CLIMATE CHANGE, MITIGATION AND ADAPTATION WITH UNCERTAINTY AND LEARNING

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1 Introduction

How does the possibility of adaptation to climate change affect how much mitigation should be done? This short note looks at some of the issues that are involved in addressing this question. If it is the case that adaptation is an alternative to mitigation then current policy choices about how much mitigation should take place will be determined by a straightforward analysis of the relative costs and benefits of adaptation and mitigation and the relation between the two. At a technical economic level this will hinge on whether adaptation and mitigation are complements or substitutes. If they are substitutes then basically the amount of each activity will be driven by the relative prices of the two types of activities, and so if adaptation becomes a cheaper activity then more of it will be done with a consequent reduction in the amount of mitigation that would be done. On the other hand if these activities are complements, then it will not be desirable to attempt to replace one with the other. If prices change in such a way that more mitigation should be done, then more adaptation should be done also. However, more complex issues arise once we include the effects of uncertainty and learning about the Climate Change process. Then, the question of the timing of actions related to Climate Change becomes much less straightforward.

We consider five propositions concerning adaptation to Climate Change. These are

1. 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.

2. When uncertainty, that arises from learning and irreversibility, is introduced into the economic model results change fundamentally.

3. When both mitigation and adaptation are available strategies, the consequences of irreversibility are weakened

4. In general, learning about what the climate future may be will always be more important than irreversibility.

5. For the water industry there is an important learning effect concerning future 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.

2 Mitigation and Adaptation- Complements or Substitutes?

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 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 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[1]. But in this context we have sketched so far, in technical economic terms, adaptation and mitigation are *substitutes*, in the sense that if, say, the cost of adaptation fell, the optimal response would be to do *more* adaptation but *less* mitigation[2]. 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. This has obviously important policy implications. For example, early generations of models of the economic response to climate

[1] This is like an income effect with normal goods.
[2] In this context we are essentially treating mitigation as a single activity and adaptation as a single activity. Of course there are many different methods of mitigation and adaptation, and we do not claim that every form of mitigation is a substitute for every form of adaptation (or even that every form of mitigation is a substitute for every other form of mitigation, and similarly for adaptation). This claim only applies in an aggregate sense.

change tended to focus only on mitigation strategies, so can be considered as treating the costs of adaptation as infinite. Later models have given more attention to adaptation options and found them to be relatively cheap and so have concluded that there is rather less need for mitigation (see for example surveys by Mendelsohn (2003) and Tol (2003)).

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, this could not happen if adaptation and mitigation are being optimally regulated. This argument is closely related to a point made by Klein *et al.* (2003) - 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[3]. 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

[3] It is sometimes argued that mitigation is more of a public good while adaptation is more of a private good (see for example Mendelson (2000), Hanemann (2000), Kane and Shogren (2000))

referred to as a case of "mal-adaptation" 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[4].

A related issue concerns the different spatial aspects of mitigation and adaptation, with mitigation dealing with a global public good, while adaptation often provides purely local benefits. We can show that 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 of a single global social planner. This again reflects the fact that adaptation and mitigation are formally substitutes for each other. 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.

A final extension is to introduce dynamic considerations. As Klein *et al.* (2003) note mitigation and adaptation differ in their temporal aspects in

[4] Scheraga and Grambsch (1998) note that many existing policies may be sub-optimal, but do not link this to the issue of "maladaptation".

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[5].

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)

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[5] Of course with many time periods we can formally think of mitigation and adaptation at different dates as different types of mitigation and adaptation, and as noted in footnote 4, with many types of mitigation and adaptation we cannot claim that every form of mitigation is a substitute for every form of adaptation.

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.

3 Introducing Uncertainty and Learning

One of the major issues in climate change policy is how to deal with the considerable uncertainty that surrounds many of the elements needed, in terms of the scientific understanding of the processes driving climate change, for example the risk of possible catastrophic effects of climate change, the impacts of any such changes on society and the economy, the extent to which these impacts might be ameliorated by future adaptation, and the economic values to be attached to these impacts, for example the appropriate social discount rate or equity weights. This raises the obvious question of how such uncertainties should affect decisions about the current level of abatement of greenhouse gas emissions and hence about the correct amount of mitigation and adaptation.

However there is a more subtle aspect to the treatment of uncertainties. Some of these uncertainties will be resolved through the process of further research, for example as exemplified in the reports of the IPCC. This process of learning raises a crucial timing question: should society delay taking action to reduce greenhouse gas emissions in anticipation of getting better information, or should it accelerate action, because we might learn that climate change is much more serious than expected but find that by the time we learn this information we cannot make the adjustments needed because of 'irreversibility' constraints. So that there is now another reason why adaptation may be advantageous.

There are two effects. Irreversibility which acts to bring forward actions against Climate Change as well as Learning which tends to postpone such actions. The process of concentration of greenhouse gases in the atmosphere is not literally irreversible, but the usual models of climate change suggest that if emissions of CO_2 stopped, atmospheric concentrations would continue rising and only revert to current levels after 300 years, and to pre-industrial levels after 1000 years. So although there is a process of decay in CO_2 atmospheric concentrations it is extremely slow. It is this irreversibility in the climate process that leads to calls for implementing a precautionary approach – that, far from delaying taking steps to reduce greenhouse gas emissions, we should take more steps now, to guard against getting bad news in the future and finding it is too late to do anything about it.

The standard intuition is that if one is making an irreversible decision under uncertainty when there is the prospect of obtaining better information in the future, then this should reduce the extent to which one makes irreversible commitments in order to better exploit the information that will become available. In simple terms it pays to keep one's options open. This insight, which can be viewed as a formal statement of the Precautionary Principle.

In relation to climate change the Precautionary Principle would seem to imply the following. Suppose one has used standard cost-benefit analysis under uncertainty in which the social planner maximises expected utility to calculate the optimal level of current abatement of greenhouse gases. If there is the chance of getting better information, and the accumulation of greenhouse gases is irreversible, then the Precautionary Principle seems to suggest that the optimal level of abatement of greenhouse gases now should be increased; this is referred to as the 'irreversibility effect'. This decision would be reflected in the use of a higher value for the current social cost of carbon by adding to the previous calculation of the social cost of carbon a premium, which we shall refer to as a 'learning premium', which reflects the benefit of reducing the extent of irreversible accumulation of greenhouse gases so as to be better able to exploit new information when it becomes available.

However, it may be the case that the prospect of obtaining better information in the future should lead to *lower* current abatement of greenhouse gases. The effect of better information, without any irreversibility constraint, may cause current emissions to be reduced or increased, and for the standard textbook model of linear marginal benefit and damage cost functions better information unambiguously causes current emissions to rise. What happens if we now introduce the irreversibility constraint? The irreversibility constraint tends to reduce current emissions. The rationale is straightforward. If, in some states of the world, the irreversibility constraint bites, this must increase expected marginal damage costs of current emissions, so making it desirable to cut current emissions relative to the situation where no irreversibility constraint is imposed

Returning then to the problem where there is both better information and an irreversibility constraint we have two effects which may go in different directions. If the prospect of getting better information would cause decision-makers to cut current emissions then adding the irreversibility constraint just reinforces this. But if the prospect of getting better information leads decision-makers to increase current emissions without an irreversibility effect then adding the irreversibility constraint gives an offsetting effect, and the overall effect is ambiguous. Can this ambiguity be resolved? Intuitively this should depend on just how severely the irreversibility constraint bites.

Other irreversibilities can arise. Suppose the precautionary principle holds for the 'environmental irreversibility', so that with the prospect of better information the decision-maker would want to reduce current build-up of irreversible emissions of greenhouse gases. If the reduction of emissions of greenhouse gases involved investing in specific forms of abatement capital (e.g. investments in tidal energy, nuclear power plants etc), which could not be easily converted to other purposes if we subsequently learn that climate change is not as serious as expected, then the same precautionary principle suggests that, if we expect to get better information in the future, we should reduce the level or date of implementation of our investment in such irreversible forms of capital. So, even if we accept the precautionary principle, we have two irreversibilities which go in opposite directions. Which one is stronger is an empirical issue, but, in general, the abatement capital irreversibility dominates the environmental irreversibility

On the other hand there is the impact of significant inertia or costs of adjustment in the use of capital which generates greenhouse gases, and show that this will lead to increasing current abatement of greenhouse gas emissions to avoid the future costs of rapidly increasing abatement if it is necessary to meet some critical target level of greenhouse gas concentrations.

The general point then is that it will be the balance between the different sources of irreversibilities that will determine the extent to which current emissions of greenhouse gases with learning and irreversibilities should be higher or lower than the level which ignores learning and irreversibilities. To summarise, even with the simplest specification of a climate change problem, economic analysis does not provide general support for the precautionary principle that, faced with the prospect of obtaining better information, the correct response is to reduce current irreversible actions. It can be the case, for quite standard models, that the correct response to the anticipation of getting better information is to increase current emissions. What the correct response should be cannot be deduced just from general theoretical arguments, but is an empirical matter.

Irreversibility by itself will always lead to the need for more mitigation now if the irreversibility constraint bites in the future. How the prospect of future learning affects current policy, in the absence of any irreversibility constraint, is in general ambiguous, and depends on the social planners attitudes to risk. In a conventional textbook model of quadratic damage and mitigation costs, the effect of learning is to reduce the need for current action. However, when the two effects are combined, even in the simple textbook model of quadratic costs, the effects of learning on current policy are ambiguous.

4 Adaptation

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. In a particular model, the irreversibility constraint became irrelevant, and the prospect of future learning unambiguously leads to less current action to deal with climate change.

We now turn to see what the empirical literature has to say. All the empirical work we are aware of deal with models where the only policy instruments are controls on emissions of greenhouse gases. This literature generally concludes that the prospect of getting better information should lead to a small reduction in current abatement levels. However this conclusion depends importantly on the particular utility functions ascribed to policy-makers. We are not aware of any empirical model which looks at optimal adaptation and mitigation with uncertainty, learning and mitigation. 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. The main criticism is that such modelling ignores the process of learning.

One empirical study that does analyse how learning affects adaptation is that of Kelly, Kolstad and Mitchell(2002
). Whilst we believe that this analysis of learning 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. 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 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.

5 Case Studies for the England and Wales Water Supply Industry

In previous sections we 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 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.

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. 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 two main case studies reported here are for data based very loosely on situations involving Yorkshire Water, and Thames Water. We look at choices that might be made between different types of extra capacity, for example, a new large reservoir, with usual public controversy, and a new de-salination plant. Also, 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. 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. 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 (2004), 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 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. 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

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 a very 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.

6. Policy Implications and Conclusions

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.

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