Tyndall°Centre
for Climate Change Research

Theory and practice of economic analysis of adaptation

Alan Ingham, Jie Ma and Alistair Ulph

2006

Tyndall Centre for Climate Change Research Technical Report 55

Theory and practice of economic analysis of adaptation

Tyndall Centre Technical Report No. 55

This is the final report from Tyndall research project *T3.34* (Theory and practice of economic analysis of adaptation).

The following researchers worked on this project:
Alan Ingham and Jie Ma, Economics Division, School of Social Sciences, University of Southampton ; Alistair Ulph, Faculty of Humanities, University of Manchester

Abstract

The aims of this project were to explore the theoretical issues associated with estimating the costs of adaptation to climate change. It focussed particularly on the inclusion in Cost-Benefit Analysis of option values to assess the correct timing of investments in adaptation strategies, based on agents current expectations and how they expect those expectations to change over time as better information becomes available. This will allow, in future studies, an analysis of the benefits and costs of additional information.

We find that mitigation and adaptation, in general, to be substitutes in the economic sense and this is a result robust to many assumptions. Only in the case where mitigation buys time for adaptation to take place can they be complementary activities.

When uncertainty, learning and irreversibility are introduced into the economic model we show that when both mitigation and adaptation are available strategies, the consequences of irreversibility are weakened. In some cases, only the learning effects matter, but, in general, learning about what the climate future may be is, will always be more important than irreversibility.

When we implement this framework empirically, we find that for the water industry there is an important learning effect concerningfuture climate change; if there is the possibility that investment decisions can take account of this, costs could be reduced by between 10% and 30% compared to when no learning takes place. The critical issue here is the balance when the investment decision is made between demand and available supply capacity.

Keywords

Adaptation, Uncertainty, Irreversibility, Learning, Learning Premium

Non-technical summary

The aims of this project were to explore the theoretical issues associated with estimating the costs of adaptation to climate change. It focussed particularly on the inclusion in Cost-Benefit Analysis of option values to assess the correct timing of investments in adaptation strategies, based on agents current expectations and how they expect those expectations to change over time as better information becomes available. This will allow, in future studies, an analysis of the benefits and costs of additional information.

We find that mitigation and adaptation, in general, to be substitutes in the economic sense and this is a result robust to many assumptions. Only in the case where mitigation buys time for adaptation to take place can they be complementary activities.

When uncertainty, learning and irreversibility are introduced into the economic model we show that when both mitigation and adaptation are available strategies, the consequences of irreversibility are weakened. In some cases, only the learning effects matter, but, in general, learning about what the climate future may be is, will always be more important than irreversibility.

When we implement this framework empirically, we find that for the water industry there is an important learning effect concerningfuture climate change; if there is the possibility that investment decisions can take account of this, costs could be reduced by between 10% and 30% compared to when no learning takes place. The critical issue here is the balance when the investment decision is made between demand and available supply capacity.

Objectives

The main objectives were:

1. To explore the theoretical issues associated with estimating the costs of adaptation to climate change.
2. To focus on the inclusion in Cost-Benefit Analysis of option values to assess the correct timing of investments in adaptation strategies, based on agents current expectations and how they expect those expectations to change over time as better information becomes available.

Work undertaken

The first part of the project involved (i) critical literature reviews; (ii) extensions of theoretical literature on irreversibility and learning to deal with adaptation.

The second part of the project applied the analysis developed in the first part to case studies in the UK water industry. It was originally intended that this part of the project would link to the Round 3 project proposed by Prof. Nigel Arnell (Effective adaptation to climate change in the water sector: coping with risk and uncertainty, T 3.33). That project was going to provide the information on options that water companies will then need to assess using some economic assessment. As this project did not take place within Phase 1 of the Tyndall Centre, it was necessary to identify a range of strategies on the supply and demand side which differ in the importance of timing and irreversibility and consider how the application of concepts of option values would modify the choice of strategies relative to conventional Cost-Benefit approaches. The case studies were selected to keep analysis tractable, and to be able to obtain appropriate data. For example, water is a regulated industry, and there are potentially important strategic interactions between the investment decisions of the water companies. This both substantially complicates the derivation of option values and makes water companies extremely reluctant to reveal information, because of its strategic value in relation to the regulators.

Results

The project reviewed the literature that has used the conventional certainty-equivalent approach to assess adaptation strategies and the optimal mix between mitigation and adaptation strategies. It then conducted a critical review of the main objections that have been raised about this approach, and assessed how far these are relevant for adaptation. Then, the

project focussed on the key issue when addressing climate change – the problem of irreversibility, uncertainty and learning. Normal intuition suggests that society would want to preserve options for exploiting better information in the future, and so it does not want to make irreversible commitments.
We showed that the simple intuition about the effects of irreversibility and learning, implied by earlier theoretical analysis, may not always apply in the case of climate change. Then we developed extensions of the theoretical literature on irreversibility and learning to deal with adaptation. Almost all of the discussion of learning, required for the question of the value of additional information, has been in the context of mitigation strategies, and we extended the analysis to include adaptation strategies.
The second part of the project applied the analysis to case studies in the UK water industry. On the supply side we consider investments in water resources, such as reservoir capacity and investments in piping to transport water from regions with surpluses to those with shortages, and adaptation that takes place through such measures as demand management. These investments differ in their durability (and hence irreversibility) and timescales for planning and implementation. Thus, crucial questions arise whether to make such investments now or delay until better information becomes available.
Computational considerations limit the number of different options and time periods that can be considered, but in practice, this may not be a serious problem. Many of these options will be quickly eliminated. The way one incorporates the learning and irreversibility effect into Cost-Benefit Analysis is by introducing option values. We did this by calculating a learning premium for the case studies, which gave an indication of the order of magnitude for the option value attached to the possibility of learning about climate change. We think this to be an important development. Recent UKCIP guidelines on costing methodologies for adaptation make a brief reference to option values but give no guidance as to how to actually implement these techniques.
The project found there to be great difficulties in liaising with water companies and obtaining information. This is due to the strategic interaction between the water companies and the two regulators, the Environment Agency and OFWAT. This situation may change with the implementation of the 2003 Water Act which makes water resource plans public documents. The issue of dual regulation and the consequences of both the different planning periods, and the form of regulation would still cause there to be under-investment in water resource capacity, and a transferring to consumers of the risk to water supplies from climate change.

Benefits and Relevance to Tyndall Centre research strategy and overall Centre objectives

The project filled a gap in addressing one of the key Research Theme 3 questions on the costs of adaptation. It was intended that the project would link to the proposal to be put forward by Prof. Nigel Arnell (Effective adaptation to climate change in the water sector: coping with risk and uncertainty), jointly with UKWIR which was intended to proceed it. This latter project will take place in the future and can utilise the methodology elaborated here.

Potential for further work

This project suggests many directions for further work. The economic models used in this project are simple, and whilst they generate useful results, some of the interesting and important aspects of the implications of climate change may not be covered, such as distributional aspects of mitigation and adaptation, adaptive capacity and catastrophic effects, etc. In addition, we have used a standard but specific functional form for costs. Whether the results obtained for learning, irreversibility would hold for more general cases rather than the quadratic one used here is an open question.
The project topic can also be extended in the direction of political economy of regulation of the UK water industry. Since there are two constituencies – the environment and price watching consumers and two regulators (The Environment Agency and OFWAT) it is natural to use a common agency situation to model regulatory policy making. The price watching and environmentally concerned consumers express their preferences, concerning the bias of

regulation, through the political voting process for alternative parties. This requires the development of game theoretic models. This would be especially useful research for considering the potential impact of the new regulatory system that will arise under the 2003 Water Act.

Communication Highlights:

Published Refereed Papers

A. Ingham, A. Ulph (2005), 'Uncertainty and Climate Change Policy' in **'Climate Change Policy' D.Helm (ed.)** Oxford University Press. (Tyndall WP 37)
A. Ingham, J. Ma, A. Ulph (2006), 'Climate Change, Mitigation And Adaptation With Uncertainty and Learning', **Energy Policy**, Special Issue dedicated to Memory of Alan S. Manne, April.

Tyndall Working Papers
A. Ingham, J. Ma, A. Ulph (2005a), 'How do the costs of adaptation affect optimal mitigation when there is uncertainty, irreversibility and learning?' Tyndall Working Paper 74.
A. Ingham, J. Ma, A. Ulph (2005b), 'Can Adaptation and Mitigation be Complements?', Tyndall Working Paper 79.

Other Papers
A. Ingham, J. Ma, A. Ulph (2005c), 'The Regulatory Background to Water Industry Investment and Climate Change', mimeo. To be submitted as Tyndall Working Paper.
A. Ingham, J. Ma, A. Ulph (2005d) , 'Learning about Climate Change:
A quantitative analysis of the effect for the UK Water Supply Industry', mimeo. To be submitted as Tyndall Working Paper.

Other Publications
'Exploring the Real Social Cost of Carbon', in **'Solutions for a Changing World'** ,Responding to Climate Change, 2005.
'Climate Change Policy', **Economic Review**, 23(3), February, 2006.

Seminars given at
University College of North Wales, Bangor
Tyndall Adaptation Workshop
Tyndall Assembly, Southampton and Cambridge

Conference Presentations
ISEE Montreal
NCCR Interlaken Switzerland

Discussions held with
3 Valleys Water / UKWIR
Thames Water
Environment Agency: Climate Change Division
Environment Agency: Water Resources Division
DEFRA (Global Atmospheres Division) Climate change impacts and adaptation: Cross-regional research programme. Topic C Water: HR Wallingford

Technical Report

1. Economic Analysis of Strategies for Adapting to Climate Change: Critical Review and Extensions

The first part of this project surveyed the literature on the economic analysis of mitigation and adaptation in the context of climate change. In particular, we discuss the extent to which adaptation and mitigation are complements or substitutes. Our analysis of uncertainty, learning and irreversibility extends the existing literature in the context of climate change, which has focussed just on issues of mitigation, to include both mitigation and adaptation. We also discuss the use of non-expected-utility approaches to deal with small probabilities of extreme events.

1.1 Mitigation and Adaptation: Substitutes or Complements?: Introduction

In research on climate change and climate variability, mitigation refers to the limitation of greenhouse gas emissions in order to prevent the future climate impacts on society; adaptation refers to adjustments in individual, group, and institutional behaviour in order to reduce society's vulnerabilities to climate (Pielke (1998) and Smit *et al*. (2000)). In principle, mitigation and adaptation are two different ways which societies can reduce the damages that might be caused by climate change. However, Klein *et al*. (2003) identify that there are three differences between mitigation and adaptation.

The first is related to the temporal and spatial scales on which they are effective. The benefits of mitigation activities carried out today will be evidenced in several decades because of the long residence time of greenhouse gases in the atmosphere, whereas many effects of adaptation measures should be apparent immediately or in the near future. In addition, mitigation has global benefits, whilst adaptation typically takes place on the scale of an impacted system, which is regional at best, but mostly local.

The second is the extent to which their costs and, in particular, their benefits can be determined, compared and aggregated. Irrespective of the diversity of mitigation options, they all serve to reduce greenhouse gas emissions and in view of its global benefits it is irrelevant where in the world the mitigation takes place. Expressed as CO_2-equivalents, the emission reduction achieved can be compared with that of other mitigation options and if the implementation costs are known, the cost-effectiveness of these options can be determined and compared. The benefits of adaptation are more difficult to express in a single metric, impeding comparisons between adaptation options. In principle, the benefits of adaptation are the climate-related damage costs one avoids by taking adaptation measures (assuming that climate change would have adverse consequences). Thus, if one quantifies the potential impacts of climate change on a system assuming no adaptation, as well as its residual impacts assuming adaptation, the benefits of adaptation are given by the difference between the two. From the value thus obtained one can subtract the costs of implementing the adaptation options to arrive at the net benefits of adaptation. However, the practice of assessing and comparing adaptation benefits is fraught with difficulties related to the uncertainty about and differences between the impacts avoided.

The third difference between mitigation and adaptation concerns the actors and types of policies involved in their implementation. Mitigation primarily involves the energy and transportation sectors in industrialized countries and to an increasing extent the energy and forestry sectors in developing countries. In addition, the agricultural sector plays a role in mitigation. Compared to adaptation, the number of sectoral actors involved in mitigation is limited. Moreover, they are generally well organized, linked closely to national planning and policy making, and used to taking medium to long-term investment decisions. Over the past decade, incentives and opportunities created by national and international climate policy have increasingly stimulated mitigation activities by the energy and forestry sectors. In contrast, the actors involved in adaptation represent a large variety of sectoral interests, including agriculture, tourism and recreation, human health, water supply, coastal management, urban planning and nature conservation. Whilst these sectors have in common that they are potentially impacted by climate change, decisions as to whether or not to adapt are taken at different levels, ranging from individual farmers to national planning agencies. For these actors, climate change is typically not of immediate concern. Moreover, in spite of the potential magnitude of climate change they often have little incentive to incorporate adaptation into decision-making, either because policy and market failures do not encourage medium to long-term planning, because responsibilities for action are unclear or because adaptation is concerned with collective goods such as safety, human health and ecosystem integrity.

The next subsections explore the implications of these differences for the optimal mix of adaptation and mitigation strategies.

1.2 Single time period, no uncertainty, and single social planner

To analyze the links between adaptation and mitigation we begin with the simplest case where we ignore dynamic aspects and uncertainties, so there is a known relationship which shows how mitigation and adaptation reduce the damage costs caused by climate change, and known costs of adaptation and of mitigation. A single social planner can choose the optimal mix of adaptation and mitigation to minimize total social costs. It is straightforward to show (see section 2 of Ingham, Ma and Ulph (2005b)) that in general the optimal combination of mitigation and adaptation will require the use of both strategies. This just reflects the rather mild assumption that the first bit of mitigation or adaptation is cheap relative to the marginal reduction in damage costs they bring about. This confirms the view of Kane and Yohe (2000) and Parry *et al*. (2000) that we need to have an integrated approach to adaptation and mitigation, and we cannot rely on either mitigation alone or adaptation alone to deal with climate change.

It is sometime claimed that this joint determination of mitigation and adaptation means that adaptation and mitigation are complementary (IPCC (1996), Pielke (1998)). Thus, an increase in damage costs would be expected to lead to an increase in both adaptation and mitigation. But in the context we have sketched so far, in technical economic terms, adaptation and mitigation are substitutes (Kane and Yohe (2000)), in the sense that if, say, the cost of adaptation fell, the optimal response would be to do more adaptation but less mitigation. This just reflects the fact that these are two different ways of reducing damage costs, so if one becomes more expensive we should make more use of the other.

Now the above argument is based on a simple partial economic analysis, and it is conceivable in principle that with general equilibrium effects adaptation and mitigation might become complements. For example, if increased mitigation caused energy prices to fall this could make it more attractive to use some forms of adaptation, but such general equilibrium effects would need to be quite powerful to outweigh the direct partial effect, and we are not aware of evidence which shows such results.

There is another sense in which it is sometimes thought there may be a complementary relationship between adaptation and mitigation. Suppose an increase in the optimal use of air conditioning to adapt to climate change caused such an increase in power generation and associated emissions of greenhouse gases that it was necessary to increase mitigation, then adaptation and mitigation might be considered complements. However, as we argue in Ingham, Ma and Ulph (2005b), this could not happen if adaptation and mitigation are being optimally regulated. Why is that? This results from assuming that the damage cost of the emissions, which will arise from the adaptation emissions, have not been factored into the private costs of adaptation. But provided mitigation is optimally regulated, at the adaptation stage we do not need to factor into the adaptation costs the social costs of adaptation emissions because these will have been taken account of in the mitigation strategy. So, it should not be the case that the social costs of the additional emissions, associated with adaptation, have to be reflected in the user cost of adaptation. This is a case of an optimal corner solution where adaptation is not employed. It reflects again the fact that mitigation and adaptation need to be jointly determined.

This argument is closely related to the third point made by Klein *et al*. (2003) quoted above – that adaptation and mitigation often involve different actors. Mitigation decisions inevitably require some form of government intervention because of the public good nature of climate change damages, whereas it is sometimes thought that adaptation decisions can be made more locally, even individually. However the question of whether decisions can be devolved to individuals is just as much an issue for adaptation as for mitigation. Thus getting energy prices right, i.e., to reflect the social costs of energy use, will be just as important for adaptation choices that use energy (e.g. the use of air conditioning) as for mitigation decisions, such as switching to low petrol consuming cars. The example above is sometimes referred to as a case of 'maladaptation' (Scheraga and Grambsch (1998)) whereby private decisions to adapt may not be optimal and require offsetting mitigation. But it is rather an example of mal-regulation; provided energy use is optimally regulated such an outcome cannot arise and mitigation and adaptation are substitutes.

1.3 Multi-agents

There is a related issue arising from the first point of Klein *et al*. (2003) concerning the different spatial aspects of mitigation and adaptation, with mitigation dealing with a global public good since what affects the damage on any one country is the global level of mitigation, while adaptation often provides purely local benefits as each country's adaptation affects only that country. As we show in Ingham, Ma and Ulph (2005b) this has the obvious implication that if we move away from the assumption of a single social planner (who would have to be a global government of some type) and recognize that individual nation states may set their adaptation and mitigation policies independently then the non-cooperative outcome will involve each state setting too little mitigation and too much adaptation, relative to the case where countries cooperate. Why is that? In the former case, each country will choose to mitigate at the point where the marginal cost of an additional unit of mitigation equals its own private benefit from mitigation, and similarly for adaptation. In the latter case, in the mitigation decision what is relevant for each country is the marginal reduction in global damage costs from an extra unit of mitigation. This is the standard free-rider problem. And the failure to get global agreement on mitigation means that there will be too little mitigation, and countries respond by carrying out too much adaptation. This again reflects the fact that adaptation and mitigation are formally substitutes for each other.

As we note in section 1.1, these operate at very different levels, with mitigation operating at national/international level because of the public good/externality failure involved. Adaptation is much more local, and for the most part requires little government intervention. Klein *et al*. (2003) draw the conclusion that the two policies should be kept separate. But we think this actually means something more subtle. The key point is that it is difficult to construct sensible empirical policy models that operate correctly at the right level of scale for the two types of response. Therefore in building models of mitigation, which need to operate at appropriate national/international level, one will have to make some kind of assumption about adaptation (to get the optimal level of mitigation), but one should not then assume that this tells us much about actual policy on adaptation.

1.4 Two-period models, no uncertainty

We now introduce dynamic considerations. As Klein *et al*. (2003) note mitigation and adaptation differ in their temporal aspects in that the effects of mitigation in one period will produce benefits for all future periods while adaptation is often thought to produce benefits only for the period in which adaptation takes place. However while this may be true, a forward looking social planner will want to choose time paths for both mitigation and adaptation which are optimal, and in a broad sense all the results for the static model carry over to a dynamic model, including the notion that mitigation and adaptation are substitutes.

1.5 When cost of adaptation depends on amount of mitigation

Nevertheless it is sometimes believed (see for example Parry *et al*. (2000)) that there may again be a kind of complementarity between mitigation and adaptation in that mitigation ‘buys time’ for adaptation. It is not clear what underlies this belief. In part it might reflect issues to do with the ability to learn, but that cannot be captured in the analysis so far which assumes certainty. Partly this could just reflect the fact that it takes time to accumulate a stock of adaptive capital – if one has many decades available then the costs of moving a coastal city inland will be relatively small compared to the costs of doing this within a few decades, essentially because the former can rely on the natural process of replacing obsolescent capital to achieve adaptation, whereas in the latter one has to retire capital early. The increased difficulty of adaptation the faster is the rate of change in climate can also reflect problems for non-human agents whereby over time species might be able to migrate or mutate to adapt to climate change, but if it is too rapid they could be wiped out, or conversely, slowing the rate of climate change through mitigation may allow crops to adapt to become drought-resistant. However, what we are concerned with here is how the rate of change of climate might affect human adaptation. Whatever the underlying explanation, a crude way of capturing this in our analysis might be to assume that in later periods the costs of adaptation also depend on the level of mitigation in earlier periods, with more mitigation in earlier periods (and hence slower rate of change of climate in later periods) reducing the cost of adaptation in later periods. It can be shown that now mitigation and adaptation could indeed be complements, since lowering costs of mitigation increases mitigation, which slows climate change and makes adaptation more effective.

2. Introducing Uncertainty, Learning and Irreversibility

2.1 Theoretical Models

So far we have ignored the important issue of uncertainty about future damage costs from climate change. But as IPCC (2001) notes there are still significant uncertainties attached to climate change (see also Roughgarden and Schneider (1999), Goodess, Hulme and Osborne (2001), Brooks and Adger (2003), Dessai *et al*. (2003) for attempts to quantify the different dimensions of climate change risks). This raises the important question of how such uncertainty, and the prospect of getting better information in the future, affecting optimal policy towards mitigation and adaptation. In an earlier paper (Ingham and Ulph (2005)) we have reviewed the literature on uncertainty and learning in the context of climate change, but we focussed on the implications only for mitigation strategies. We showed that introducing uncertainty would lead to an increase in current mitigation relative to a model in which all parameters took their certainty equivalent values, and empirical models showed this effect to be significant. However introducing the possibility of learning, together with the irreversibility of emissions, have ambiguous effects on the optimal current policy towards mitigation, although in empirical applications this effect is small. In this section we begin by asking how these results are affected when we allow for both mitigation and adaptation, on which there has not been much formal analysis.

It is straightforward to show that if one introduces an exogenous risk of climate change damages into the simple models of the previous sections, then the main results go through in a straightforward way: an increase in the risk of climate change will cause the optimal levels of mitigation and adaptation to rise, but adaptation and mitigation remain substitutes. Kane and Shogren (2000) obtain slightly different results by using a static model in which adaptation and mitigation play asymmetric roles: the level of damage costs can be reduced by adaptation, but mitigation reduces the risk of climate change, so risk is now endogenous. They show that an exogenous increase in risk has an ambiguous effect – it always leads to an increase in adaptation but the effect on mitigation depends on whether an exogenous increase in risk causes an increase or decrease in the marginal effectiveness of mitigation in reducing risk, and they give examples of how this effect could go either way.

However, in Ingham, Ma and Ulph (2005b), we allow for uncertainty about damage costs. There are two possible damage costs: positive and zero. The probability of positive damage costs depends on a parameter, which represents exogenous risk. We also allow for this probability to depend endogenously on the level of mitigation. This yields a model similar to the previous section but with endogenous risk along the lines suggested by Kane and Shogren (2000). However mitigation only affects the probability of damage and not its level which depends solely on the amount of adaptation. We show that it remains the case that adaptation and mitigation are substitutes, in the formal economic sense in which we have been using this term, and so that our result from the previous section is robust to extension to endogenous probability. This is confirmed by some empirical examples Kane and Shogren provide from the agriculture sector of US. They find that mitigation and adaptation are clear substitutes. However, there is the possibility of maladaptation. For example, when people turn to energy intensive practises to overcome a significant loss in agricultural productivity associated with climate change, more agrochemical use and irrigation would increase the demand for fossil-based energy, which will then add carbon dioxide into the atmosphere, and thus would reduce the effectiveness of adaptation. The strength of this negative effect will depend on the severity of the loss of agricultural productivity expected from such a change in climate, inducing adaptation investments.

The above analysis is static and so does not allow for important dynamic aspects of the problem: the possibility that over time one can acquire better scientific information which may reduce current uncertainties and the fact that the atmospheric concentration of greenhouse gases is effectively irreversible. This raises an important timing question: should we moderate the current level of action to deal with climate change while we wait to get better scientific information, or should we increase the level of current action in case we learn that climate change is a much more serious problem that we currently expect but then find that because of irreversibility the costs of taking effective action are prohibitive. This question, which is closely linked to the ‘precautionary principle’ has been much studied both theoretically and empirically, and, as already noted, in our earlier survey of the literature (Ingham and Ulph (2005)) we found that the answer to this timing question was theoretically ambiguous (in the sense that in a general model the answer can go either way) but empirically small.

However almost all the analysis focuses on the case where policy-makers have a single action to deal with climate change – mitigation. In Ingham, Ma and Ulph (2005c), we want to address the question of how the results set out above are affected if we allow for the possibility that society can reduce the effects of climate change damages both through mitigation and adaptation. Might it be the case that while the result for mitigation is ambiguous, the result for adaptation is clear-cut? Or might it be the case that one uses the presence of two instruments to deal with climate change to resolve the ambiguity by, say, doing more mitigation and less adaptation when faced with irreversibility and learning, but with the net effect being ambiguous? To the best of our knowledge there is no theoretical work which addresses the timing question when the policy maker can use both mitigation and adaptation.

In the rest of this section we provide the first steps towards such analysis by discussing how the results of Ulph and Ulph (1997) would be affected by introducing adaptation as well as mitigation. We recognise that this is a very simple model and by no means captures all the interesting issues that might arise. We begin by summarising the results of Ulph and Ulph (1997). As already noted, when there is both the prospect of future learning and irreversibilities, there are fundamental ambiguities about whether the prospect of getting better information in the future should lead to more or less action now to combat climate change. Irreversibility by itself leads to a need for increased current action. Learning by itself has an ambiguous effect, but in the standard textbook model with quadratic costs, the model used by Ulph and Ulph (1997), learning leads to less need for current action. Combining the two makes it ambiguous whether we should take more or less current action when faced with the prospect of future learning. Ulph and Ulph (1997) showed that in the context of their model, a sufficient condition for the prospect of learning to lead to more mitigation now was that the irreversibility constraint should bite in the case where there is no prospect of learning.

In the Technical Annex of Ingham, Ma and Ulph (2005c), we present two different ways of introducing adaptation into this model. In both cases we assume that adaptation only takes place in period 2. One possible justification is that this is when damages occur, but in principle adaptation could take place in anticipation of future damages (or we could think of there being a stock of adaptation capital which accumulates over time). However our justification is only simplicity, for our results would be robust to introducing adaptation in both periods.

In the first model we assume that adaptation acts to reduce damage costs in period 2 by reducing the stock of greenhouse gases. There are quadratic costs of adaptation. We showed that the presence of adaptation reduces the effect of the irreversibility constraint, and hence makes it more likely that the prospect of future learning will reduce the current level of mitigation. In particular the sufficient condition found by Ulph and Ulph (1997) to ensure that the prospect of learning would lead to increased current mitigation actions, no longer applies.

It can be argued that the previous model is too simplistic for it essentially treats adaptation like another form of mitigation. In a second model of adaptation (see section A.3 of the Annex of Ingham, Ma and Ulph (2005c)) we allow adaptation to effectively reduce damage costs rather than operating directly on the stock. However we now assume that there are constant marginal costs of adaptation. This has the first effect that the amount of mitigation done in period 2 is independent of the stock of greenhouse gases in period 2, because the level of mitigation in period 2 is determined just by the condition that the marginal cost of mitigation equals the (constant) marginal cost of adaptation. But it also turns out that this means that the irreversibility constraint has no effect on the comparison of expected marginal benefits of period 1 mitigation with and without learning, which depends only on the effect of learning, and so, for this model, expected marginal benefits of period 1 mitigation are lower with learning than with no learning, irrespective of whether there is an irreversibility constraint.

The general conclusion from these admittedly very simple models is that allowing for adaptation reduces the relevance of the irreversibility constraint, and results depend more on the pure learning effect.

The above analysis of learning makes the rather stark contrast between a scenario in which no learning takes place, and one in which learning occurs, which is modelled as the extreme case of exogenous perfect learning taking place at a given moment of time. In reality, the process by which agents collect information on which to update their expectations about the future risk of climate change, and hence to adapt their behaviour, is a much more complex process than this simple model suggests, and has been at the heart of a lot of debate about the impact of adaptation on mitigation. As noted in section 1.1, if, as our analysis suggests, adaptation and mitigation are substitutes, then the inclusion of adaptation in models of climate change which previously ignored adaptation is likely to lead to a significant reduction in the optimal level of mitigation (see for example Mendelson (2000, 2003)). However this conclusion has come in for a lot of criticism. There are some technical criticisms of the methodology (mainly the use of cross-section analysis) used to assess how agents respond to different climatic environments (see e.g. Hanemann (2000)). But the main criticism is that the modelling ignores the process of learning.

2.2 Empirical models

In this section we briefly review the attempts that have been made to assess the implications of uncertainty, irreversibility, learning and precaution in the context of empirical models of climate change. We are not aware of any empirical model which looks at optimal adaptation and mitigation with uncertainty, learning and irreversibility. We consider here a rather different aspect. As noted earlier, if adaptation and mitigation are substitutes, then the inclusion of adaptation in models of climate change which previously ignored adaptation is effectively equivalent to assuming that costs of adaptation are now finite rather than infinite, and so is likely to lead to a significant reduction in the optimal level of mitigation (see for example Mendelson (2000, 2003)). However this conclusion has come in for a lot of criticism. There are some technical criticisms of the methodology (mainly the use of cross-section analysis) used to assess how agents respond to different climatic environments (see e.g. Hanemann (2000)). But the main criticism is that the modelling ignores the process of learning.

The comparison between models which exclude or include adaptation is sometimes expressed as the difference between the 'dumb farmer' and the 'clairvoyant farmer' hypotheses (see e.g. Hanemann (2000)). Assuming that agents do not respond to climate change – the 'dumb farmer' – means that the burden of dealing with climate change falls on mitigation. However much of the early modelling of adaptation assumed that agents could immediately adjust to changes in climate – the 'clairvoyant farmer'. This implicitly assumed that costs of adaptation are rather low, and so leads to much less reliance on mitigation. The reality is likely to be somewhere between these two extremes, and a crucial aspect of this is how quickly agents learn from information, such as say weather patterns, and adjust their behaviour. A number of studies have noted this point (e.g. Yohe (1996), Kane and Yohe (2000), Lempert *et al*. (2000), and Reilly and Schimmelpfennig (2000)) have sought to characterize different features of society which might affect society's ability to adapt, but rather fewer studies have explicitly modelled the learning process and its impact on adaptation.

Perhaps the best analysis to date of learning and adaptive behaviour is by Kelly, Kolstad and Mitchell (2002) – hereafter denoted KKM. They set up a model of an individual firm (say a farm) deciding what inputs to use, but where the firm's production process is subject to random shocks, and so profits are in turn uncertain. The firm has to choose its inputs to maximize expected profits. However, the process generating these shocks is subject to a once and for all change. If the firm knew what this change was, it would simply adapt and choose a new mix of inputs to maximize expected profits given the new process generating the shocks. But the firm cannot directly observe the change in the process (i.e., it cannot directly observe climate change) – all it can observe is how the pattern of shocks it has experienced has changed. KKM assume the firm uses the information it gets from observing the shocks to gradually update its understanding of the process generating the shocks (using Bayesian learning), and eventually learn what the new process is. They distinguish between the costs of adaptation, which are essentially the difference between the long-run steady state costs the firm faced with the old and the new process generating the shock (i.e., it is the difference in costs the firm would face if it could adapt instantaneously to the new process generating uncertainty) and the costs of adjustment, which reflect the extra costs the firm faces in the process of learning because it has not fully learned the change in the distribution of shocks.

KKM apply this analytical framework to an empirically estimated model of farm behaviour in five states of the USA, to see how farmers respond to changes in climate and weather (where climate is the process which generates the (random) pattern of weather). They then simulate the effects of a change in climate which takes place gradually over a 100 year period, and compare profits when farmers have to learn about the change in climate to profits if farmers were fully informed about the change in climate. They show that while climate change has a long-run beneficial effect, raising profits per acre by $1.86 per acre in present value terms (so the ‘costs’ of adaptation are negative) the costs of adjustment are $5.47 per acre, so the net costs of climate change are $3.61 per acre. While these are not large percentage changes in overall profits of farming, the analysis shows that when one allows for the process by which agents have to learn about climate change the costs of climate change may be much higher than the costs if one assumes instantaneous perfect adaptation. In terms of our earlier discussion this implies that properly modelling the process by which agents learn about climate change in order to adapt their behaviour may significantly raise the costs of adaptation and hence require more mitigation than would be the case if one just assumed perfect learning and hence perfect adaptation.

While we believe that the analysis of learning by Kelly, Kolstad and Mitchell is the most sophisticated we are aware of in the context of climate change, there are a number of limitations to their model from a more general perspective of the economics of information and learning. (This is not a criticism of their work, rather it shows how much more there is to do to study the link between learning and adaptation properly). There are five aspects we consider.

(i) KKM use a model of passive learning – agents just take actions to maximize expected profits given their current beliefs about climate, and update their beliefs about climate as they get observations of the weather. But this may overstate the time it takes for agents to learn, because they could become active learners – i.e., if they suspected climate change was taking place they might try out a range of different crops or input patterns to see which worked best, i.e., they could use experiments to learn more about climate change.

(ii) KKM assumes that the only information available to agents is observations about the weather in their own location. But agents may be able to observe changes in patterns of weather across the globe, and draw inferences more generally about climate change.

(iii) The model employed by KKM is a representative agent model. But in an economy agents also learn from others, partly through social networks through which agents share information (families, neighbourhoods, social groups, etc.), partly through agents observing directly what other agents do, and partly by observing the consequences of what other agents do, for example through prices. This has a number of implications. At one level the ability of agents to learn from others implies that information may disseminate very quickly in an economy. One area where this has been widely studied by economists is in the field of financial markets where agents can observe what happens to prices of assets. Even if there are only a relatively small number of 'informed' agents in a market, their behaviour, buying or selling assets in response to information, can change prices which in turn 'reveal' their information to uninformed agents. Economists have long argued for the importance of prices as conveying information in an economy. But there are problems. This kind of learning behaviour can generate pathologies – such as herd behaviour and speculative bubbles. Furthermore, if there are costs to agents acquiring information, but agents realize that the information they gain will be quickly learned by others, then this substantially reduces their incentives to sink the costs to acquire information. The classic situation where this arises is research and development, where there can be substantial costs to developing new products or technologies and if these can be easily imitated then the incentive to engage in R&D investment is sharply reduced. The standard policy response is either to provide patent protection or to carry out the research in public laboratories and make the results freely available.

(iv) KKM assumes that the only changing source of uncertainty is climate and the random weather patterns it generates. But in an economy there is a multitude of sources of uncertainty facing agents. One, just referred to, is change in technology and products, which can wipe out firms and industries. In addition there can be changes in consumer preferences, or changes in government policies. Climate change is just one other source of uncertainty and one other factor agents need to take on board.

(v) The final point is that markets are not only a means of conveying information between agents, they are also a mechanism for selecting which firms survive. In the idealized model of a market economy, competition selects the efficient firms (both in the static sense of cost-minimizing and in the dynamic sense of innovating new technologies and products that consumers want) and weeds out the inefficient. This would suggest that the competitive process will be one of the mechanisms for ensuring that those who successfully and quickly adapt to climate change will flourish, while those who do not will go out of business. Of course this idealized model of market behaviour is far from a description of actual economies, and economists are aware that there are deep reasons why actual markets will not perform this way (e.g. Dutta and Radner (1999)). The point is simply that this kind of consideration is absent from most analyses of learning and adaptation.

2.3 Catastrophes

In the previous discussions, both adaptation and mitigation can reduce the risk due to climate change and climate variability. Generally speaking, they are substitutes, i.e., for the purpose to reduce the (potential) damage cost, you can either use more adaptation and less mitigation if adaptation is relatively cheap or you can use less adaptation and more mitigation if mitigation is relatively cheap. But it should be noted that such arguments are based on a notion that the climate change is continuous and slow and climate variability is small, i.e., the change of climate and climate variability is marginal. So through adaptation, society can compensate for the effects of climate change by undertaking actions. This approach can be thought of as being consistent with the notion of weak sustainability, i.e., that if natural capital is eroded by climate change then there is the possibility of its replacement by physical capital of some form.

However, it is thought that various aspects of climate change may not allow for the possibility of substitution. One important reason for this is that climate models can generate all sorts of sudden and large events considered to be catastrophic in nature which come with large damage costs , for example substantial loss of biodiversity because of the inability of species to adapt rapidly, and hence no possibility of substitution through physical capital. This situation is closely related to the notion of strong sustainability. In such situations the scope for adaptive options may be very limited. What does this imply for adaptation and mitigation policies?

Three types of catastrophic effects modelled in Integrated Assessment Models (IAMs) have been characterized by Wright and Erickson (2003b). These are:

1. Low Probability – High Impact Events

2. Threshold Phenomena

3. Lack of Knowledge with readily resolved uncertainty

For catastrophes of type 1, the issue is one of surprise as opposed to climate effects being smooth and gradual, as in is the ‘translated climate’ approach used by Peck and Teisberg (1992) or Mendelsohn and Neumann (1999), where the distribution function of climate parameters is shifted by climate change. With catastrophes of type 1 there is a switch to a completely different distribution function of climate parameters and the magnitude of effects is much larger than might be expected from what are termed ‘regular’ parts of the climate domain. For these concerns to be of importance, events must be of low probability – otherwise they would not be a surprise (there is some notion of incomplete information about what the climate responses are) – and high impact because otherwise the impacts would not be especially noticeable.

For catastrophes of type 2, there does not need to be a low probability attached to the event. In fact if the threshold is crossed, effects will occur with certainty. These thresholds are those for which ‘significant’ effects are to be noticed although no definition is made of what ‘significant’ is. Nordhaus (1994) and Peck and Teisberg (1992) are cited as examples of these.

For catastrophes of type 3, it is noted that whether uncertainty can be resolved has an important impact on the results obtained from IAM policy optimizations. Catastrophe here is seen as having a Hazard Function – i.e., the event classed as a catastrophe cannot be determinably foreknown.

These catastrophe types are then related to the scientific background of climate events causing geophysical catastrophe, such as runaway greenhouse, rapid sea level rise, or ocean circulation change. The linkage of these scenarios with their catastrophe characterizations gives particular implications for climate economics. For example, catastrophes can give rise to the possibility of negative discount rates arising out of negative economic growth, and affect how damage assessments should be incorporated, and consequences for adaptation.

Incorporating such catastrophic effects into conventional IAMs is not straightforward. In a study of ocean/atmospheric circulation changes as a possible consequence of climate change Keller *et al*. (2000) suggest an inverse approach. They subject DICE to a constraint of maintaining the Thermo-Haline Circulation (THC) system, and then estimate the cost that THC shutdown would need to exceed to make this an efficient policy. However Wright and Erickson (2003b) see the role of damage assessment in models such as those of Keller *et al*. (2000) and Mastandrea and Schneider (2001) as problematic in that they use perfect foresight which conflicts with catastrophe as necessarily involving uncertainty of crossing thresholds.

The consequences of catastrophes of type 3, where there is decreased predictability, can lead to the possibility that mitigation and adaptation could be complements. Wright (2000) uses an option value model and shows that reductions in mitigation which lead to increased variability of climate can lead to reductions in adaptation. This arises from those situations in which the adaptive strategy requires predictability for effectiveness. It also can lead to increased pre-adaptation damages. Further the predictability decreases arising from increased variability do not decay with time. This is closely related to the argument we made in section 1.5 that if the costs of adaptation depend on the stock of greenhouse gases because more mitigation slows the rate of change of climate and hence makes adaptation easier, then adaptation and mitigation may be complements. This effect does not arise in Bayesian models of learning such as Kelly and Kolstad (1999) in which expectations are based on past observations. Whilst learning is slow in this model, after several decades uncertainty is resolved.

The increased difficulty in making predictions is also analyzed by Fisher and Rubio (1997) where the increase in hydrological uncertainty leads to an increase in the size of optimal water infrastructure. However, predictability decreases, arising from increased variability, do not decay with time, and represent an enduring degradation of information. Consequently more observations are needed to establish an understanding of climate change. Omitting increased climate variability into adaptation models leads to an overestimate of the gains to be made from adaptation, and a consequent under estimate of climate change damages.

Wright and Erickson (2003a) consider timing in relation to adaptation. The key feature of their model is that they consider climate change as being characterized by the extreme levels and the degree of variability rather than the mean value (such as mean temperature). They determine adaptation timing within an optimal stopping model, which extends the Conrad (1997) model. Increasing temperature variability here delays the optimal adaptation time and increases cumulative damages. They conclude that failing to take into account the dynamic effects of variability on adaptation timing leads to overstating the damage reductions to be obtained from adaptation and so makes mitigation a more attractive strategy. Climate variability delays action by individual actors, the delay depending on characteristics of the particular sector that they are in.

2.4 Catastrophic effects and the Tolerable Windows Approach

The models of catastrophic effects in the previous section attempted to incorporate such effects into conventional IAM models based on choosing optimal mitigation and adaptation policies. However this involves solving a complex decision problem which has dynamic as well as uncertainty aspects. The mathematical complexity of the problem will be enhanced by the presence of non-linearities such as sudden increases in damage costs, and when these include considerable uncertainty as to when they occur, and how large they are, correspond to ‘surprises’ or ‘catastrophes’.

An alternative approach, the Tolerable Windows Approach (TWA), effectively denies the possibility of simple trade-offs between mitigation and adaptation policies in the presence of catastrophic effects. Rather what this approach does is to establish a critical range of values (tolerable window) for a variable such as the stock of greenhouse gases and requires that mitigation policies are set to ensure that this variable always remains within this critical range. Adaptation policies are therefore only relevant as long as mitigation policies keep climate within the tolerable window.

A more detailed discussion of models that use the TWA is given in Ingham, Ma and Ulph (2005a). A key question addressed there is how the Tolerable Windows are set. This requires either knowledge or a judgment about what are the most important elements of uncertainty, and this is why the TWA is seen as being inappropriate by some. For example Tol (1999) sees the constraints, known as guardrails, imposed as being dependent on geological records and so possibly an extreme position. He suggests that the requirement that future climate scenarios not fall outside past experience reflects a naturalistic fallacy, or status quo effect, that deviations from past experience are inherently undesirable. He has similar criticisms of the ecological considerations for the quantities corresponding to a Safe Window. This difference between the views of natural scientists and economists as to the seriousness of large emission increases is supported by surveys conducted by Nordhaus (1994) and Morgan and Keith (1995) of subjective estimates of the extent to which a changing climate would create economic damage. For social scientists, it is estimated that a 6^{o}C increase in temperature would lead to a 6% of GWP damage, whereas for natural scientists it is estimated that this would be 37%. One reason for this large range is that social scientists may regard there as being more possibility of substitution and adaptation possibilities.

The Tolerable Windows Approach starts from what is thought to be acceptable climates and then works back to the adaptation and mitigation strategies that are consistent with these. Further reasons that are given for its use are:

1. IAMs are complex models for which, in practice, dynamic optimization may not be feasible except for drastic simplification of the climate model.

2. The TWA is the inverse problem to that of dynamic optimization models. TWA asks the question ‘If we have a view as to where we wish the climate and economy to be at some time in the future, what paths would be consistent with that?’

3. It is argued that TWA better addresses the questions posed by policy makers without having to calculate the full solution to the optimization problem, because policy makers are primarily concerned with unacceptable climate change impacts or unacceptable mitigation costs. TWA is thus seen reflecting the stated preferences of policy makers in the context of a detailed IAM.

4. Another reason why TWA is thought to appeal to policy makers is that it provides a simpler way of dealing with timing issues. If climate change and emissions negotiations take time, then the time at which policy must start, and Business as Usual (BAU) ends, becomes an important issue. The set of paths arising out of the TWA

analysis may show (and, in examples, do indeed show) that there is a date after which no tolerable path can be the same as that of BAU.

5. The optimal control problem may display an aspect of separability so that the process of optimisation can be divided into one of determining a set of emission paths that satisfy the scientific climate change model and constraints and then selecting one of those paths according to other (presumably economic) criteria.

6. The TWA approach is seen by some as avoiding perceived problems with the use of the Cost-Benefit Analysis approach to climate change decision analysis (for example, Bruckner *et al*. (1999) and Toth (2002)). One perceived difficulty is that it is thought that there is a major problem in obtaining reliable monetary valuation of climate change impacts where temperatures and related impacts are outside of those recently experienced. A second difficulty is that CBA is interpreted as being a tool of aggregate 'utilitarian' analysis. Finally, CBA is seen as being a tool designed to produce a single optimal path in models such as DICE. However the outcome of the CBA calculation may not turn out to be acceptable to policy makers where the resulting emissions/climate outcomes fall outside (maybe well outside) of current experience. Other economic criteria can then be considered such as cost effectiveness or ones having a Rawlsian approach towards distributional considerations. So that if a set of possible emission paths is determined, then the one with the most desirable distributional consequences in terms of the worst off could be selected. It should be noted that in the examples produced the economic constraints are an important component of the TWA approach and, whilst authors sometimes claim that they are avoiding the problems of using cost-benefit analysis, in setting limits they believe to be arbitrary, CBA is often used as a justification for those particular levels.

2.5 Concluding Remarks

In the first part of this project, we surveyed the literature on economic approaches to climate change. We find that under a wide range of circumstances adaptation and mitigation can be thought of as substitutes. While this conclusion is a reasonably robust result, the one area where this may not be the case is when consideration is given to catastrophic effects and extreme variability of climate, when mitigation, as a means of reducing the risk of catastrophes or reducing extreme variations in climate, may help adaptation to occur and so build complementarity between mitigation and adaptation. However, it should be pointed out that while there has been progress in developing some of the conceptual frameworks for thinking about issues of adaptation and mitigation, there is much yet to be done if we are to translate these concepts into models that would provide practical tools for policy making.

As to uncertainty, learning and irreversibility, we extended the model of Ulph and Ulph (1997) to deal with both mitigation and adaptation. We show that including adaptation weakens the effect of the irreversibility constraint and so, for this model, makes it more likely that the prospect of future learning should lead to less action now to deal with climate change. We are not aware of any empirical model which looks at optimal adaptation and mitigation with uncertainty, learning and irreversibility. One empirical study that does analyse how learning affects adaptation is that of Kelly, Kolstad and Mitchell (2002). We believe that a key need for future work is to embed a model of endogenous learning of the type used by Kelly, Kolstad and Mitchell (2002) into a model of optimal climate policy with mitigation and adaptation. This would capture possibly important interactions between mitigation and adaptation policy – that a key rationale for stricter mitigation policy now would be to allow more time for agents to learn how to adapt. This feature is not captured by either the theoretical or empirical literature referred to in this paper, though we do not underestimate the difficulty of constructing such a model.

3. The Background to Water Industry Investment and Climate Change

3.1. Introduction

The industry used for case studies is that of the England and Wales Water Industry. This is a highly regulated industry, and the response of individual companies to climate change is very much determined by the regulatory approach. This has already been noted and commented on in the Final Report for the Adapt Project (Berkhout, Hertin, and Arnell (2004)). Other recent discussion as to how the water industry in England and Wales is regulated can be found in Balance and Taylor (2005). Here we focus on those parts that are particularly important for climate change, especially in relation to learning and uncertainty. A more complete discussion can be found in Ingham, Ma, Ulph (2005c). A central point here is one that has been pointed out by various House of Commons Select Committees which is that the incentives that exist within the current regulatory framework are not ones that encourage long term thinking or action about these issues. Both the financial incentives provided to water companies and the conflict in time horizons provided by the two regulatory bodies lead companies to operate on a short term basis. Yet both investment by the water industry and climate change are long term issues. The water industry has assets which are both long lived and take a long time to implement and put into operation. Although it should be said that much of the very long time it is usually quoted for the planning and construction of a large reservoir is taken up by the need for public consultation and acceptance. So that in the UK, 20 – 25 years is the time quoted for the period from initial planning to operation for a reservoir, whereas in the USA, e.g. Texas, where 3 years is specified as the time required. Climate change has additional long term aspects such as the question as to whether to wait for information about climate change, then finding that some options have been foreclosed, or to implement actions when there is a full range of choice but in the absence of full information, such as about future costs, water availability and demand.

The main points we wish to make are:

1. Price Cap regulation is found to discourage investment.
2. Conflict in planning periods between the price and quantity regulator discourages long term planning.
3. The quantity regulator has two possibly conflicting aims – security of supply and environmental/ecological protection from water abstraction. This, together with other factors has led to an emphasis on demand management measures and a hierarchy of options towards future needs which does not take climate change into consideration.
4. To negotiate the regulatory maze water companies in conjunction with regulators have developed a set of guidelines, which whilst enabling companies to make use of current climate change research, leads them to fail

to exploit local information and conditions, and so be reactive to climate change rather than pro-active.

First we look at the most important features of the water industry. It is almost a pure monopoly in that it is very hard to imagine there being real competition in the distribution of water to consumers. It is also a very capitally intensive industry with long lived assets. The fact that many of these assets have been in place for a very long time causing particular replacement problems at present. It also brings the issue that the high capital intensity of the industry and the long life of capital, together with a relatively short time scale for the price reviews means that the possibility of future changes in regulation carries substantial risks for shareholders, consequently raising the cost of capital and the willingness of companies to invest.

3.2. How Regulation of the Water Industry works

Water is regulated via a form of Price Cap Regulation. Prices are regulated by OFWAT by the Director setting annual price caps for five years, although there is a possibility of interim price changes if there were to be sudden changes in circumstances. We comment on this later. As water companies can provide a range of services (drinking water and waste water) price regulation requires that the percentage weighted average of charges increase (WACI) does not exceed the charges limit which is RPI + K + u, where K is the adjustment factor is determined every five years by the Periodic Review, and u is the unused K carried over from the previous three years.

K can be negative, in which case the price cap is of the more usual form RPI – x where x represents an efficiency factor. For the water industry on privatisation it was realised that there was a large investment programme for required clean water infrastructure investment. As this infrastructure was for providing clean beaches which would not generate an income stream of their own, an alternative source of funding through increased water bills was proposed. K is therefore related to both efficiency savings and a water company's investment programme which varies from area to area. Where there is disagreement between a water company and OFWAT there is the option of referring the disagreement to the Competition Commission for adjudication and this is an alternative source of information on the details of the referred company's plans. However, all quantitative information is removed because of requirements of the Competition Act.

An important issue in the calculation of WACI is the balance between metered (or measured basket item) and unmetered (unmeasured basket item) water supply. Metering, and subsequent appropriate pricing, are seen as ways in which demand management can be introduced to reduce demand in times of water shortages. This requires substantial uptake of metering. Nearly all properties built after 1990 are metered. For those built before there is an expectation that there will be a ratcheting effect encouraging take up of meters. Unmeasured customers with a high charge (based on high Rateable Value but relatively low use) will have a financial incentive to switch to metering and reduce their bills. This lowers revenue and enables the water company to increase its charges to remaining unmeasured consumers. This encourages more consumers at the new higher margin to switch to meters. The limit of this process would be where almost all consumers are metered. However this effect has been slow to take place, and a recent survey suggest that a substantial number of unmetered properties may remain so.

The prices that water companies are allowed to charge are not completely fixed within the time review period, and this has implications for how forward looking a water company needs to be. Should costs rise unexpectedly then there is the possibility of an ‘Interim Determination’. This system of price controls is intended to provide incentives for improvements in efficiency. But the long period of the price cap could lead to problems where costs change unexpectedly. So Interim Determinations allow for K to change in response to cost changes arising from various specified factors. Included in this are cost changes arising from higher than expected households opting to be charged via metering. In relation to unexpected climate change effects, the only one of the specified circumstances that might allow for an interim determination is that of a change of circumstances related to licences, consents or authorisations given by the Secretary of State or the Environment Agency (EA) for the purpose of carrying on functions of a water undertaker.

Price cap regulation is just one form that can be applied for the regulation of utility companies. It was developed in the 1980’s as a way of tackling both excessive pricing and efficiency. A survey of the working and effect of price cap regulation on risk sharing is given by Cowan (2002, 2003). In as far as it is designed to limit (and protect) the water companies revenue, it could be thought of as being a form of revenue cap regulation, and Cowan sets out the consequences of this for the sharing of risk between water companies and consumers.

3.3. Quantity Regulation

Following the 1995 drought, for which we consider some of the implications in one of the case studies in the next section, a series of reviews led to the adoption of a 25 year planning framework for the management of abstraction. This is monitored by the Environment Agency, which is the latest in a long history of regulatory bodies overseeing water resources in England and Wales. They repeatedly state a framework of a ‘twin track approach’. This derives from the view of some years ago that the problem of water shortage was a lack of capacity and hence a water engineering problem. This has meant an emphasis on leakage reduction and metering. Whilst metering is supported by OFWAT on equity grounds and a more rational basis for charging, and by Environment Agency as a way of reducing water use, it is opposed by other groups such as the National Consumer Council because of its potential distributional consequences and effects on low income households. This arise from the low price elasticity of demand for water. This low elasticity suggests that it may not be a very efficacious way of reducing water demand. Reduced water usage has, in fact, been observed where metering has been introduced. But this can be attributed to lower than average water users having the greatest incentive for meter installation.

The most recent update of the Environment Agency’s Strategy Document ‘Water Resources for the Future’ suggests a stated vision of environmentally and economically sustainable abstraction. Management of abstractions are achieved through a licensing system. These authorise abstraction of a given amount of water. Immediate questions relate to the trade-off between these, if one exists, and the question as to whether sustainability is of the weak or strong versions. But the

Environment Agency has a duty to take account of costs and benefits in exercise of functions and regard to economic and social well-being of rural communities. Economic regulation done through OFWAT, with 5 yearly price reviews.

The planning process follows four principles:

1. Sustainable Development
2. Twin Track (this means operating on both supply and demand at the same time)
3. Robustness to Uncertainty
4. Precautionary Principle

The strategy is developed along lines of:

- Identify options for meeting any gap between supply and demand
- For 25 years ahead consider biggest increment in demand
- Identify set of options to meet this demand
- Look at strengths and weaknesses of solution indicated by sustainability appraisal, application of risk framework, robustness to climate change
- Identify weaknesses and constraints of chosen options, could others make more contribution to SD, increased resilience to climate change or reduce uncertainty
- Look at effectiveness 10 years ahead
- Consider effectiveness in other three scenarios
- Review set of options to obtain a robust solution

3.4 The Regulatory Game between OFWAT and the Environment Agency

This regulatory game has been discussed by Meran and Schwalbe (2004). It is specially important in how the water companies react. The presence of the two regulators has led the water companies to believe that they are caught in the middle between the EA's desire for improved environmental performance, in terms of waste water and reduced water abstraction, and OFWAT's limitations on prices.

On the privatisation of the water industry in 1989, it was originally intended that there would be a single regulator, as in other utility sectors, which would regulate the industry for both price and efficiency reasons. However, this did not make any allowance for the independent regulation of environmental matters. Maloney (1996) has reported that there were tensions between the regulators in relation to reasons for increasing water bills. The issue of water bills and prices became highly politicised, a situation which remains to the present (see two recent Select Committees on Water Pricing, EFRA) One of the early complaints of OFWAT against the then environmental regulator, the NRA, was that it did not consider the economic consequences of its regulatory decisions, and that only OFWAT stood for consumers' interests. Maloney points out that the extent of the disagreement can be gauged by the unusual extent of public acrimony and disagreement between regulators. In his view two different constituencies have arisen, those around cost issues who support a cost-benefit approach to water issues, and an environmental constituency which sees decision being made on a political basis with much greater reliance on a sanctioning approach to regulation backed up by legal enforcement.

A very important feature is that not only is there a tension between the quantity and price sides of regulation but also a tension in time scales. This is frequently mentioned by water companies as a barrier to their planning for Climate Change. For example, OFWAT accepts in principle the need for investment to maintain supplies in the face of climate change, but there is often a mismatch of planning horizons between OFWAT, the economic regulator (five years) and the Environment Agency (30 years). This creates difficulties for water companies which have to make large investments over long timescales and lead-in times (as mentioned earlier, the usual time for a reservoir is of the order of 20 years) which are likely to be affected by climate change.

3.5 The Future Regulatory Agenda

In a speech to the Water UK City Conference in early 2005, the Director General of OFWAT set out the future agenda for economic regulation. This includes the price increases in the last regulatory round, the extent of assumed efficiency gains, the amount of activity that water companies undertake, and the cost of financing. The reaction of city institutions to the level of price increases permitted, and the consequences for the cost of capital, is taken to be of special concern, given that companies have experienced negative cash flow for the past 15 years. An element of this is the issue of uncertainty that can arise from details of the required capital investment programme. This is seen as being handled by the possibility of passing such cost increases on to future price setting rounds ("logging up") or by the use of interim determination should cost increases be large. A question that this raises, although not addressed, is the incentive for firms to reduce investment costs by anticipatory expenditure. Interim determinations have to relate to items of uncertainty notified at the start of the current pricing period. For the 2005-2010 round this does not include any item that is climate change related apart from the possibility that climate change effects might alter the abstraction charges from controlled waters levied by the EA, and this raises the question of coordinated regulation between the EA and OFWAT.

Future developments are dependent on how the new regulatory structure of the WSRA (Water Services Regulation Authority) and the new 2003 Water Act operate in practice. Here, climate change appears under the heading of Sustainable Development. Whilst reference is made to the need for long term planning and development, the Director General of OFWAT believes that the existing approach adequately covers these issues.

3.6 The Current Approach to Water Investment Planning

The approach is to allow for a sufficient margin between available supply and demand. This margin is set at a level for which all uncertainty in either supply or demand can be covered. There are two types of uncertainty considered. First is that applicable to the present time. This is to do with failures of plant, e.g. pumps at pumping stations, major leaks. This is referred to as "Outage". The type of uncertainty to which Climate Change applies is that relating to the future - this is called "Headroom". Headroom is a margin added on to expected demand to allow for all possible future uncertainties.

Uncertainty applies to both Demand and Supply. There are important differences in the degree and nature of uncertainty for these. The uncertainties in demand are high, and demand is seen as being the major problem for future planning with regard to climate change. One reason for this is the difficulty of obtaining good and plentiful data on water usage in the absence of large scale metering. However the determinants of demand are likely to be similar across different water companies and regions, and so this is taken for all companies from a large study of demand for water, undertaken by the Stockholm Environment Institute at Oxford, (CCDeW).

Supply is more specific to individual companies so that there is much less scope for the sharing of research, and a common industry approach. Supply is taken to be a “worst-case” scenario. Spare capacity is not seen as being especially problematic because of the nature of regulation by OFWAT. OFWAT allows a regulatory rate of return so that assets are allowed to earn that rate of return by amending charges to customers. As long as the provision of the asset has been approved by OFWAT, that return can be made. Further, extra capacity can be used to reduce overall costs, as like nuclear power, water supply, once in place has to be used. So regretted provision of capacity (stranded or redundant assets as a consequence of irreversibility) is generally unlikely. One example might be the planned desalination plant at Folkestone, which would be operated at peak times only. The scheme is driven by the need for appropriate headroom, and if the uncertainty leading to this did not materialise then plant would not be used – so this is somewhat different to capacity which is part of the overall water infrastructure, and so has to be used.

Capacity is then increased where demand plus headroom falls below current supply provision. There are usually a variety of different options that can be used to increase capacity. For example, 3 Valleys Water Company indicated that they had a currently feasible option list of about 40 – 50 schemes, and this commensurate with other cases. This list included the development of underused resources such as increasing extraction where a current licence covers increased rate, which can be done almost instantly with very low costs. Where a variation in license is required, whilst the construction of new borehole takes about 2 years, but the obtaining of approval from the Environment Agency could take from 1 – 5 years longer, if an Environmental Impact Assessment were required.

3.7 Determination of Headroom

“Target headroom is : The minimum buffer that a prudent water company should allow between supply (including raw water imports and excluding raw water exports) and demand to cater for specified uncertainties (except for those due to outages) in the overall supply-demand balance. Introducing this buffer into the overall supply-demand balance will help to ensure that the water company’s chosen level of service can be achieved.”

Available Headroom is the difference between WAFU (Water Available for Use) and Demand or DYD (Resource Zone Dry Year Annual Average Unrestricted Daily Demand) at specified moment in time. Where Target headroom becomes negative will be the occasion for implementation of measures to increase WAFU or reduce demand. Of course, consideration of these measures will take place at the start of the planning cycle. Climate Change therefore impacts on both the buffer in headroom and the demand level used to define it, although the buffer is a forward looking impact and the demand level a backward looking aspect.

The headroom methodology is designed to include all the principal sources of uncertainty that water companies face, and to convert these into a headroom allowance. So water companies plan not for Climate Change on its own, but for all uncertainties at the same time.

Sources of uncertainty included are:

Supply related:

1) Vulnerable surface water licences
2) Vulnerable ground water licences
3) Time limited licences
4) Bulk transfers
5) Gradual Pollution causing a reduction in abstraction
6) Accuracy of Supply side data
7) Single source dominance and critical periods
8) Uncertainty of Climate Change on yield

Demand related

9) Accuracy of sub component demand
10) Demand Forecast variation
11) Uncertainty of Climate Change on Demand

Whilst demand considerations play a relatively small role in the maximum for what target headroom might be, discussions with water companies revealed that they considered them to be the most important consideration. In fact they considered the uncertainties surrounding future demand to dominate those of Climate Change. In part this is because of the approach of the two regulators. Uncertainties surrounding supply are handled by considering worst case UKCIP scenarios. These are attractive to water companies if they justify increased investment on which a regulatory rate of return can be made. Uncertainties in demand which lead to costly action, which cannot be recuperated, lead to reduced profits. So learning about demand is seen as being more important than learning about supply. However, whilst there are many between-company differences in supply conditions, the determinants of uncertainty in demand are generally common across all water companies. A cross sector study of the influence of Climate Change uncertainty on demand, CCDeW is used to determine this.

Headroom is calculated by means of scores which are chosen for each item in the above list according to specified criteria. Some of the items are region specific, so will not change over time. It is expected, though, that the score for Climate Change will increase over time as uncertainty for forecasting climate change increases into the future.

It is calculated in the following way:

Let $x_i(t)$ be the value of the score for factor i at time t.

$$y(t) = \sum_{1}^{5} x_i \;;\quad z(t) = \sqrt{\sum_{6}^{11} x^2{}_i}$$

h(t) = (t/T) (y(T) + z(T) – y(0)) , and target headroom is h(t)×WAFU(t)

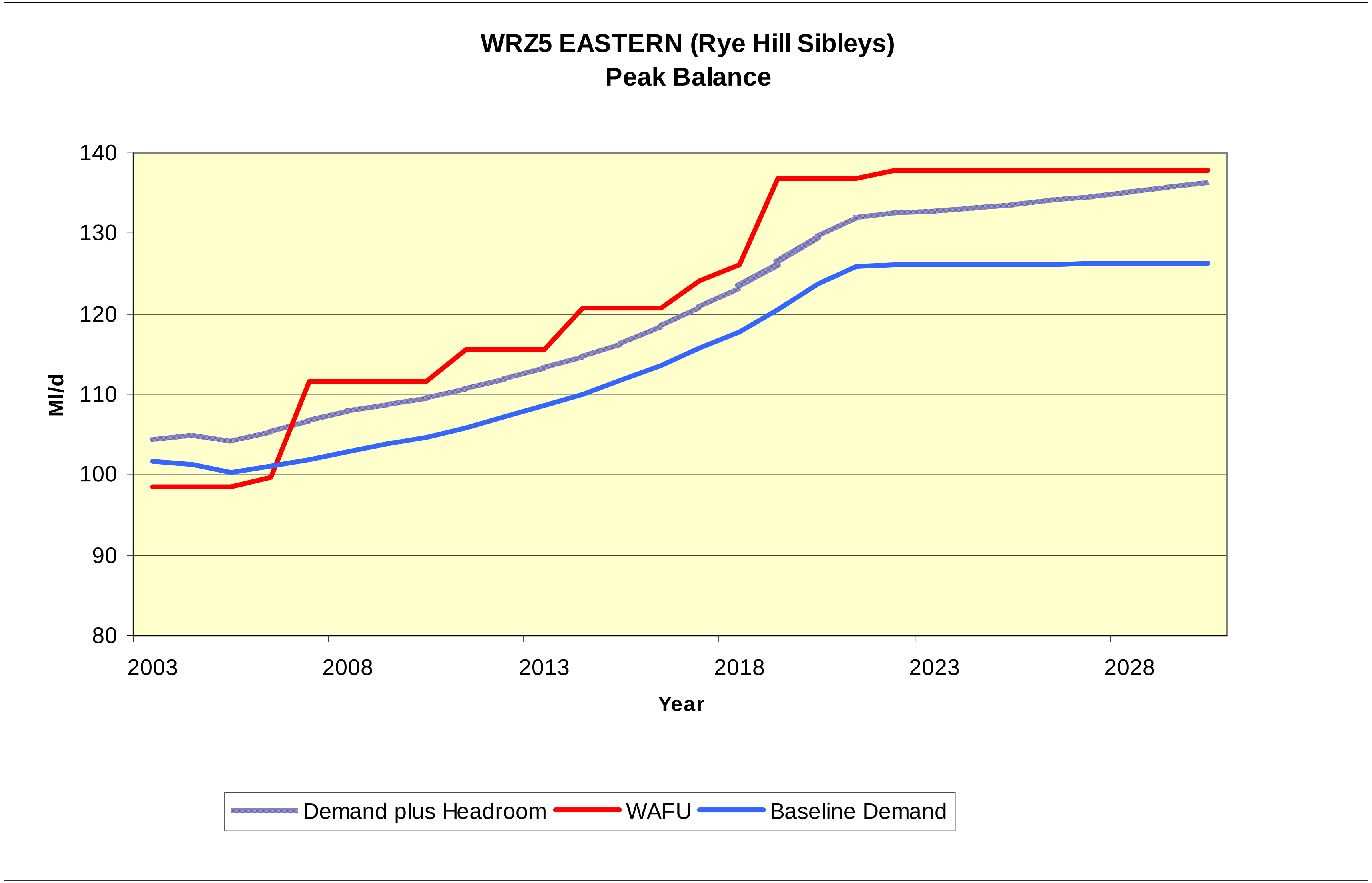
A Prudent Plan is then defined to be one where DYD(t) $<$ (1 − h(t))WAFU(t)

And, if at some time this is not satisfied, there is justification for action either with regard to measures increasing WAFU, or reducing DYD. Presumably, as WAFU increases so does target headroom which seems paradoxical if increases in WAFU come about as a way of planning against Climate Change uncertainties.

The two Climate Change variables have a relatively minor role here, although this depends on the level of other uncertainties. The maximum value for h(t) is 80% or 0.8 of which $x_6 + x_{11}$ (accuracy of supply data and climate change) can contribute between 0.15 in the case of no other uncertainties and 0.05 in the case that all other uncertainties are at a maximum level. So climate change has least impact where the world is already very uncertain.

An example of how headroom works, the following diagram shows one water zone for 3 Valleys Water. The blue line is projected demand, the grey line demand plus allowance for headroom and the red line planned supply capacity, where the steps correspond to new supply capacity becoming available.

In conclusion, within this framework investment towards climate change is quite tightly specified with little scope for individual company assessment or action. We now turn to some case studies to look at what might be the case if investment in assets related to climate change were to be the result of an optimisation exercise where the consequences of uncertainty, irreversibility and learning are taken into account.


WRZ5 EASTERN (Rye Hill Sibleys)
Peak Balance
140
130
120
110
100
90
80
Ml/d
2003
2008
2013
2018
2023
2028
Year
Demand plus Headroom
WAFU
Baseline Demand

4. Case Studies for the England and Wales Water Supply Industry

4.1 Introduction

Sections 1 and 2 describing the first part of this project discussed the question as to whether the possibility of learning about the extent and costs of climate change might cause investment decisions to be postponed. In those simple textbook models it was clear that this was ambiguous from a theoretical point of view and that the question as to whether a ‘wait and see’ or a ‘precautionary’ approach was optimal would depend upon the quantities involved. This part considers what the magnitude of the learning effect might be for a particular industry[1].

The water industry in the UK has some large advantages for a case study but also some big disadvantages. The main advantage is that it is an industry which is likely to have a strong and direct effect from climate change. Climate Change in the UK will change the amount and distribution of rainfall. The effect of this on runoff into rivers and their subsequent flow levels has been documented by Arnell (2004). Reduction in river flows will have strong ecological effects were water extraction takes place and it would seem likely that environmental pressures, and policies such as the European Union’s Water Framework Directive, will be to limit the amount of water that can be extracted in order to avoid problems of low flow. One possibility of adaptation to such climate change effects would be to provide alternative water sources. So we address the issue of what optimal adaptation in the UK Water Industry would be when we are uncertain about the appropriate model of climate change and may obtain information about this in the future.

The main disadvantage, as mentioned in the previous section is that the UK water industry is highly regulated. It is regulated both for price purposes by OFWAT and for quantity purposes by the Environment Agency. This has meant that there are strong incentives for strategic game playing between water companies, regulators and the government. As a result, information about companies’ plans and activities are extremely limited and hard to put together on a consistent basis. As evidence for this one has only to read the verbatim report of evidence given to the recent House of Commons Select Committee on ‘Climate Change Water Security and Flooding’.[2] However there have been since privatisation areas of intense concern related to Water Companies’ performance with regard to investment and water security and these have led to more information being available for some water companies on a consistent basis than is true across the industry as a whole. This situation will change in the near future as the 2003 Water Act requires that Water Resources plans that companies have to provide to regulators are made publicly available.

The two main case studies reported here are for data based very loosely on situations involving Yorkshire Water, and Thames Water. The Case Study for Yorkshire Water derives from the crisis during the drought year of 1995 which led to an independent inquiry under the Chairmanship of Prof. John Uff QC, Uff (1996). One element of his

---

[1] Full details of this are contained in Ingham, Ma, Ulph (2005d).

[2] See discussion between the Chairman Mr Michael Jack MP and Peter Spillett of Thames Water and Water UK Ev 19 – 21 Q55 – Q64.

remit was to investigate future possibilities for avoiding drought related water supply shortages and as a result the report includes a list of investment options, and cost figures, together with demand shortfalls which allow for a calculation of optimal investment plans under climate change model uncertainty. The simulations can be seen as suggesting which of the various options might be implemented when this uncertainty is taken into account, and whether this issue is important in deciding what to do.

The second main case study is based on publicly available information relating to Thames Water. Information here arises from Government criticism of it for its leakage record and performance, and its narrow margin between water supply and demand especially for London. Whilst it has not been the subject of an enquiry such as that for Yorkshire Water, there has been sufficient public discussion of its investment plans and needs for extra capacity for a similar database to be put together. Thames Water has a particularly interesting choice between two quite different types of extra capacity – a new large reservoir, with usual public controversy[3], and a new de-salination plant, also controversial because of its potential for climate change mal-adaptation and consequent planning rejection by the GLA[4]. As well, there is the issue of the failure to meet the targets for leakage reduction set by OFWAT, and new sources of groundwater. This gives an interesting range of possible choices.

We do not have all of the information that we need, though. In particular, we do not have any information about the beliefs of water companies concerning the climate change risks that they face. Nor does there seem to be any learning by water companies about these risks. This is because the structure of regulation does not require water companies to address such issues, and, as with Yorkshire Water in the 1990's, they are more than content to follow the rulings of the regulators on these matters. Where information on the industry such as this is lacking we have had to impose our own assumptions, but a sensitivity analysis is undertaken in order to assess the importance of such information.

A relatively simple decision model is used in order to derive an optimal investment plan with and without learning. This is set out in the next section. Despite it being simple, when it comes to implementation it imposes limitations on the number of options to be considered within the investment plan and the number of time periods that can be considered because of computer limitations. Of course for a full analysis more computer power could be used but here we wish to investigate orders of magnitude and the limited model used gives an indication of that.

The difference between expected present value costs of the optimal investment plans with and without learning is what we call a 'learning premium' The size of this learning premium tells us how important it is for water companies to build into their investment planning the 'option value' of delaying decisions to allow better information to be collected and used in future decisions.

The calculation of this 'learning premium' and the optimal investment plans is undertaken for a variety of case studies in sections 4.3 to 4.5. One of these, 4.3, is

---

[3] See BBC Radio 4 File on Four 'Water Shortage', 19, July, 2005.
[4] See David Hopkins edie news centre www.edie.net 29, April, 2005.

perhaps best described as a ‘pseudo-case study’ as it depends on constructed data, although the numbers are based on types of investments available to the Water Supply Industry. Their main purpose is to see how the model works and the orders of magnitudes that might result where there are real decisions to be made. Often, as is seen in the other case studies in which numbers reflect actual situations, there is one type of investment that dominates all the others as it has both lower capital and operating costs in all states of world. Consequently, there is no decision to be made. The first case study uses cost data where this does not happen and considers what the learning premium is and how the investment plan changes as parameters of the model: supply capacity, demand, capital and operating cost data, and parameters for the probability structure change.

4.2 The Model

The following is simple model for the choice between different capacity investments in the water supply industry. It is implemented in a computer program written in GAUSS which is then used for simulations in the next section.

There are N different investments, two time periods, 1 and 2, and two states of the world for the climate, a good state and a bad state. The good state is taken to be one in which there is little or no climate change and supply capacity is relatively high and demand relatively low.

The state of the world is observed in each period, but investment decisions have to be taken before the state is known.

For each of the investment options, for example – reservoirs, desalination plant, river abstraction etc., there is the following basic data

1) Total capital cost for option i, C_i
2) Unit operating cost for option i, γ_i
3) Capacity in the good state for option i, $K^g{}_i$
4) Capacity in the bad state for option i, $K^b{}_i$

Investment is taken to be of a fixed size, for example a reservoir of a fixed size. As there are N different investments, there could be investments of several different sizes of reservoir, although if these were to be at same location then it would be necessary to impose constraint that if one is built then other may not be at same time. It may be that for different time periods that there is a later reservoir investment corresponding to the same location which would be an extension to an existing reservoir. However when it comes to computer simulation memory restrictions severely limit how many options can be considered. However in practice many options are either automatically undertaken or ruled out, so that choices tend to be between a very limited number of options.

Demand in the good state in the two time periods , and demand in the bad state in the two time periods, are given by d_t^s t= 1,2 ; s=g,b .

Uncertainty about Climate Change is captured in two ways. First there is *inherent uncertainty*, in the sense that for any given model of climate change there is a risk of getting a good or bad state of the world in any period. Second there is *scientific uncertainty* in that there may be different models of climate change held by different scientists, with different probabilities of getting a good or bad state. To capture these uncertainties in the simplest way we assume that there are two competing models of climate change, given by m = 1, 2. p^m is the probability of the good state arising if model m is true. We assume that $p^1 > p^2$, i.e. model 1 is the more 'optimistic' model of climate change. At the start of period 1 there is a prior probability that model 1 is correct, given by π_1.

It is assumed that learning is solely about *scientific uncertainty*. If learning takes place at the start of period 2 then a signal $\mu = 0,1$ is received. The signal enables the probabilities of the truth of the two models to be revised. If signal 0 is received then the posterior probability that model 1 is correct is given by $\pi_2^0 > \pi_1$, and if message 1 is received then the probability that model 1 is correct is $\pi_2^1 < \pi_1$. So signal 0 is an 'optimistic signal' (it increases the chances that the optimistic model of climate change is the correct model), signal 1 is a pessimistic signal. The probability of getting the optimistic signal $\mu = 0$ is λ. If no learning takes place, no signal is received, and the probability of model 1 being correct remains π_1.

The overall objective is to choose the investment plan **x**, and the usage plan **y** to minimise the expected present value of overall costs, subject to the condition that there is sufficient capacity in place to meet demand in all states of the world.

The analysis is carried out in two stages. First, for any given investment plan, **x**, i.e. any given choice of options, the usage plan is chosen to minimise operating costs in each period and each state of the world, subject to usage of any option not exceeding capacity in that state, and subject to total usage meeting demand in that period and state of the world. This is ensured first by ordering investments in increasing order of operating cost, and adding up capacity until the demand level is reached. If the level of demand level has not been reached when all available investments in a particular investment plan have been used up then that investment plan is *infeasible*, and to ensure it does not get selected the operating cost is set at a very large value.

The second stage is then to choose the investment plan, **x**, which minimises the expected present value of capital costs and operating costs.

The model calculates the optimal investment plan and associated expected present value costs with learning and without learning, and the difference between these expected present value costs is the 'learning premium'.

4.3 Simulation of the Model using constructed data and the Learning Premium

In this part of the analysis, data is chosen for a range of parameters for demand, costs, capacities and probabilities so that a sensible range of outcomes is possible and learning can have some effect. This depends on the balance between supply and demand, and the probabilities of good and bad states and of receiving the optimistic signal 0 or the pessimistic signal 1.

The benefit of learning is then calculated as the saving in expected present value of costs as a proportion of the expected present value of costs with learning. This amounts to between 6% and 20% for a wide range of parameter values except for those cases where there is nothing to be gained from learning, because the period two decision is the same whether there is, or is not, any learning.

So one immediate finding is that for a range of parameter values, the learning premium is significant – saving between 10% and 20% of costs for a company is an important matter.

A further question that can be addressed within this framework is the extent to which the amount of adaptation might affect investment plans and the learning premium. Domestic customers might progressively change their behaviour and adapt to changing temperatures. Of course, they could also adapt to water shortages and react to consumer water saving campaigns. In evidence to the Select Committee on Water and Climate Change,[5] Thames Water suggest that for their area the effect of increased temperature would be to increase the use of water for personal and clothes washing, and to increase outdoor use such as watering of gardens and use in swimming pools. Whilst there is not expected to be any increase coming from the industrial sector it is thought that use in agriculture could increase due to irrigation.

To measure what effect might come from increased used of water through reaction to climate change, this model is simulated by increasing the level of demand in the bad state relative to the good state. The level of demand is increased in steps from being the same in both good and bad states to the bad state having 25% more demand.

There is little difference, as the increases in demand are in general within the spare capacity margins that the chosen investment plan has in place. As has been seen in other places the difference arises where a threshold is crossed and a given investment plan is no longer sufficient to meet anticipated demand.

If educational programmes related to climate change and water shortage are successful, and lead to adaptation away from water use then the effect would be to lower water demand in the bad state in relation to the good state. Reductions in demand lead to similar conclusions. There is no change in the investment plan until a sufficiently large reduction in demand occurs.

Overall, these simulations show that the learning premium when it is non zero, that is there is something to be learnt, varies from between 6% and 20%. Looking at the various changes made to parameters what is most important is the supply demand balance. This is not surprising. Where there happens to be a large margin between supply and demand then the impact of the changes between good and bad states will be limited. Where demand is close to the supply capacity then there will be both a large value for learning what the state will be in planning future investment and it will also be important for what investment is put in place. This case of constructed data now allows us a background for two real cases to which we now turn.

4.4 The Yorkshire Water Drought of 1995

[5] Ev 133- 137 EFRA (2004)

Yorkshire Water is of special interest as a case study as it was the first case of major concern about the failure of a privatised water company to invest sufficiently in order to meet obligations towards security of supply. This failure came about as a result of the 1995 drought, which could be taken as indicative of the situation for water demand and supply that might arise in situations of increased climate change. The water shortage that resulted raised many issues that have influenced the development of policy towards water security over the subsequent years. In particular has been the suggestion that policy should move more towards 'demand management' measures such as the increased use of metering and leakage control. For leakage control, this was interpreted as being reducing leakage to that corresponding to an 'economic level'[6].

As a result the capital programme was expanded. One measure that was implemented in the short term was to build an emergency pipeline to bring water from Kielder reservoir in Northumberland where there was a surplus arising from past over-forecasting of demand. The Tees-Wiske transfer scheme is included in the list of projects considered below. However the pipeline was never connected, and according to ODPM (2002) is unlikely to be required into the future. Despite the costs of providing alternative water supplies, penalties from the regulator, OFWAT, and emergency capital expenditure, there was no decline in the share price of the parent company, which declared a 10% increase in its pre-tax profits.

One of the main problems that Yorkshire Water faced was a large increase in demand during the drought period. Thus in the simulations that follow, we consider relatively large increases between good and bad states. These are indicative of the situations that might need to be faced if investment plans have to be put in place that ensures demand in all climate states is met.

An important question here is the extent to which the drought resulted from normal economic processes or from regulatory failure where these processes were hindered by the structures that had been put in place at the time of privatisation.[7] Haughton (1998) in particular sees the role of profits and the extent of the investment plan as being central to the ability to accommodate drought in 1995. Table 1 of Haughton (1998) shows both Yorkshire Water and Thames Water as having high increases in profits, leakage, and declines in investment, as well as large falls in the investment level in the early 1990's.

The 1995 water crisis in Yorkshire was investigated by a number of inquiries. An independent inquiry under the chairmanship of Prof. John Uff QC, Uff (1996) highlighted the lack of new water capacity and recommended that various new schemes were considered, primarily the, now postponed, Tees-Wiske transfer scheme. This focus on new capacity as a solution, along with discussion about the role of increased leakage in causing the problem, has led to the suspicion amongst commentators and regulators[8] that water shortages and droughts are used as excuses for capacity expansion which is attractive to water companies because of the financial incentives arising from elements of rate of return regulation that exist within the

---

[6] For recent analysis of the 'economic level of leakage' see Tripartite Group (2002).
[7] As suggested by Haughton (1998).
[8] For example the Environment Agency's evidence to the Select Committee on Water and Climate Change EFRA (2004a) .

current regulatory system. The report has many important economic implications for the security of water supply in relation to climate change and the way that the water industry is regulated. But whilst its recommendations are supported by the analysis carried out for this project, they have still not been implemented. The report noted that the drought raised particular issues about the design of the water supply system. No new reservoir capacity had been built since the early 1980's[9]. Recent additions to capacity all came from river abstraction. Resource planning was based on forecasts for falls in demand, and there were also assumptions of large declines in leakage.

The recommendations of the Uff inquiry included the provision of a new resource, and whilst it was recommended that the Tees-Wiske river transfer scheme should be implemented this was not to be seen as being a permanent solution. Questions were raised about the extent to which this was a result of climate change and the extent to which such future droughts might be expected with increased frequency. The report suggested that uncertainty surrounding climate change, (captured in our model by the uncertainty about which of two climate models might be correct) pointed to the need for adequate planning margin rather than, as our analysis suggests, to the need for flexibility and particular types of investments in capacity.

The simulations that follow develop some of the issues arising from discussions of the Yorkshire water crisis. In particular how much capacity, and of what type should be put in place? What is the role of uncertainty here in terms of what different types of capacity will deliver under different climatic conditions especially when we are unsure about how likely those conditions are, and how much investment should be done now and how much might be postponed until new information arrives.

To provide a range of investment options commensurate with the new net demand increases we take the following options

1) Tidal Barrage at Cawood
2) Tees Wiske transfer (River Abstraction Scheme)
3) Collingham Reservoir
4) River Aire at Knostrop (River Abstraction)
5) River Trent (River Abstraction)

This analysis of the optimal investment plans with and without learning yields a learning premium of 30.7%, and for learning an investment plan in which you build a Tidal barrage in period 1 and the reservoir in period 2 if you receive a pessimistic signal, while without learning you build the reservoir in period 1 and the tidal barrage in period 2.

A second simulation looks at five options spread across different types of water scheme. These are :

1. Tidal Barrage at Cawood
2. Tees Wiske transfer (River Abstraction Scheme)
3. Hellifield Reservoir
4. Brompton (Swale) Pumped Storage
5. Reduced Leakage stage 2

[9] This is still largely true for most of England and Wales.

In this case the learning premium increases to 34.5 %, and now the investment plans chosen show that reduced leakage is not the immediate priority and is only used in period 2. When there is learning it is only used for the pessimistic state.

The Uff report considered 42 different possible schemes for providing future water capacity. These varied considerably, in terms of both capital and operating costs, and in the time necessary for the schemes to be implemented. These ranged from 1 to 2 years for some groundwater and river abstraction schemes to 10 to 15 years for schemes such as new reservoirs or reduced leakage. If we are to compare the costs of these options we should take into account the value of keeping options open that will accrue to those schemes that can be quickly implemented in the future when some learning about climate change has taken place. We consider here how this might affect the cost ranking of all the options that were considered in the Uff inquiry.

We use the lower of the learning premiums that we have calculated for a two period model. The investment options available fall into two groups those that take five years or less to implement, and those taking ten to fifteen years. There are none in the intermediate range. These periods fall into the planning cycle for the OFWAT price review. So we take each period as being five years long, and two time periods. In period 2 we will learn about climate change, but if we want to implement in period 2 those schemes taking 10 or more years to build we need to make a decision in period 1 before that information is obtained. Alternatively, we could wait until we obtain the information in period 2 and consider only those schemes taking 5 or less years.

So we divide the investment options into two groups and include the learning premium to those schemes for which learning is possible before implementation takes place, and so are those for which options are kept open. We then see how this changes the cost rankings of the schemes. A reduced table for this is given below. There are three broad groups of schemes. There are those which are both quick to implement and cheap to build and operate such as the Doncaster groundwater scheme. There are schemes which are costly to build and slow to implement such as Hellifield reservoir, and there are schemes which appear in the middle of the cost rankings which are quick to implement but expensive to install such as metering. It is these for which the inclusion of the learning premium changes the cost rankings.

At the time of the Uff inquiry, there were sufficient options that could be quickly implemented for learning not to be an issue but that once these river and ground water abstraction schemes had been fully utilised then learning does make a difference to the cost order of investment options. Further, if the environmental costs of river and groundwater abstraction were to increase, or external pressures such as the EU Water Framework Directive were to lead to groundwater schemes being unavailable, then the timing and learning issues would become an increasingly important issue.

Overall conclusions are that it can be seen there is support for the recommendation of the Uff Inquiry that the Tees-Wiske transfer pipeline should be a priority candidate for new water capacity investment. However, it is quite close in expected cost ranking to reservoirs, and so whether it should be built in period 1 or period 2 depends on whether there is learning or not. When there is learning, additional schemes are implemented in period 2 if the pessimistic signal is received. Leakage reduction is not an immediate priority, and there is only investment in it if there is learning and the pessimistic signal is received, and utilisation of it should the bad state occur.

So the emphasis would appear to be more on capacity enhancement rather than leakage reduction. In popular discussion it would appear that leakage reduction is seen as coming for free. In fact it is an expensive option. For both sets of investment options considered the learning premium was high and above 30%. One reason for this is the large difference between how much extra capacity would appear to be needed between good and bad states in period 2.

Whether learning is important or not depends on the implementation time of investment options. This ranges from 1 year for some river abstraction schemes to over 20 years for some reservoirs. However, much of the delay in building reservoirs comes from planning inquiries, public relations campaigns and over coming local opposition, so that if there were a real water shortage implementation might be much faster. But there would still be a delay in implementation.

Data on Future Resource Options for Yorkshire Water 1995 (Uff 1996) applying a 30.7% learning premium

Scheme	Type	Yield (tcmd)	Available (year)	Total Capital Cost (£m.)	Operating Costs (£m. /yr.)	Unit cost without learning premium	rank	Unit cost with learning premium	rank
Doncaster	Groundwater schemes	20	2	5	0.3	0.476	3	0.330	3
Tees Wiske	River transfer	150	4	68	6.7	1.128	17	0.781	17
Ouse/Elvington Moor Monkton	River abstraction	20	1	18	0.4	1.202	18	0.833	18
R. Aire Esholt	River abstraction	50	10	35	2.2	1.364	23	1.364	27
Metering		28	3	30	0.8	1.503	25	1.041	22
Hellifield	Reservoir	100	20	90	4.5	1.579	27	1.579	29
Ouse Eccup	River abstraction	20	1	25	0.8	1.854	30	1.285	24
Reduced Leakage		60	10	71	9	3.447	37	3.447	38
Desalination		20	2	35	3.3	4.241	39	2.939	37

4.5 Simulation Based on data for Thames Water

The following is a case study based, very loosely, on the limited information publicly available for Thames Water. Much in the way of interpolation and assumption has had to be done. It does not intend to represent reality, but instead to point to orders of magnitude and issues of importance. For the data in this case we explore fully how sensitive results on the optimal investment plan, and the learning premium, might be to parameter variations.

Thames Water has a significant gap of 150 million litres/day (Ml/d) between demand and supply following a review of their water supply forecasts for London. This gap exists even after potential leakage savings are taken into account. OFWAT required a solution to the water supply shortfall to be implemented within 2-3 years. The solution identified was for a desalination plant on the tidal Thames at Beckton. This would provide additional water supply in the short to medium term for London. It would also lead to a sufficient safety margin (as required by the water industry regulators, OFWAT and the Environment Agency) to provide security of supply in dry weather conditions.

In the longer term , Thames Water has already started planning for a new reservoir in south-west Oxfordshire near Abingdon in the Upper Thames valley. It therefore, plans to achieve target headroom by 2008 with the construction of a desalination plant in the tidal Thames. High leakage is planned to fall by 2011, but then rise again to 2030. Thames Water plans to achieve much of this fall in leakage with mains replacement. It has relatively low levels of metering and does not plan to increase this significantly

We look at some of these investment options that have been reported as being available and calculate how the learning premium relates to the various options available to Thames Water. They are:

1) Upper Thames Reservoir
2) Beckton desalination
3) ELRED and other groundwater developments
4) Reduced Leakage
5) Increased Metering

Demand data is based on the resource development numbers indicated by the EA (2004), This indicates that there will be 200 Ml/d of new water capacity development by 2010, although their graph for demand shows a plateau throughout the 2003 to 2030 period. It also suggests that there will be a further 430 Ml/d of resource development by 2030. But this figure when added to the 2010 figure is more than the total new capacity indicated above.

In contrast to the previous case of Yorkshire Water where a list of options was reported, here we only have details of what is actually planned and likely to be built. So that the question of which options to invest in has already been answered. One solution would be to expand the size of the options and to one extent we do this in respect of the reservoir option.

The reservoir option is small in capacity relative to the other four options presented in the list above. Further it was not clear quite what capacity the reservoir option would correspond to given that feasibility studies were being carried out for a range that doubled the reservoir volume. So for simulations we increase the reservoir capacity by 50%, so that it becomes an alternative to reduced leakage. It is this choice which is often discussed as being on offer.

Effect of required level of new capacity in period 2

For demand we take 200 Ml/d as being the level of period 1 new demand and a range of demand levels for period 2 from 200 Ml/d to 400 Ml/d. For the bad state we at first assume an increase of 10% over the good state.

The conclusions obtained are that firstly groundwater is the first option that will be used. It is cheap in both capital and operating costs. Reservoirs have relatively low operating costs but their high capital costs mean that they are built only when there is a high level of capacity that needs to be provided. Only in limited cases does the requirement for new reservoir capacity depend on what the state of the world is. This is for a demand increase of between 144 Ml/d and 174ML/d [10] when there is learning and the reservoir would be built for the bad state of the world. If there were no learning then the reservoir is built in period 1 for demand increases above 144Ml/d when there is learning the reservoir is constructed for period 1 for demand increases between the two.

Desalination, reduced leakage and metering appear to alternate as the required level of extra capacity increases. This suggests that if the amount of capacity coming from these were allowed to vary then the optimal solution would be to do some of all three. In general, it can be said that for a required large amount of extra capacity then metering and leakage control will be implemented but not immediately. So it is not the immediate answer to water shortage that it is often presented as.

Effect of Size of Reservoir

Does it matter what the yield of the reservoir is? The next simulations look at varying this yield for a level of required extra capacity in period 2 at which with base capacity the reservoir would appear to be marginal. This is taken to be 420 ML/d in the good state and an extra 10% in the bad state.

The results of this are that the reservoir comes into consideration once its capacity reaches 211 Ml/d, then it is installed in period 1 and used when there is learning only. Leakage reduction and desalination are used in the bad state in period 2. When there is no learning at that reservoir capacity level, leakage reduction in both periods and desalination and metering in period 2 are used. For slightly increased reservoir capacity, above 215 Ml/d, then the reservoir is used both when there is and when there is not learning, and there is no action on leakage reduction.

[10] This is for increase in demand above a base level. Using numbers that correspond to those for Thames Water , the new demand of 210 – 420 Ml/d should be contrasted to a base demand level of approximately 3000 Ml/d.

Effect if climate change impacts more on reservoirs in the bad state

This takes the data from the above case of period 2 good state demand at 420 Ml/d, a reservoir capacity which will lead in the above to it being used both with and without learning, 228 Ml/d, and then increases the climate change effect by reducing the bad state capacity.

Here what happens is that investment plan remains the same until the bad state reservoir capacity is 27% below that in the good state. At that point investment in reservoir capacity is replaced by investment in leakage reduction.[11] So in that case new reservoirs and leakage are alternatives. It requires there to be a sufficiently large climate change effect for that to happen.

Effect of probability of the signal

We take as base the case where reservoir will be built: period 2 good state demand at 420 Ml/d, a reservoir capacity 228 Ml/d, the bad state reduces capacity by 10%, and then vary the strength of the signal whilst retaining model 1 more likely than model 2, and keeping the rest of the probabilistic structure the same.

The investment plan changes once the probability of receiving an optimistic signal, λ, exceeds 0.8. If the signal that model 1 is correct is received with probability below 0.8 then the reservoir is built both when there is and is not learning. When this probability exceeds 0.8, then when there is learning the reservoir is only constructed if the pessimistic signal is received and the reservoir is replaced by leakage control. So leakage control is the optimal response when we get a strong signal about which model is correct to use for the probabilities of the good and bad states.

The next stage of analysis is to look at how differences between model probabilities might affect these conclusions.

Differences in probabilistic models for good and bad states

We take the same values as in previous simulation and set λ at its base value of 0.7. The probabilities, of the good state for the two models, are allowed to vary between 0.2 and 0.9 for both models. We have stronger belief in model 1 than model 2. For low probabilities of the good state for model 1 a higher probability of the good state in model 2 is required to justify investment in reservoir capacity rather than leakage control.

Effect of prior and posterior beliefs in models

These simulations look at how changes in the prior and posterior probabilities might change the optimal investment plan, for the base case considered above. The probability of getting a signal 0, λ, is set at 0.7. Variations are considered in the probabilities π_1, the prior probability which is allowed to vary between 0.5 and 0.75, and the posterior probabilities conditional on getting the signal $\mu = 0$, or 1, π_2^0, π_2^1.

[11] In that for effect of the bad state on reservoir capacity of a 27% reduction below the good state then leakage control is not used but there is investment in a new reservoir, whilst for this effect being greater than 27% , there is now leakage control but no investment in a new reservoir.

Because of the restriction that $\pi_2^0 > \pi_1 > \pi_2^1$ the posterior probabilities are set 25% above or below the prior probability respectively. These ranges ensure that all probabilities lie below 1.

The optimal investment plan takes one of two possibilities. The Learning Premium varies slightly between 10% and 9.8% across the changes in probability structure for belief in the two models. The premium decreases as the prior probability increases. From this it can be concluded that leakage control implemented only when posterior gives us strong confidence in which model is correct.

4.6 Conclusions

We have developed here a model that allows us to see what the consequences of learning about climate change models might be for the investment profile. A signal is received giving information on which of two competing climate models might be more appropriate. Using this signal the decision maker considering investment options revises the prior probability of the two models. Finally the decision maker uses the posterior probabilities in order to calculate the expected present values for all of the many different combinations of investment plans. This number is large because there is the choice for each investment option of when to put the option in place, and, with learning, for what value of the signal. Nevertheless, the model can be implemented on a PC for the case of 5 possible investment options, two or three time periods, two states of the world for climate change and two competing models for the underlying stochastic process.

The size constraint is made more serious by the fact that it is exponential in the number of options and time periods. So, further extension will soon run into problems of computing constraints. This is just another example of the 'Curse of Dimensionality'. However to some extent this constraint is perhaps not as limiting as might first be thought. Whilst there often very many individual types of future resource option, as can be seen from those outlined for Yorkshire Water, there are only a few different types of option. For other more recent cases such as discussion of the options available to Thames Water, and in fact for all of the water companies as outlined in EA (2004a), there are only a small number of schemes being seriously considered. As a basis for considering what the optimal investment plan might be and how aspects of learning about the climate model might fit into this, the problem is not that there are a large number of options. Rather it is that the urgent need to increase capacity and the timescale for implementation does not allow for a choice to be made.

Does the learning make a difference? The answer to this can be seen from calculations of the cost savings from being able to invest when there is the possibility of learning about the state of the world and when there is not. This premium lies between 7% and 20% in a wide variety of cases. In some situations, there is no cost advantage to learning, but in two case studies based fairly closely on real data that situation does not arise. This premium depends heavily on the demand – supply balance, the size of the investment options, and the extent to which different climate scenarios increases what demand will be and decreases what the yield of different options will be.

The other important driver for the learning premium is that of the probability of receiving the optimistic signal. Increases in the probability of this signal, not surprisingly, increase the amount that can be saved by learning. When the probability that this signal is obtained is 0.5 then the learning premium is around 8%. When it becomes almost certain that this signal is obtained, the learning premium is 16%. Changes in other parameter values have some but only limited effect.

The model simulation was then used to consider what might result if there were to be increased adaptation by water users, and that there are successful education programmes that reduce water use in reaction to climate change. These were modelled by increasing the level of demand in the bad state relative to the good state, and lowering water demand in the bad state in relation to the good state. For both of these there is a phenomenon of banding in terms of the investment plan. There is no change in the investment plan until a sufficiently large reduction in demand. So for these to have any effect they have to be sufficiently large. In the simulation they replace one type of investment by another.

For the first of two case studies based on real world data, we find that the model supports the investment plan for future resources that an independent inquiry suggested. In that example there is a high value for learning. Applying the learning premium to all of the possible options for future resource development that were available to Yorkshire Water at that time suggests that it is when river and groundwater schemes have been fully utilised that the cost advantages arising from learning will become important. Increasing restrictions on the use of these sources such as those arising out of the Water Framework Directive will make the issue of learning about climate change and the timing of investment strategies increasingly important.

The second case study was based, very loosely because of the absence of definite data, on a current investment choice problem. An issue that has been prominent there has been that of the choice between what are termed 'Demand Management' measures such as Leakage and Metering, as opposed to investment in new capacity such as Reservoirs. A position taken both by politicians and regulators is that there should be no expansion in new resource capacity until leakage levels are substantially reduced. The calculations we made show that this depends on how much new capacity is needed to be put in place, and also on how large the reservoir will be. For a small reservoir, reduced leakage is implemented but the reservoir not until there is a sufficiently high level of new capacity required, when implementation of the reservoir in the first period delays action on leakage to the second. But if the reservoir yield were to be much higher then leakage reduction becomes more marginal.

5. Policy Implications

By studying mitigation, adaptation and climate change from an economist's perspective, we show that mitigation and adaptation are substitutes in an economic sense, and that this result is robust to changes and extensions in the modeling framework. This has important policy implications. For example, early generations of models of the economic response to climate change, for example the 1996 IPCC volume, tended to focus only on mitigation strategies. In effect these can be considered as treating the costs of adaptation as being infinite. Later models have given more attention to adaptation options and have found them to be relatively less costly. They have concluded that there is rather less need for mitigation (for example, recent surveys by Mendelsohn (2003) and Tol (2003)). But one should not rely on adaptation on its own either. Our result implies that we need to have an integrated approach to adaptation and mitigation, and we cannot rely on either mitigation alone or adaptation alone to deal with climate change. But increasing the amount of one type of strategy, mitigative or adaptive, reduces the amount of the other that should be undertaken. This is contrary to suggestions of some policy analysts who advocate increasing amounts of both. It is not appropriate to consider just one approach on its own. However, the possibility of adaptive options biases policy towards a 'wait and see' rather than a 'precautionary' policy, and our later empirical modelling suggest that the cost implications of this may make the shift towards adaptation large.

When there is the combination of uncertainty, learning, irreversibility, we have shown that when both mitigation and adaptation are available, adaptation acts to weaken the effects of the irreversibility constraint, so it is now more likely that the implications of learning for current policy are determined by the pure learning effect, which is for a reduction in current actions to deal with climate change. When we allow adaptation to effectively reduce damage costs rather than operating directly on the stock of Greenhouse Gases, the irreversibility constraint becomes irrelevant, and the prospect of future learning unambiguously leads to less current action to deal with climate change. So we should not worry as much about making irreversible decisions when there is the possibility of adaptive options. This will change the investment appraisal for research and development into adaptive strategies as the benefits for these should include the cost savings that arise from potentially irreversible investments that are no longer needed.

Maladaptation, which is the increasing emissions of GHGs due to adaptive strategies which enhance climate change, is often cited as a problem with many adaptive strategies. A current example of this is the decision by the GLA to refuse planning approval for a water desalination plant for London. We have shown that this is a consequence of policy failure with the regulation of energy prices, and should be seen as requiring modification of policies elsewhere rather than being an argument against particular adaptive strategies.

Though derived from this simple model of climate change, the empirical model we developed supports this conclusion. We calculated the premium that applies to being able to learn about climate models. This enables us to calculate the magnitude of the consequences of learning about climate change models. We applied this to the investment profile of the UK water industry. We conclude from this that the issue of learning is very important. If learning is possible then there can be high cost savings arising from an optimal choice of investment plan. This could be of the order of 10% - 30% of overall costs, and given the way in which price regulation is undertaken in water bills as well.. However, this requires that water companies are forward looking and pro-active in their investment decisions. But this may be deterred by reaction to the form of regulation within the UK water industry which causes there to be under-investment. What we show is that this comes with its own high cost for delivering water capacity.

6. *Bibliography*

Arnell, N. W. (2004). "Climate change impacts on river flows in Britain: The UKCIP02 scenarios", *Journal of the Chartered Institute of Water and Environmental Management*, vol. 18, pp. 112-117.

Arrow, K. and Fisher, A. (1974). "Environmental preservation, uncertainty and irreversibility", *Quarterly Journal of Economics*, vol. 88, pp. 312-319.

Azar, C. and Lindgren, K. (2003). "Catastrophic events and stochastic cost-benefit analysis of climate change", *Climatic Change*, vol. 56, pp. 245-255.

Babiker, M., Reilly, J. and Jacoby, H. (2000). "The Kyoto Protocol and developing countries", *Energy Policy*, vol. 28, pp. 525-36.

Bakker, K. (1998). "Yorkshire Water and Yorkshire's water: Flows of water/capital in the drought of 1995", EGRG Working paper 98/01.

Bakker, K. (2000). "Privatizing water, producing scarcity: The Yorkshire drought of 1995", *Economic Geography*, vol. 76, pp. 4-27.

Balance, A. and Taylor, A. (2005). *Competition and Economic Regulation in Water*. London: IWA Publishing.

Barker, T. (2001). "Representing the integrated assessment of climate change, adaptation and mitigation", Tyndall Centre Working Paper 11.

Baron, D. (1985). "Non cooperative regulation of a nonlocalized externality", *Rand Journal of Economics*, vol. 16, pp. 553-68.

Berkhout, F., Hertin, J. and Gann, D. M. (2004). "Learning to adapt: Organisational adaptation to climate change impacts", Tyndall Centre Working Paper 47.

Berkhout, F., Hertin, J. and Arnell, N. W. (2004). "Business and climate change: Measuring and enhancing adaptive capacity", The ADAPT project, Tyndall Centre Technical Report 11.

Blackwell, D. (1951). "Comparison of experiments", in (J. Neyman, ed.) *Proceedings of the Second Berkeley Symposium on Mathematical Statistics and Probability*, Berkeley and Los Angeles: University of California Press, pp. 93-102.

Brooks, N. and Adger, W. (2003). "Country level risk measures of climate related natural disasters and implications for adaptation to climate change", Tyndall Centre Working Paper 26.

Bruckner, T., Petscel-Held, G., Toth, F. L., Fussel, H-M., Helm, C., Leimbach, M. and Schellnhuber, H-J. (1999). "Climate change decision-support and the Tolerable Windows Approach", *Environmental Model Assessment*, vol. 4, pp. 217-234.

CCDeW. (2003). *Climate Change and Demand for Water*. Oxford: Stockholm Environmental Institute.

Chichilnisky, G. (2000). “An axiomatic approach to choice under uncertainty with catastrophic risks”, *Resource and Energy Economics*, vol. 22, pp. 221-231.

Clarke, H. and Reed, W. (1994). “Consumption/pollution tradeoffs in an environment vulnerable to pollution-related catastrophic collapse”, *Journal of Economic Dynamics and Control*, vol. 18, pp. 991-1010.

Conrad, J. M. (1997). “Global warming: When to bite the bullet”, *Land Economics*, vol. 73, pp. 164-173.

Cowan, S. (2002). “Price-cap regulation”, *Swedish Economic Policy Review*, vol. 9, pp. 167-188.

Cowan, S. (2003). “Optimal risk allocation for regulated monopolies and consumers”, *Journal of Public Economics*, vol. 88, pp. 285-303.

Cropper, M. (1996). “Regulating activities with catastrophic environmental effects”, *Journal of Environmental Economics and Management*, vol. 3, pp. 1-15.

Dalhuisen, J., Florax, R., de Groot, H. and Nijkamp, P. (2001). “Price and income elasticities of residential water demand”, Tinbergen Institute Discussion paper TI 2001-057/3, Vrije Universitet Amsterdam.

Dasgupta, P. and Mäler, K.-G. (2003). “The economics of non-convex ecosystems: Introduction”, *Environmental and Resource Economics*, vol. 26, pp. 499-525.

Dessai, S., Adger, W., Hulme, M., Kohler, J., Turnpenny, J. and Warren, R. (2003). “Defining and experiencing dangerous climate change”, Tyndall Centre Working Paper 28.

Dixit, A. and Pindyck, R. (1994). *Investment under Uncertainty*. Princeton: Princeton University Press.

Dutta, P. and Radner, R. (1999). “Profit maximization and the market selection hypothesis”, *The Review of Economic Studies*, vol. 66, pp. 769-798.

EFRA. (2004a). “Climate change, water security and flooding”, House of Commons, Environment, Food and Rural Affairs Committee, 16th report, session 2003-2004, HC 558, Stationery Office, London.

EFRA. (2004b). “Water pricing: Follow up”, House of Commons, Environment, Food and Rural Affairs Committee, 19th report, session 2003-2004, HC 1186, Stationery Office, London.

EFRA. (2004c). “Climate change, water security and flooding: Government reply to the Committee’s Report”, House of Commons, Environment, Food and Rural Affairs Committee, 2nd Special Report, Session 2004–2005, Stationery Office, London.

EA. (2003). *Securing Water Supply*. Bristol: Environment Agency.

EA. (2004a). *Maintaining Water Supply*. Bristol: Environment Agency.

EA. (2004b). *Review of Water Company Water Resources Plans, 2004*. Bristol: Environment Agency.

Environmental Audit Committee. (2004). "Water: The periodic review and the environmental programme", 4th report, session 2003-2004, HC 416, Stationery Office, London.

Epstein, L. (1980). "Decision making and the temporal resolution of uncertainty", *International Economic Review,* vol. 21, pp. 269-284.

Fankhauser, S., Smith, J. B. and Tol, R. S. J. (1999). "Weathering climate change: Some simple rules to guide adaptation decisions", *Ecological Economics,* vol. 30, pp. 67-78.

Fisher, A. (2002). "Irreversibilities and catastrophic risks in climate change", in (E. van Ierland, H. Weikard, and J. Wesseler, eds.) *Risk and Uncertainty in Environmental and Resource Economics*, Environmental Economics and Natural Resources Group, Wageningen University.

Fisher, A. and Hanemann, W. M. (1986). "Environmental damages and option values", *Natural Resource Modelling*, vol. 1, pp. 111-124.

Fisher, A., Hanemann, W. M. and Narain, U. (2002). "The irreversibility effect: Necessary and sufficient conditions", in (E. van Ierland, H. Weikard and J. Wesseler, eds.) *Risk and Uncertainty in Environmental and Resource Economics,* Environmental Economics and Natural Resources Group, Wageningen University.

Fisher, A. and Rubio, S. (1997). "Adjusting to climate change: Implications of increased variability and asymmetric adjustment costs for investment in water reserves", *Journal of Environmental Economics and Management*, vol. 34, pp. 207-227.

Fletcher, P. (2005). "The future regulatory agenda", Speech at Water UK City Conference.

Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C. S., Walker, B., Bengtsson, J., Berkes, F., Colding, J., Danell, K., Falkenmark, M., Gordon, L., Kasperson, R., Kautsky, N., Kinzig, A., Levin, S., Maler, K.-G., Moberg, F., Ohlsson, L., Olsson, P., Ostrom, E., Reid, W., Rockstrom, J., Savenije, H. and Svedin, U. (2002). "Resilience and sustainable development: Building adaptive capacity in a world of transformation", Environmental Advisory Council, Sweden.

Freixas, X. and Laffont, J-J. (1984). "On the irreversibility effect", in (M. Boyer and R. E. Kihlstrom, eds.) *Bayesian Models in Economic Theory*, Amsterdam: North-Holland, pp. 105-113.

Gjerde, J., Gredderup, S. and Kverndokk, S. (1999). "Optimal climate policy under the possibility of a catastrophe", *Resources Policy,* vol. 21, pp. 289-317.

GLA. (2003). "London's water supply: A report by the London Assembly's Public Services Committee", London.

GLA. (2004). “Desalination plant, Beckton”, Planning Report PDU/0953/01.

Gollier, C., Jullien, B. and Treich, N. (2000). “Scientific progress and irreversibility: An economic interpretation of the ‘Precautionary Principle’”, *Journal of Public Economics*, vol. 75, pp. 229-253.

Goodess C., Hulme M. and Osborne, T. (2001), “The identification and evaluation of suitable scenario development methods for the estimation of future probabilities of extreme weather events”, Tyndall Centre Working Paper 6.

Graham-Tomasi, T. (1995). “Quasi option value”, in (D. Bromley, ed.) *The Handbook of Environmental Economics,* Oxford: Blackwell, pp. 594-614.

Greenough, G., McGeehin, M., Bernard, S., Trtanj, J., Riad, J. and Engelberg, D. (2001). “The potential impacts of climate variability and change on health impacts of extreme weather events in the United States”, *Environmental health Perspectives*, vol. 109, pp. 191-198.

Ha-Duong, M. and Treich, N. (2004). “Risk aversion, intergenerational equity and climate change”, *Environmental and Resource Economics*, vol. 28, pp. 195-207.

Ha-Duong, M., Grubb, M. and Hourcade, J-C. (1997). “Influence of socio-economic inertia and uncertainty on optimal CO2-emission abatement”, *Nature*, vol. 390, pp. 270-273.

Hanemann, W. M. (2000). “Adaptation and its measurement: An Editorial”, *Climatic Change*, vol. 45, pp. 571-581.

Haughton, G. (1998). “Private profits – public drought: The creation of a crisis in water management for West Yorkshire”, *Transactions of the Institute of British Geographers*, vol. 23, pp. 419-433.

Haurie, A. (2002). “Integrated assessment modeling for global climate change: An infinite horizon optimization viewpoint”, NCCR-WP4 Working Paper, Swiss National Centre of Competence, University of Geneva.

Henry, C. (1974a). “Investment decisions under uncertainty: The irreversibility effect”, *American Economic Review*, vol. 64, pp. 1006-1012.

Henry, C. (1974b). “Option values in economics of irreplaceable assets”, *The Review of Economic Studies*, vol. 41(S), pp. 89-104.

Huntington, E. (1917). “Climatic change and agricultural exhaustion as elements in the fall of Rome”, *The Quarterly Journal of Economics*, vol. 31, pp. 173-208.

Ingham, A. and Ulph, A. (2005), “Uncertainty and climate change Policy”, in (D. Helm, ed.) *Climate Change Policy*, Oxford: Oxford University Press.

Ingham, A., Ma, J. and Ulph, A. (2005a). “How do the costs of adaptation affect optimal mitigation when there is uncertainty, irreversibility and learning?”, Tyndall Centre Working Paper 74.

Ingham, A., Ma, J. and Ulph, A. (2005b). “Can Adaptation and Mitigation be Complements?”, Tyndall Centre Working Paper 79.

Ingham, A., Ma, J. and Ulph, A. (2005c). ‘The regulatory background to water industry investment and climate change”, mimeo.

Ingham, A., Ma, J. and Ulph, A. (2005d). “Learning about Climate Change: A quantitative analysis of the effect for the UK water supply industry”, mimeo.

Ingham, A., Ma, J. and Ulph, A. (2006). “Climate change, mitigation and adaptation with uncertainty and learning”, *Energy Policy*, Special Issue dedicated to Memory of Alan S. Manne, forthcoming.

Intergovernmental Panel on Climate Change (IPCC). (1996). (R.T. Watson, M. C. Zinyoewera and R. H. Moss, Eds.) *Climate Change 1995 – Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*. Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2001). (J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken and K. S. White, Eds.) *Climate Change 2001 – Impacts, Adaptation, and Vulnerability*. Cambridge: Cambridge University Press.

Joos, F., Muller-Fustenberger, G. and Stephan, G. (1999). “Correcting the carbon cycle representation: How important is it for the economics of climate change?”, *Environmental Modelling and Assessment*, vol. 4, pp. 133-140.

Kane, S. and Shogren, J. F. (2000). “Linking adaptation and mitigation in climate change policy”, *Climatic Change*, vol. 45, pp. 75-102.

Kane, S. and Yohe, G. W. (2000). “Societal adaptation to climate variability and change: An introduction”, *Climatic Change*, vol. 45, pp. 1-4.

Kann, A. and Weyant, J. (2000). “Approaches for performing uncertainty analysis in large-scale energy/economic policy models”, *Environmental Modelling and Assessment*, vol. 5, pp. 29-46.

Karp, L. and Zhang, J. (2002). “Regulation with anticipated learning about environmental damages, mimeo.

Keller, K., Tan, K., Morel, F. M. M. and Bradford, D. F. (2000). “Preserving the ocean circulation: Implications for climate policy”, *Climatic Change*, vol. 47, pp. 17-43.

Kelly, D. L. and Kolstad, C. D. (1999). “Bayesian learning, growth and pollution”, *Journal of Economic Dynamics and Control*, vol. 23, pp. 491-518.

Kelly, D. L. and Kolstad, C. D. (2001). “Solving infinite horizon growth models with an environmental sector,” *Computational Economics*, vol. 18, pp. 217-31.

Kelly, D. L., Kolstad, C. D. and Mitchell, G. (2002). “Adjustment costs from environmental change induced by incomplete information and learning”, Discussion Paper 1099, Department of Economics, University of California, Santa Barbara.

Klein, R. J. T. (2003). *Part 3 of Resilience and Adaptation to Climate Change: An Interdisciplinary Perspective*, PhD Thesis, Christian-Albrechts-Universität zu Kiel.

Klein, R. J. T., Schipper, E. L. and Dessai, S. (2003). “Integrating mitigation and adaptation into climate and development policy: Three research questions”, Tyndall Centre Working Paper 40.

Kolstad, C. D. (1993). “Looking vs leaping: The timing of CO2 control in the face of uncertainty and learning in (Y. Kaya, N. Nakicenovic, W. D. Norhaus and F. L. Toth, eds.) *Costs, Impacts and Benefits of CO2 Mitigation*, IIASA, Austria, pp. 63-82.

Kolstad, C. D. (1996a). “Fundamental irreversibilities in stock externalities”, *Journal of Public Economics*, vol. 60, pp. 221-233.

Kolstad, C. D. (1996b). “Learning and stock effects in environmental regulations: The Case of greenhouse gas emissions”, *Journal of Environmental Economics and Management*, vol. 31, pp. 1-18.

Kolstad, C. D. and Toman, M. (2001). “The economics of climate policy”, Discussion Paper 00–40REV, Resources for the Future.

Kriegler, E. and Bruckner, T. (2002). “Global and Annex I emissions corridors for the 21st century”, in (A. E. Rizzoli and A. J. Jakeman, Eds.) *Integrated Assessment and Decision Support Proceedings of the 1st Biennial Meeting of the IEMSS*, vol. 3, Lugano, Switzerland, pp. 151-156.

Kriegler, E. and Bruckner, T. (2004). “Sensitivity analysis of emissions corridors for the 21st century”, *Climatic Change*, vol. 66, pp. 345-387.

Leimbach, M. and Bruckner, T. (2001). “Influence of economic constraints on the shape of emission corridors”, *Computational Economics*, vol. 18, pp. 173-191.

Lempert, R. M., Schlesinger, M., Bankes, S. and Andronova, N. (2000). “The impacts of climate variability on near-term policy choices and the value of information”, *Climatic Change*, vol. 45, pp. 129-161.

Maddison, D. (1995). “A cost-benefit analysis of slowing climate change”, *Energy Policy*, vol. 23, pp. 337-346.

Maloney, W. A. (1996). “Regulating the privatised water industry: Complexity, conflict and compromise”, *Contemporary Political Studies*, vol. 2, pp. 957-968.

Manne, A. and Richels, R. (1992). *Buying Greenhouse Insurance: The Economic Cost of CO2 Emissions Limits*. Cambridge, MA: The MIT Press.

Manne, A. and Richels, R. (1995). “The greenhouse debate: Economic efficiency, burden sharing and hedging strategies”, *The Energy Journal*, vol. 16, pp. 1-38.

Marschak, J. and Miyasawa, K. (1968). “Economic Comparability of Information Systems”, *International Economic Review*, vol. 9, pp. 137-174.

Mastrandrea, M. and Schneider, S. (2001). “Integrated assessment of abrupt climatic changes”, *Climate Policy*, vol. 1, pp. 433-449.

Mendelson, R. (2000). “Efficient adaptation to climate change”, *Climatic Change*, vol. 45, pp. 583-600.

Mendelson, R. (2003). “The social cost of carbon: An unfolding value”, DEFRA Social Cost of Carbon Seminar.

Mendelsohn, R. and Neumann, J., eds. (1999). *The Impact of Climate Change on the United States Economy*. Cambridge: Cambridge University Press

Mensink, P. and Requate, T. (2005). “The Dixit-Pindyck and the Arrow-Fisher-Hanemann-Henry option values are not equivalent: A note on Fisher (2000)”, *Resource and Energy Economics*, vol. 27, pp. 83-88.

Meran, G. and Schwalbe, U. (2004). *Price and Quality Regulation in the Water Industry: The Need for Co-ordination*. Berlin: Deutsches Institut für Wirtschaftsforschung.

Morgan, M. G. and Keith, D. W. (1995). “Subjective judgments by climate experts”, *Environmental Science & Technology*, vol. 29, pp. A468-A476.

NAO. (2000). “Leakage and water efficiency”, Report by the Comptroller and Auditor General, National Audit Office, HC 971, Session 1999-2000, London.

Narain, U. and Fisher, A. (1998). “Irreversibility, uncertainty, and catastrophic global warming”, Working Paper 843, Department of Agricultural and Resource Economics, University of California, Berkeley.

Narain, U., Hanemann, W. M. and Fisher, A. (2004). “The temporal resolution of uncertainty”, mimeo.

NCC. (2002). *Towards a Sustainable Water Charging Policy*. London: National Consumer Council.

Nordhaus, W. D. (1994). “Expert opinion on climate change”, *American Scientist*, vol. 82, pp. 45-51.

Nordhaus, W. D. and Popp, D. (1997). “What is the value of scientific knowledge? An application to global warming using the PRICE model”, *The Energy Journal*, vol. 18, pp. 1-47.

ODPM. (2002). *Regional Planning Guidance for the North East (RPG1)*. Government Office for the North East.

O’Halloran, J. (2005). BBC Radio 4 File on Four ‘Water Shortage’, 19 July 2005.

Parry, M., Arnell, N., McMichael, T., Nicholls, R., Martens, P., Kovats, S., Livermore, M., Rosenzweig, C., Iglesias, A. and Fischer, G. (2000). “Millions at risk: Defining critical climate change threats and targets”, *Global Environmental Change*, vol. 11, pp. 181-183.

Peck, S. C. and Teisberg, T. J. (1992). “CETA: A model of Carbon emissions trajectory assessment”, *The Energy Journal*, vol. 13, pp. 55-77.

Pielke, R. A., Jr. (1998). “Rethinking the role of adaptation in climate policy”, *Global Environmental Change*, vol. 8, pp. 159-170.

Pindyck, R. (1991). “Irreversibility, uncertainty and investment”, *Journal of Economic Literature*, vol. 29, pp. 1110-1148.

Pindyck, R. (2000). “Irreversibilities and the timing of environmental policy”, *Resource and Energy Economics*, vol. 22, pp. 233-259.

Pizer, W. (2003). “Climate change catastrophes”, Discussion Paper 03-31, Resources for the Future.

POST. (1995). “The 1995 drought”, Parliamentary Office for Science and Technology, London.

Ramakrishnan, P. (1998). “Sustainable development, climate change, and the tropical rain forest landscape”, *Climatic Change*, vol. 39, pp. 583-600.

Reilly, J. and Schimmelpfennig, D. (2000). “Irreversibility, uncertainty, and learning: Portraits of adaptation to long-term climate change”, *Climatic Change*, vol. 45, pp. 253-278.

Roughgarden, T. and Schneider, A. (1999). “Climate change policy: Quantifying uncertainties for damages and optimal carbon taxes”, *Energy Policy*, vol. 27, pp. 415-429.

Salathé, T. (2003). “Climate change and wetlands: Impacts, adaptation, and mitigation”, mimeo.

Scheraga, J. and Grambsch, A. (1998). “Risks, opportunities, and adaptation to climate change”, *Climate Research*, vol. 10, pp. 85-95.

Schneider, S. (2004). “Climate change”, mimeo.

Schneider, S., Easterling, W. and Mearns, L. (2000). “Adaptation: Sensitivity to natural variability, agent assumptions and dynamic climate changes”, *Climatic Change*, vol. 45, pp. 203-221.

Schulz, P. and Kasting, J. (1997). “Optimal reductions in CO2 emissions”, *Energy Policy*, vol. 25, pp. 491-500.

Smit, B. and Pilifosova, O. (2001). “Adaptation to climate change in the context of sustainable development and equity”, in *Climate Change 2001: Impacts, Adaptation, and Vulnerability – Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Smit, B. and Pilifosova, O. (2003). “From adaptation to adaptive capacity and vulnerability reduction”, in (J. B. Smith, R. J. T. Klein and S. Huq, eds.) *Climate Change, Adaptive Capacity and Development*, London: Imperial College Press.

Smit, B., Burton, I., Klein, R. J. T. and Wandel, J. (2000). “An anatomy of adaptation to climate change and variability”, *Climatic Change*, vol. 45, pp. 223-251.

Smith, J., Klein, R. J. T. and Huq S. (2003). *Climate Change, Adaptive Capacity and Development*. London: Imperial College Press.

Tol, R. S. J. (1998). “On the difference in impact between two almost identical climate scenarios”, *Energy Policy*, vol. 26, pp. 13-20.

Tol, R. S. J. (1999). “Safe policies in an uncertain climate: An application of FUND”, *Global Environmental Change*, vol. 9, pp. 221-232.

Tol, R. S. J. (2001). “Equitable cost-benefit analysis of climate change”, *Ecological Economics*, vol. 36, pp. 71-85.

Tol, R. S. J. (2002). “Adaptation and mitigation: Trade-offs in substance and method”, mimeo.

Tol, R. S. J. (2003). “Is the uncertainty about climate change too large for expected cost-benefit analysis?”, *Climatic Change*, vol. 56, pp. 265-289.

Tol, R. S. J. and Dowlatabadi, H. (2001). “Vector-borne diseases, climate change, and economic growth”, *Integrated Assessment*, vol. 2, pp. 173-181.

Tol, R. S. J., Downing, T. E., Kuik, O. J. and Smith, J. B. (2004). “Distributional aspects of climate change impacts”, *Global Environmental Change*, vol. 14, pp. 259-272.

Tompkins, E. and Hurlston, L-A. (2003). “Report to the Cayman Islands’ Government: Adaptation lessons learned from responding to tropical cyclones by the Cayman Islands’ Government, 1988-2002”, Tyndall Centre Working Paper 35.

Torvanger, A. (1997). “Uncertain climate change in an intergenerational planning model”, *Environmental and Resource Economics*, vol. 9, pp. 103-124.

Toth, F. L., ed. (2000). “Climate impacts: Thresholds and response Function”, *Climatic Change*, vol. 46, Special Issue.

Toth, F. L. (2002). “State of the art and future challenges for integrated environmental assessment”, EFIEA Conference on Sustainability Assessment.

Tripartite Group. (2002). “Best practice principles in the economic level of leakage”, Department for Environment Food and Rural Affairs, the Environment Agency and the Office of Water Services.

Tsur, Y. and Zemel, A. (1996). “Accounting for global warming risks: Resource management under event uncertainty”, *Journal of Economic Dynamics and Control*, vol. 20, pp. 1289-1305.

Tsur, Y. and Zemel, A. (1998). “Pollution control in an uncertain environment”, *Journal of Economic Dynamics and Control*, vol. 22, pp. 967-975.

Uff, J. (1996). *Water Supply in Yorkshire: Report of the Independent Commission of Inquiry*. Leeds: Yorkshire Water Services Ltd.

Ulph, A. (1998). “Learning about global warming”, in (N. Hanley and H. Folmer, eds.) *Game Theory and the Environment*, Cheltenham: Edward Elgar, pp. 255-286.

Ulph, A. (2002a). “International environmental agreements with a stock pollutant, uncertainty and learning”, Discussion Paper 0207, Department of Economics, University of Southampton, http://www.socsci.soton.ac.uk/economics/Research/Discussion_Papers/2002/0207.pdf

Ulph, A. (2002b). “International environmental agreements, uncertainty and learning – The case of stock-dependent unit damage costs”, Discussion Paper 0208, Department of Economics, University of Southampton, http://www.socsci.soton.ac.uk/economics/Research/Discussion_Papers/2002/0208.pdf

Ulph, A. (2004). “Stable international environmental agreements with a stock pollutant, uncertainty and learning”, *Journal of Risk and Uncertainty*, vol. 29, pp. 53-73.

Ulph, A. and Ulph, D. (1997). “Global warming, irreversibility and learning”, *Economic Journal*, vol. 107, pp. 636-650.

Van Asselt, M. and Rotmans, J. (1999). “Uncertainty in integrated assessment modelling: A bridge over troubled water”, mimeo.

Wright, E. L. (2000). *Catastrophe, Uncertainty, and the Costs of Climate Change Damages*, Ph.D. Dissertation, Department of Economics, Rensselaer Polytechnic Institute, Troy, NY.

Wright, E. L. and Erickson, J. D. (2003a), “Climate variability, economic adaptation, and investment timing”, *International Journal of Global Environmental Issues*, vol. 3, pp. 357 – 368.

Wright, E. L. and Erickson, J. D. (2003b). “Incorporating catastrophes into integrated assessment: Science, impacts, and adaptation”, *Climatic Change*, vol. 57, pp. 265-286.

Yohe, G. W. and Toth, F. L. (2000). “Adaptation and the guardrail approach to tolerable climate change”, *Climatic Change*, vol. 45, pp. 108-128.

Yohe, G. W. (1996). “Exercises in hedging against extreme consequences of global change and the expected value of information”, *Global Environmental Change*, vol. 6, pp. 87-10.

Yohe, G. W. (2000). “Assessing the role of adaptation in evaluating vulnerability to climate change”, *Climatic Change*, vol. 46, pp. 371-390.

Yohe, G. W. (2001). “Mitigative capacity - The mirror image of adaptive capacity on the emissions side”, *Climatic Change*, vol. 49, pp. 247-262.

Yohe, G. W. (2003). “Estimating benefits: Other issues concerning market impacts”, OECD Workshop on the Benefits of Climate Policy: Improving Information for Policy Makers.

Yohe, G. W. (2003). “More trouble for cost-benefit analysis”, *Climatic Change*, vol. 56, pp. 235-244.

Yohe, G. W. and Tol, R. S. J. (2002). “Indicators for social and economic coping capacity – Moving toward a working definition of adaptive capacity”, *Global Environmental Change*, vol. 12, pp. 25-40.

Tyndall°Centre
for Climate Change Research

The inter-disciplinary Tyndall Centre for Climate Change Research undertakes integrated research into the long-term consequences of climate change for society and into the development of sustainable responses that governments, business-leaders and decision-makers can evaluate and implement. Achieving these objectives brings together UK climate scientists, social scientists, engineers and economists in a unique collaborative research effort.

The Tyndall Centre is named after the 19th century UK scientist John Tyndall, who was the first to prove the Earth's natural greenhouse effect and suggested that slight changes in atmospheric composition could bring about climate variations. In addition, he was committed to improving the quality of science education and knowledge.

The Tyndall Centre is a partnership of the following institutions:

University of East Anglia
University of Manchester
University of Southampton
University of Sussex
University of Oxford
University of Newcastle

The Centre is core funded by the following organisations:

Natural Environmental Research Council (NERC)
Economic and Social Research Council (ESRC)
Engineering and Physical Sciences Research Council (EPSRC)

For more information, visit the Tyndall Centre Web site (www.tyndall.ac.uk) or contact:

Communications Manager
Tyndall Centre for Climate Change Research
University of East Anglia, Norwich NR4 7TJ, UK
Phone: +44 (0) 1603 59 3906; Fax: +44 (0) 1603 59 3901
Email: tyndall@uea.ac.uk

Recent Tyndall Centre Technical Reports

Tyndall Centre Technical Reports are available online at http://www.tyndall.ac.uk/publications/tech_reports/tech_reports.shtml

- Barker T. and Köhler J., (2007) **Creating an integrated UK energy-economy-emissions model for the Tyndall Centre E3MG-UK Project T3.2A:** Tyndall Centre Technical Report No. 54.
- Anderson D., Barker T., Foxon T., Pan H., Warren R. and Winne S., (2007) **Linking air pollution with climate change:** Tyndall Centre Technical Report No. 53.
- Arnell N. and Osborn T., (2007) **Interfacing climate and impacts models in integrated assessment modelling:** Tyndall Centre Technical Report No. 52.
- Warren R., de la Nava Santos S., Ford R., Riley G., Bane M., Barton C., and Freeman L., (2007) **SoftIAM: Integrated assessment modelling using distributed software components:** Tyndall Centre Technical Report No. 51.
- Challenor, P., (2007) **Estimating uncertainty in future assessments of climate change:** Tyndall Centre Technical Report No. 50.
- O'Riordan T., Watkinson A., Milligan J, (2006) **Living with a changing coastline: Exploring new forms of governance for sustainable coastal futures:** Tyndall Centre Technical Report No. 49.
- Anderson K., Bows A., Mander S, Shackley S., Agnolucci P., Ekins P., (2006) **Decarbonising Modern Societies:Integrated Scenarios Process and Workshops**, Tyndall Centre Technical Report 48.

- Gough C., Shackley S. (2005) **An integrated Assesment of Carbon Dioxide Capture and Storage in the UK**. Tyndall Centre Technical Report 47.
- Nicholls R., Hanson S., Balson P., Brown I., French J., Spencer T., (2005) **Capturing Geomorphological Change in the Coastal Simulator**, Tyndall Centre Technical Report 46
- Weatherhead K, Knox J, Ramsden S, Gibbons J, Arnell N. W., Odoni, N, Hiscock K, Sandhu C, Saich A., Conway D, Warwick C, Bharwani S, (2006) **Sustainable water resources: A framework for assessing adaptation options in the rural sector**, Tyndall Centre Technical Report 45
- Weatherhead K, Knox J, Ramsden S, Gibbons J, Arnell N. W., Odoni, N, Hiscock K, Sandhu C, Saich A., Conway D, Warwick C, Bharwani S, (2006) **Sustainable water resources: A framework for assessing adaptation options in the rural sector**, Tyndall Centre Technical Report 44
- Lowe, T. (2006) **Vicarious experience vs. scientific information in climate change risk perception and behaviour: a case study of undergraduate students in Norwich, UK**, Tyndall Centre Technical Report 43
- Atkinson, P, (2006) **Towards an integrated coastal simulator of the impact of sea level rise in East Anglia: Part B3- Coastal simulator and biodiversity - Modelling the change in wintering Twite Carduelis flavirostris populations in relation to changing saltmarsh area,** Tyndall Centre Technical Report 42B3
- Gill, J, Watkinson, A. and Sutherland, W., (2006) **Towards an integrated coastal simulator of the impact of sea level rise in East Anglia: Part B2- Coastal simulator and biodiversity - models of biodiversity responses to environmental change** Tyndall Centre Technical Report 42B2
- Ridley, J., Gill, J, Watkinson, A. and Sutherland, W., (2006) **Towards an integrated coastal simulator of the impact of sea level rise in East Anglia: Part B1- Coastal simulator and biodiversity - Design and structure of the coastal simulator** Tyndall Centre Technical Report 42B1
- Stansby, P., Launder B., Laurence, D., Kuang, C., and Zhou, J., (2006) **Towards an integrated coastal simulator of the impact of sea level rise in East Anglia: Part A- Coastal wave climate prediction and sandbanks for coastal protection** Tyndall Centre Technical Report 42A
- Lenton, T. M., Loutre, M. F, Williamson, M. S., Warren, R., Goodess, C., Swann, M., Cameron, D. R., Hankin, R., Marsh, R. and Shepherd, J. G., (2006) **Climate change on the millennial timescale**, Tyndall Centre Technical Report 41
- Bows, A., Anderson, K. and Upham, P. (2006) **Contraction & Convergence: UK carbon emissions and the implications for UK air traffic**, Tyndall Centre Technical Report 40
- Starkey R., Anderson K., (2005) **Domestic Tradeable Quotas: A policy instrument for reducing greenhouse gas emissions from energy use**:, Tyndall Centre Technical Report 39
- Pearson, S., Rees, J., Poulton, C., Dickson, M., Walkden, M., Hall, J., Nicholls, R., Mokrech, M., Koukoulas, S. and Spencer, T. (2005) **Towards an integrated coastal sediment dynamics and shoreline response simulator**, Tyndall Centre Technical Report 38
- Sorrell, S. (2005) **The contribution of energy service contracting to a low carbon economy**, Tyndall Centre Technical Report 37
- Tratalos, J. A., Gill, J. A., Jones, A., Showler, D., Bateman, A., Watkinson, A., Sugden, R., and Sutherland, W. (2005) **Interactions between tourism, breeding birds and climate change across a regional scale**, Tyndall Centre Technical Report 36
- Thomas, D., Osbahr, H., Twyman, C., Adger, W. N. and Hewitson, B., (2005) **ADAPTIVE: Adaptations to climate change amongst natural resource-dependant societies in the developing world: across the Southern African climate gradient**, Tyndall Centre Technical Report 35
- Arnell, N. W., Tompkins, E. L., Adger, W. N. and Delany, K. (2005) **Vulnerability to abrupt climate change in Europe**, Tyndall Centre Technical Report 34

- Shackley, S. and Anderson, K. et al. (2005) **Decarbonising the UK: Energy for a climate conscious future**, Tyndall Technical Report 33
- Halliday, J., Ruddell, A., Powell, J. and Peters, M. (2005) **Fuel cells: Providing heat and power in the urban environment**, Tyndall Centre Technical Report 32
- Haxeltine, A., Turnpenny, J., O'Riordan, T., and Warren, R (2005) **The creation of a pilot phase Interactive Integrated Assessment Process for managing climate futures**, Tyndall Centre Technical Report 31
- Nedic, D. P., Shakoor, A. A., Strbac, G., Black, M., Watson, J., and Mitchell, C. (2005) **Security assessment of futures electricity scenarios**, Tyndall Centre Technical Report 30
- Shepherd, J., Challenor, P., Marsh, B., Williamson, M., Yool, W., Lenton, T., Huntingford, C., Ridgwell, A and Raper, S. (2005) **Planning and Prototyping a Climate Module for the Tyndall Integrated Assessment Model**, Tyndall Centre Technical Report 29
- Lorenzoni, I., Lowe, T. and Pidgeon, N. (2005) **A strategic assessment of scientific and behavioural perspectives on 'dangerous' climate change**, Tyndall Centre Technical Report 28
- Boardman, B., Killip, G., Darby S. and Sinden, G, (2005) **Lower Carbon Futures: the 40% House Project**, Tyndall Centre Technical Report 27
- Dearing, J.A., Plater, A.J., Richmond, N., Prandle, D. and Wolf , J. (2005) **Towards a high resolution cellular model for coastal simulation (CEMCOS)**, Tyndall Centre Technical Report 26
- Timms, P., Kelly, C., and Hodgson, F., (2005) **World transport scenarios project**, Tyndall Centre Technical Report 25
- Brown, K., Few, R., Tompkins, E. L., Tsimplis, M. and Sortti**,** (2005) **Responding to climate change: inclusive and integrated coastal analysis**, Tyndall Centre Technical Report 24
- Anderson, D., Barker, T., Ekins, P., Green, K., Köhler, J., Warren, R., Agnolucci, P., Dewick, P., Foxon, T., Pan, H. and Winne, S. (2005) **ETech+: Technology policy and technical change, a dynamic global and UK approach**, Tyndall Centre Technical Report 23
- Abu-Sharkh, S., Li, R., Markvart, T., Ross, N., Wilson, P., Yao, R., Steemers, K., Kohler, J. and Arnold, R. (2005) **Microgrids: distributed on-site generation**, Tyndall Centre Technical Report 22
- Shepherd, D., Jickells, T., Andrews, J., Cave, R., Ledoux, L, Turner, R., Watkinson, A., Aldridge, J. Malcolm, S, Parker, R., Young, E., Nedwell, D. (2005) **Integrated modelling of an estuarine environment: an assessment of managed realignment options**, Tyndall Centre Technical Report 21
- Dlugolecki, A. and Mansley, M. (2005) **Asset management and climate change**, Tyndall Centre Technical Report 20
- Shackley, S., Bray, D. and Bleda, M., (2005) **Developing discourse coalitions to incorporate stakeholder perceptions and responses within the Tyndall Integrated Assessment**, Tyndall Centre Technical Report 19
- Dutton, A. G., Bristow, A. L., Page, M. W., Kelly, C. E., Watson, J. and Tetteh, A. (2005) **The Hydrogen energy economy: its long term role in greenhouse gas reduction**, Tyndall Centre Technical Report 18
- Few, R. (2005) **Health and flood risk: A strategic assessment of adaptation processes and policies**, Tyndall Centre Technical Report 17
- Brown, K., Boyd, E., Corbera-Elizalde, E., Adger, W. N. and Shackley, S (2004) **How do CDM projects contribute to sustainable development?** Tyndall Centre Technical Report 16
- Levermore, G, Chow, D., Jones, P. and Lister, D. (2004) **Accuracy of modelled extremes of temperature and climate change and its implications for the built environment in the UK**, Tyndall Centre Technical Report 14
- Jenkins, N., Strbac G. and Watson J. (2004) **Connecting new and renewable energy sources to the UK electricity system**, Tyndall Centre Technical Report 13
- Palutikof, J. and Hanson, C. (2004) **Integrated assessment of the potential for change in storm activity over Europe: Implications for insurance and forestry**, Tyndall Centre Technical Report 12
- Berkhout, F., Hertin, J., and Arnell, N. (2004) **Business and Climate Change: Measuring and Enhancing Adaptive Capacity**, Tyndall Centre Technical Report 11
- Tsimplis, S. et al (2004) **Towards a vulnerability assessment for the UK coastline**, Tyndall Centre Technical Report 10

- Gill, J., Watkinson, A. and Côté, I (2004). **Linking sea level rise, coastal biodiversity and economic activity in Caribbean island states: towards the development of a coastal island simulator**, Tyndall Centre Technical Report 9
- Skinner, I., Fergusson, M., Kröger, K., Kelly, C. and Bristow, A. (2004) **Critical Issues in Decarbonising Transport**, Tyndall Centre Technical Report 8
- Adger W. N., Brooks, N., Kelly, M., Bentham, S. and Eriksen, S. (2004) **New indicators of vulnerability and adaptive capacity**, Tyndall Centre Technical Report 7
- **Macmillan, S. and Köhler, J.H., (2004) Modelling energy use in the global building stock: a pilot survey to identify available data**, Tyndall Centre Technical Report 6
- Steemers, K. (2003) **Establishing research directions in sustainable building design**, Tyndall Centre Technical Report 5
- Goodess, C.M. Osborn, T. J. and Hulme, M. (2003) **The identification and evaluation of suitable scenario development methods for the estimation of future probabilities of extreme weather events**, Tyndall Centre Technical Report 4
- Köhler, J.H. (2002). **Modelling technological change**, Tyndall Centre Technical Report 3
- Gough, C., Shackley, S., Cannell, M.G.R. (2002). **Evaluating the options for carbon sequestration**, Tyndall Centre Technical Report 2
- Warren, R. (2002). **A blueprint for integrated assessment of climate change**, Tyndall CentreTechnical Report 1