water markets. This is understandable due to the highly constrained allocation rules associated with option 3. At the same time, however, option 4 is more vulnerable to climate change than option 3 in the sense that the climate change damages associated with option 4, both in absolute terms and relative to the full adjustment net welfare estimates shown in the diagonal elements of Tables 4 and 5. These differences narrow somewhat as the reference climate shifts toward Pr(0, 1). This is surprising in the sense that intuition and the difference in net welfare levels under full adjustment for the two options tells us that combining water markets with a reservoir is economically more efficient than just building the reservoir. But I think this is explainable in a more general conceptual framework of vulnerability and adaptation that I will leave to the end of the paper.

Table 6. Estimates of Climate Change Damages, Imposed Cost of Climate Change and Net Benefits of Adaptation for Project Option 4

Damage-Benefit Categories For the Different Probability Combinations	States of Nature Probability Combinations		
	Pr(.9, .1)	Pr(.25, .75)	Pr(0, 1)
Pr(1, 0)	Expected Welfare Estimates		
Climate change damages[1]	-3.924	-29.429	-39.238
Imposed cost of climate change[2]	-2.725	-12.934	-16.443
Net benefits of adaptation[3]	1.199	16.495	22.795
Pr(.9, .1)			
Climate change damages		-13.219	-18.303
Imposed cost of climate change		-10.209	-13.718
Net benefits of adaptation		3.010	4.585
Pr(.25, .75)			
Climate change damages			-3.549
Imposed cost of climate change			-3.509
Net benefits of adaptation			0.040

[1] With partial adjustment
[2] With both partial and full adjustment
[3] Due to full adjustment

4.1 Adding no regrets

The final issue I want to discuss in connection with this example is the estimation of climate change damages, the imposed cost of climate change and the net benefits of adaptation for "no regrets" projects. Let me first do this in the context of options 3 and 4.

It seems perfectly acceptable to view options 3 and 4 as development projects. The net benefits of these two options are shown in the middle panels of Table 2 for various climate combinations. But as I have already have shown, these projects can also reduce climate change damages, and this is not taken into account in these estimates. To find out what the adaptation benefits of a development project are, we have to ask the question for each option: "what would climate change damages be if we built the reservoir without taking the possibility of climate change during the life of the reservoir into account"? The answer to this question lies in the results in Tables 5 and 6. For example, if the historical data suggested the existing climate was characterised by pr(.9, .1) and the climate was in fact changing so that it would be more like pr(.25, .75), the climate change damages associated with option 3, taking into account only partial adjustment, would still be $15.007 million and the net adaptation benefits of building a larger reservoir $0.636 million. For option 4, the corresponding damage and net benefit values would be $13.219 million and $3.01 million. Thus, the general definitions of various climate change benefits and costs apply equally to all types of projects, no matter what the objective.

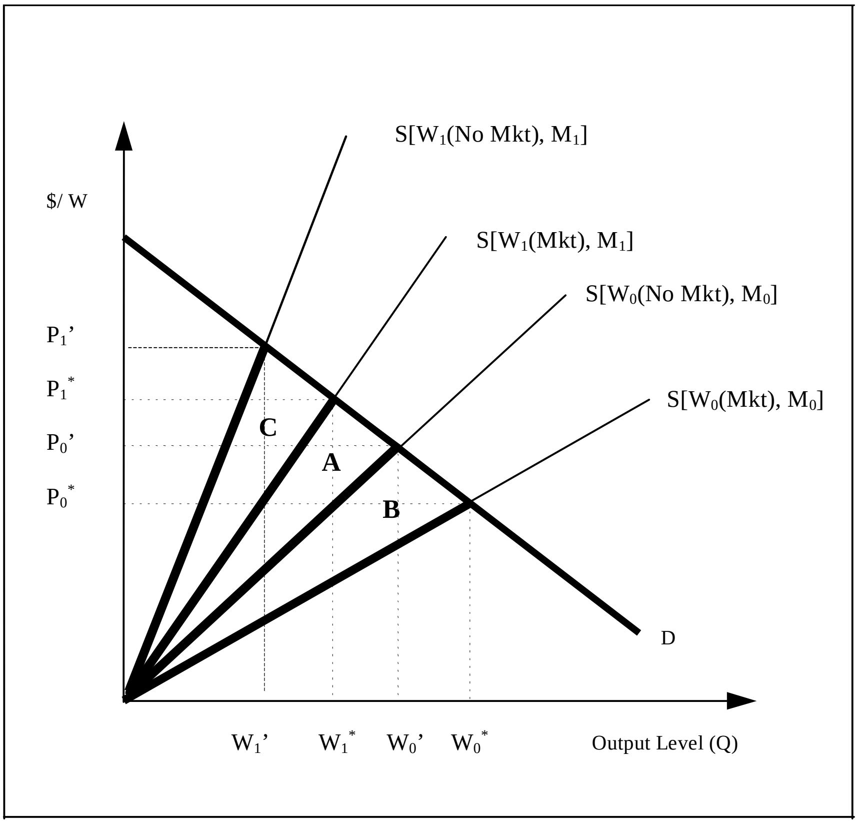
However, while the net adaptation benefits may be a good measure capturing the contribution of a development project to a climate-related objective, it is important to distinguish between no-regrets projects that are risky and those that are not. While options 3 and 4 face always improve social welfare compared to the status quo they both face the risk that the optimal reservoir storage capacity levels will be too large or two small if climate does, or does not, change in the way we expected. I have already calculated the costs of these planning "errors" for option 3 under these same probability combinations. The same types of risk exist for options 4. The point is that while many no regrets projects may be better than other alternatives under any climate, they still may face "climate regret", as is the case in options 3 and 4, if the physical investment is climate sensitive. So, it seems reasonable to make a distinction between no regrets options that face potential climate regrets and those that do not. I have not heard that distinction being made in the literature about no regrets or anticipatory adaptation (Smith and Lenhart 1996), but I think it may be implied.

Option 2 is important from this perspective in that it represents an anticipatory, no regrets action that has no climate risk associated with it. This point is illustrated for option 2 in Figure 3, involving the same shift in the climate probability combinations from pr(.9, .1) to pr(.25, .75). In this figure the demand curve, D, is the derived aggregate demand for water, W, and P is the marginal value of water in the basin. As in the previous figures, the demand curve is portrayed so that it is not affected by climate change, to keep the graphic analysis as uncomplicated as possible. Initially there are no water markets and climate is characterised by M_0. The aggregate water supply curve in the basin, corresponding to this, is S [W_0(No Mkt), M_0]. After water markets are adopted and the climate changes, the relevant aggregate water supply curve is S[W_1(Mkt), M_1]. The expected net welfare loss between these two is represented by the area A. These are the net project benefits of option 2, taking into account climate change and the change in water allocation rules. It is the smallest welfare loss that can be achieved, relative to the no action cases.

The figure is presented to compare option 2 with the next best alternative, the status quo. The welfare loss due to climate change under the status quo option is measured by the areas between the supply curves, S[W_0(No Mkt), M_0] and S[W_1(No Mkt), M_1], or A+C. If water markets are instituted, under either climate, the welfare change associated with doing this is positive. Under the initial probability combination, pr(.9, .1), the resulting expected welfare gain associated with the supply curve, S[W_0(Mkt), M_0], is measured by the area B. If climate has changed the relevant supply curve is S[W_1(Mkt), M_1], and the resulting expected welfare gain is measured by the area C. In other words, water managers and users are always better off no matter what the climate is. Thus, there is no climate regret associated with this option, as welfare is always improved by adopting water markets.

So, what are the net adaptation benefits of option 2, if water markets are adopted and ex-post we learn that climate has changed? By adopting water markets sooner rather than later, water managers and users will avoid the potential expected welfare loss measured by the area C. As such, the area C represents the adaptation benefits of instituting water markets as a form of insurance against climate change, which water managers and users may not even be able to detect and can only predict with error. In short, adapting water markets will always dominate over not adapting them, no matter how much information we have or don't have about climate change and doing this will avoid potential climate change damages that water managers and users can not detect or predict with certainty.

Figure 3. Illustration of adaptation for a no "climate regrets" project



I want to conclude this subsection just by saying that I think in selecting various options for anticipatory or proactive adaptation, it is important to separate out those that have climate regrets associated with them and those that do not and concentrate on those that face no climate regret. At the same time I think it is important to quantify the expected value of the net adaptation benefits associated with these options to give an idea of how much better off they will make society if climate is changing and we are not able to detect it yet. The job of assessing the adaptation benefits and costs of policies that have potential climate regrets is not a technically complicated task. Even though we may not have very much reliable information about climate change to undertake resource planning at small geographic scales, this should not prevent us from looking at the expected adaptation benefits of these projects under alternative ex-ante ex-post subjective probabilities to better assist us to understand the costs of making Type I and Types II errors. There is ample precedent for doing this in water resources planning when there is risk associated with using historical stream flow records in planning storage capacity. Adding climate change risk is conceptually no different.

4.1 Assessment modeling

One of the points made in Callaway et al. (1999) was that there were no sector level studies available that measured the net benefits of adaptation or climate change damages in developed or developing countries. This remains almost as true today as it was then. Since the appearance of Mendelsohn and Neumann (1999) this and several other studies (Mendelsohn et al., 1996, Yohe et al., 1996, Fankhauser, 1996) have concentrated on measuring the imposed cost of climate change, only. This measure, as we have indicated, places a monetary value on the impacts of climate change, taking into account the fact that adaptation takes place. More recently, Darwin and Tol (2001) constructed the proper paradigm for separating out the benefits and costs of adaptation, but were unable to relate the imposed cost of climate change to adaptation benefits and costs in a consistent accounting framework because they used different models to calculate adaptation costs and the imposed cost of climate change.

More recently, Mendelsohn (2000) and Mendelsohn and Dinar (1999) have suggested that the net benefits of adaptation can be "parsed" out by comparing his earlier estimates of the imposed cost of climate change in the US agricultural sector (Mendelsohn et al. 1994) using the "Ricardian"[15] approach with so called "agronomic"[16] studies of climate change damages by Adams et al. (1993 and 1999) for the US agricultural sector. The difference between the two, he suggests, will yield an estimate of the net benefits of adaptation. The problem with this argument, as Darwin (1999) has pointed out, is that the "agronomic" studies have been conducted using price-endogenous sector models that may, in fact, include more adaptation possibilities than does the Ricardian method. Thus, according to Darwin, both sets of studies have actually presented estimates of the same measure, the imposed cost of climate change. Since the studies use vastly different databases for the US agricultural sector, it is probably these differences and not adaptation that explain the differences in the results of the two sets of studies (Hanemann 2000).

So, how the economic research community can best estimate climate change damages, net adaptation benefits and the imposed cost of climate change remains an open question. My proposal as to how to do this is based on implementing a conceptual framework that links adaptation to climate change to adaptation to climate change variability. In putting forth this proposal, I am a little ambivalent about the geographic and market scope of this framework, but I question the ability to capture "everything" in the context of a global or national CGE models and lean in favour of partial equilibrium price-endogenous sector models (McCarl and Spreen 1980), at the national or global (i.e., world trade) level. This preference is based on the data and computational problems associated with embedding a model detailed enough to depict adjustments to climate variability and climate change in a climate-sensitive sector model within a detailed CGE framework.

The "ideal"approach would involve:

- Explicit linkages between outputs and input use and exogenous meteorological/environmental variables, such that changes in the exogenous variables:
  - Directly influence output,
  - Endogenously influence input and output prices, and as such
  - Endogenously influence input and output adjustment to both climate variability and climate change.

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[15] The "Ricardian" approach involves developing a regression relationship between net farm income in a cross-sectional, time series database and meteorological variables. The imposed cost of climate change is simulated by evaluating the regression equation with different values for the meteorological variables in a Base Case and in a Climate Change Scenario. This valuation function is also better known as a "hedonic price" function and it was initially developed to explain the impacts of environmental externalities on human welfare through changes in housing/land prices.

[16] So called because Mendelsohn did not believe that these studies allowed crop prices to reflect the pure effects of climate change. A true "agronomic" model would hold crop prices constant at Base Case levels and changes in net farm income would only reflect the impacts of the pure effect of climate change. If that had been true in the studies cited by Mendelsohn, his point would have been theoretically correct.

- The ability to include management, technological, and infrastructure options for adaptation to both climate variability and climate change and allow these to be selected endogenously in the model, based on marginal benefits and costs.

- The ability to simulate, and distinguish between, short-run adjustments of variable inputs and long-run adjustments to quasi-fixed inputs.

- A stochastic approach to modelling both climate variability and climate change by:

- Simulating inputs of meteorological/environmental variables stochastically, and

- Relating climate change to climate variability by explicit changes in the distributions of (or the probabilities of occurrence of specific values) these variables.

- Linkages to the rest-of-the world through trade, partially, through excess demand (or supply) functions or fully.

This may seem like a tall order, especially on the climate scenario side, given that there is not very much information about changes in climate variability associated with climate change, and emission scenario modelers are reluctant to attach subjective probabilities to the emissions scenarios that drive GCMs. I think we should not let that us hold back, especially if, as so many climate experts tell us, GCM results should not be treated as forecasts. In that regard, it is also tempting to believe that we need a lot of meteorological information in climate forecasts, if only because state of the art impact models have voracious appetites for data. But, since the source of much of the meteorological information that already goes into these models for climate runs is highly "massaged" in the first place, I think we should not let that hold us back either. We should not become too focused on forecasts of individual meteorological variables and the need to fit the partial and joint distributions of a large number of meteorological variables in constructing climate scenarios.

Instead, I think we ought to concentrate on developing climate scenarios, or climate states, that depend on only a few "random" variables in the historical record and vary these, not only based on the weak links we have to global and regional GCM models, but more importantly based on the existing historical record of climate variability, closer to the extremes than the middle. Good examples of this would be to shift the intensity and timing of Asian monsoons or African rainy seasons to coincide with those events that occur more rarely and to which Asian and African resource managers and governments are presumably not that well adapted (even though they do occur). By doing this we can gain, not only insights into the autonomous and strategic benefits and costs of investments required to better adapt to more infrequent, but very important, weather patterns, but also a better appreciation of the role which short-run adjustments to climate variability already play, and will play, in adapting to these changes.

One of the features that is not easy to incorporate in large-scale assessment models is climate variability. This is a problem, computationally, because of the need to simultaneously simulate climate variability and market adjustment to it in a number of regions. However, this is possible at smaller geographic assessment scales, for example in river basins, and in planning models for individual projects. Thus, how to relate adjustments to existing climate variability to adjustments to climate change in large scale assessment model represents an important area of further research and development.[17]

[17] Such an effort is underway, I believe, under the title *Close-Coupling of Ecosystem and Economic Models: Adaptation of Central U.S. Agriculture to Climate Change* at Montana State University.

5. CONCLUSION: VULNERABILITY, ADAPTATION AND ECONOMIC DEVELOPMENT

I have already tried to illustrate how adaptation to climate variability can play an important role in adapting to climate change. However, adaptation to climate variability and climate change are affected by many of the same factors. In this final section, I want to try to link the adaptation framework developed in the previous section to two questions:

- What makes a region vulnerable to climate change, and
- How does this relate to the capacity of a region to adapt to climate change?

In addition, we relate these to more general sustainable development issues and policies in developing countries.

One of the issues that natural scientists and economists have been debating, implicitly, is how to relate the physical effects of climate change to the adjustments that individuals and organisations make to avoid these effects. In the previous section, I tried to show that adjusting to climate change occurs along a continuum from no or extremely limited adjustment as a result of the pure effect of climate change, to partial adjustment which occurs when climate is changing but it is perceived as climate variability, and so only short-run adjustments are made, to full adjustment where individuals and organisations adjust quasi-fixed factors based on reliable information about climate change.

The question is, do we define vulnerability to climate change before or after these adjustments take place. Or put in terms of the definitions presented in this paper, do we define vulnerability to climate change in terms of the pure effect of climate change, where climate change damages are at a maximum, or in terms of the imposed cost of climate change, after partial and full adjustment have taken place? I think this question is best approached by looking at three extreme cases, where:

1. The maximum climate change damages are very large in relation to the existing climate and the imposed cost of climate change is small in relation to the maximum climate change damages (implying relatively large net adaptation benefits),
2. The maximum climate change damages are very large in relation to the existing climate and the imposed cost of climate change is also very large in relation to the maximum climate change damages (implying relatively small net adaptation benefits), and
3. The maximum climate change damages are quite small relative to the existing climate and the imposed cost of climate change is large in relation to the maximum climate change damages (implying relatively small net adaptation benefits).

Each of these cases is perfectly plausible. In each case, I assume that society is well adapted to the existing climate. Therefore, Case 1 represents a situation where the climate is very different, after climate change, but the capacity to adjust partially and fully to climate change is large. This is to be contrasted with Case 2, where climate change is large, but the capacity to partially and fully adjust to it is limited. Case 3 represents a situation where not much adaptation needs to take place, because the climate does not change a great deal.

These three cases focus attention on the importance of adaptation adjustments relative to climate change damages. Breaking down adaptation to climate change into its two parts, partial adjustment and full adjustment, provides further insights. As indicated previously, partial adjustment, in itself, creates net benefits measured by the reduction in maximum climate change damages. These benefits are due to the already built in capacity to adjust to existing climate variability, without making new investments in quasi-fixed factors. To measure these net benefits explicitly one has to be able to simulate the pure effects of climate change. If this cannot be done, as in the case of the example in this paper, then there is no way to measure the contribution of partial adjustment to adaptation to climate change. This point illustrates the practical importance of the capability to simulate the pure effects of climate change in sectoral assessment models. Full adjustment to climate change gives rise to further adjustments that individuals and organisations make to adapt to climate change by adjusting quasi-fixed factors consistent with the altered climate. As indicated previously, full adjustment generally will not occur unless information about climate change is reliable enough for individuals and organisations to risk incurring relatively large investment costs. The example in this paper illustrated this point for measures where society faced potential climate regret as a result of making the wrong decision regarding reservoir capacity.

Thus, it seems reasonable to suggest that adaptation capacity is also composed of two parts: the capacity to adapt to climate change due to the ability to adjust to existing variability and the capacity to adapt to climate change by making long-run investments. The effects of both of these are measurable in terms of avoided damages, both physical and economic[18], and by characterising the actions that individuals and organisations are able to take to avoid climate change damages. One way to measure the contribution of adaptation capacity to avoiding climate change damages totally, or in its parts, is by the ratio(s) of avoided damages to maximum climate change damages.

Going back to our original question, we are still left with the following conceptual possibilities for quantitatively evaluating the relationship between vulnerability and adaptation. These are: to measure vulnerability independent of adaptation through various measures of climate change damages, or to measure vulnerability after we net out adaptation through partial and full adjustment through measures of the imposed cost of climate change. In the first case, it is possible to create both physical and economic indices of vulnerability by the ratio of the appropriate measure of climate change damages to a base case measure. From a welfare accounting perspective this index could be represented by the ratio of the maximum climate change damages to base case welfare. In the second case, vulnerability can also be measured in relative terms through the ratio of the imposed cost of climate change to a base case measure, which could be characterised in welfare accounting terms by the ratio of the imposed cost of climate change to base case welfare.

In a recent unpublished paper, Antle et al. (2002) have arrived independently at similar conclusions. Combining their definitions with the terms in Callaway et al. (1999) and this paper, they identify the following indices:

- Relative climate variability (without adaptation) = Climate change damages/Base Case Welfare
- *Relative climate variability (with adaptation)* = Imposed cost of climate change/Base Case Welfare
- *Relative adaptive gain* = Net benefits of adaptation/Base Case Welfare

Much of the literature on climate change impacts and adaptation to climate change has tended to view the issues of vulnerability and adaptation, fundamentally, as resource management issues (See for example: Mendelsohn and Neumann 1999; Downing et al. 2001; McCarthy et al. 2001). The IPCC's *Third*

[18] Through both Marshallian surplus and Hicksian variation measures and through changes in sectoral income accounts.

Assessment Report (2001b) investigated the links between sustainable development and adaptation capacity, but in doing so failed to relate it in specific terms to the underlying structural features in the macro-economies of developing countries that make it difficult for them to adjust to environmental and other "shocks." They also left out any reference to the growing body of literature on sustainable development using computable general equilibrium models. This is perhaps reflective of the fact that sustainable development as a concept and sustainable development financing as a practice have tended to focus on resource and environmental management and on human and social capital development, as opposed to infrastructure development and domestic structural adjustment policies (in the macro-economic sense). While this perspective makes a great deal of sense when looking at partial adjustments to climate change, it misses the point somewhat when it comes to full adjustment. And thus, I think the emphasis on adaptation, as a resource management issue is especially overstated when it comes to assessing vulnerability and adaptation in developing countries.

There are at least two reasons for this. First, the ability to partially adjust to climate change in developing countries is primarily limited by structural factors that, in many cases, can only be adjusted in the long-run. While it is often true that resource managers in some developing countries have trouble responding to climate variability, in the short-run, due to poor resource management practices, this may not be the key problem. Rather, it may due to the fact that the economic systems in which they operate are often highly constrained in structural terms. This limits the ability of resource managers to respond to environmental shocks of any kind, whether this comes from global climate change or hoards of locusts. These limiting factors, which I have taken loosely from Winters et al. (1998), include briefly:

- Highly constrained resource mobility, nationally and internationally,
- Lack of differentiation and specialisation in natural resource sectors that are dominated by household production,
- Limited technological possibilities for output and input substitution,
- High prices of inputs that can be substituted for, or counteract the effects of, environmental inputs affected by climate change, relative to their marginal productivity in natural resource sectors,
- Thin domestic product markets in natural resource sectors due to poor distribution and marketing systems, and
- Lack of integration in international product markets, compounded by developed country subsidy programs.

Second, if one looks over the list of factors, above, that limit the adaptive capacity of individual producers, sectors, or groups of sectors in a nation or region, it can be seen quite easily that these factors are fundamentally related to economic development issues and not resource management issues. The nexus between the capacity of individuals, singly or collectively, to adapt to climate change and their stage of economic development is critical and, until recently, has been neglected in much of the literature on adaptation to climate change. That is to say: policies that are effective in modernising the economy of a developing country, by increasing the productivity of natural resource sectors, making output and input substitutions more elastic, better integrating domestic markets into the national and international economy, and reducing both economic and non-economic constraints on resource mobility are also good climate change policies both in the long-run and the short-run. This goes for long-run adjustments in technology, infrastructure and institutions that face climate regrets and those that do not. If the climate were changing very rapidly in time scales measured by decades, the almost total focus on resource management might be warranted. But the time scale of climate change and its possible impacts are in fact quite close to the time scales we ordinarily think of in terms of economic development – perhaps half a century or more.

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