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ANALYSIS

Weathering climate change: some simple rules to guide adaptation decisions

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Abstract

This paper discusses some of the elements that may characterise an efficient strategy to adapt to a changing climate. Such a strategy will have to reflect the long time horizon of, and the prevailing uncertainties about, climate change. An intuitively appealing approach therefore seems to be to enhance the flexibility and resilience of systems to react to and cope with climate shocks and extremes, as well as to improve information. In addition, in the case of quasi-irreversible investments with a long lifetime (e.g. infrastructure investments, development of coastal zones), precautionary adjustments may be called for to increase the robustness of structures, or to increase the rate of depreciation to allow for earlier replacement. Many of these measures may already have to be considered now, and could be worthwhile in their own right, independent of climate change considerations.

Keywords: Climate change adaptation

1. Introduction

It is common to distinguish between two basic responses to climate change: mitigation and adaptation. Trade-offs between the costs of mitigation, the costs of adaptation and the impacts of the enhanced greenhouse effect not covered by either mitigation or adaptation guide the choice between policy strategies for climate change. Both mitigation and adaptation pose significant analytical and policy challenges, yet the respective discussions have evolved at a different pace so far. The study of mitigation measures is well under way and the analysis is continuously refined (cf. Hour-

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cade et al., 1996; Watson et al., 1996). Understanding is likely to increase further now that measures are starting to be implemented.[1] Adaptation options, in contrast, have been the subject of much fewer studies.

Adaptation has mainly been studied in the context of impact analysis, where some understanding of society's adaptive potential is needed to better understand the consequences of unabated climate change (see Smith et al., 1996 and Tol et al., 1998 for surveys). Knowledge about climate change impacts and vulnerability is accumulating, although progress is hampered by the complexity of the problem and the lack of empirical material. Pearce et al. (1996) and Watson et al. (1996) survey the impacts and vulnerability literature which typically assumes little or no adaptation. The adaptation-specific literature has identified an increasing number of adaptation options (see Office of Technology Assessment, 1993 Smit, 1993, also Watson et al., 1996) and methods for their assessment are being developed (e.g. Carter et al., 1994; Smith and Quan Chu, 1994; Fankhauser, 1996; US Country Studies Program, 1996; Mendelsohn and Bennett, 1997; Smith et al., 1997; Yohe and Neumann, 1997). While policy issues have been touched upon by some authors (e.g. Magalheas, 1996; Callaway et al., 1997; Downing et al., 1997; Frederick, 1997; Frederick et al., 1997; Major and Frederick, 1997; Smith, 1997), a thorough discussion of strategic policy issues has been lacking so far, leaving the field to unproven assertions and commonplace statements.

In this paper, we try to substantiate or repudiate some of these statements. Starting from first principles, the paper develops some basic rules of how adaptation could be designed to be efficient—so that the negative effects of climate change are minimised (and positive effects maximised). A wide variety of adaptation options has been put forward, with mostly differing characteristics. The paper starts with a classification of available options, and discusses how the different types of measures interact (Section 2).

One often heard statement is that, with a significant change in climate not expected for at least another two decades, there is no need for immediate adaptation. In Section 3, we discuss this point of view and analyse the optimal timing of adaptation measures. We argue that for long-lived investments, and investments sensitive to rapidly changing climate parameters (primarily extreme weather), climate change needs to be accounted for already in today's investment decisions, especially since weather extremes could be noticed much earlier than changes in mean climate (e.g. Katz and Brown, 1992). Weather-sensitive, long-lived investments particularly comprise infrastructure for water management. Forest plantations, (rail)roads and buildings are also long-lived, and may be vulnerable to changing weather conditions. Arguably, development plans (e.g. for cities), laws and regulations (e.g. for water allocation), and knowlegde bases (e.g. agricultural RD&D), although less tangible, are also long-lived and sensitive to changes in weather regimes.

The paper then goes on to discuss how investment decisions could account for a potential change in climate or weather parameters during the lifetime of a project. We argue that, given the prevailing uncertainty, the best way to account for potential climate change would be to increase the flexibility of systems to function under a wider range of climatic conditions, as well as their robustness to withstand more severe climatic shocks (Section 4). The same basic principles also hold for planning, as we briefly discuss in Section 5.

Another often heard assertion is that adaptation will be largely autonomous and will not require advance strategic policy intervention. We argue that, while individuals can certainly be expected to make adaptations to climate change, it is not certain that they will have the incentive, resources, knowledge and skills to adjust appropriately. Successful adaptation to a large extent depends on three elements: timely recognition of the need to adapt, an incentive to adapt, and

[1] To date, measures specifically aimed at carbon abatement have by and large been limited to fiscal measures and renewable energy programmes in some developed countries, and project work in developing countries undertaken by organisations such as the Global Environment Facility and, more recently, in the context of the pilot phase for Activities Implemented Jointly.

ability to adapt. Timely recognition requires access to reliable and detailed information, and the ability to process such information. Section 6 deals with these issues and the role of research and monitoring. Proper incentives and an environment that allows economic agents to adjust are areas in which governments typically have a large stake. Section 7 discusses the role of government in climate change adaptation. It also discusses which tasks need to be carried out by the public sectors, and which can be safely left to individual agents.

The analysis makes clear that, while the impact of climate change on a regional scale remains uncertain, and the increase in mean temperature expected over the next few decades may be relatively modest, it would be shortsighted to postpone adaptive actions until impacts are better understood or more strongly felt. The paper therefore concludes with a series of anticipatory adaptation measures that could be considered now.

The paper is analytical rather than empirical. Worked examples of decision analysis about adaptation can be found in Smith et al. (1998). Historical perspectives on adaptation can be found in Lamb (1982), Langen and Tol (1996) and Wigley et al. (1981). Adaptation studies focusing on the recent past and current situation include Downing et al. (1997), Miller et al. (1997) and Smit et al. (1997). Adaptation to weather variability, particularly weather-related natural disasters, has a long tradition of study (see, for example, Alexander, 1993; Burton et al., 1993).

2. Types of adaptation

To better understand the diversity of adaptation measures and to be able to develop a framework of analysis, it is useful to classify adaptive responses and to distinguish different generic types of adaptation.

2.1. Reactive and anticipatory adaptation

The distinction between reactive and anticipatory adaptation is of particular importance. Reactive adaptation measures are those that institutions, individuals, plants and animals are likely to make in response to climate change, after the fact. Anticipatory adaptations are deliberate decisions to prepare for potential effects of climate change (Smith, 1997). Anticipatory measures are taken in advance of climate change, before the fact. Intuitively, the distinction between reactive and anticipatory adaptation is clear. Climate change is a continuous process, however, and so is adaptation. In practice, it may therefore be hard to delineate before and after.

Anticipation requires foresight and planning, whereas reaction does not require but may involve foresight and planning. For example, in reaction to the floods of the Meuse and the near-floods of the Rhine, the government of The Netherlands decided on a long programme of river flood protection improvement that included climatic change in its design. Suppose the Meuse floods were partly climate-change induced (an assertion that cannot be proven). In this case, the action by the Dutch government would have been fully anticipatory had it heeded earlier warnings and acted before the floods. It would have been fully reactive if only current and past flood regimes had been considered in the flood improvements. In reality, it was a mixture of reaction and anticipation.

2.2. Autonomous and planned adaptation

This provides the connection to another classification: autonomous versus planned adaptation. Carter et al. (1994) define autonomous adaptation as ‘natural or spontaneous adjustments in the face of a changing climate’. Planned adaptation, on the other hand, requires conscious intervention. Again, the distinction is intuitively clear, but may be blurred in practice. Migration of species to new locations in response to climate change is clearly an example of autonomous adaptation. Farmers switching crops and management practices is autonomous adaptation from the perspective of their government, but planned from a farmer’s viewpoint. A research project to improve long-term weather forecasting would be a form of planned adaptation.

Planned adaptation can directly reduce the negative impacts of climate change. One example is building sea walls. In addition, planned adaptation may also be used to influence (autonomous) adaptation by other actors (Smith and Lenhart, 1996).

2.3. Substitutes and complements

To describe the interlinkage between anticipatory/planned and reactive/autonomous adaptation it is useful to distinguish between measures that are substitutes and those that are complements to each other.

If the two types of adaptation are 'complementary'—i.e. if anticipatory adaptation increases the marginal benefit of reactive adaptation and vice versa—additional anticipatory measures can be used to leverage the scope for subsequent reactive action. Removing crop subsidies, for instance, will enable changes in supply and demand for crops to be more readily seen in crop prices, which will enable farmers to react more quickly to climate change (Lewandrowski and Brazee, 1993) and force non-reactive farmers out of business.[2] Conversely, if for some reason it is believed that no advantage will be taken of anticipatory measures in the future, such efforts will not be worthwhile. Research into heat-resistant crops, for example, would be futile if farmers are unlikely to use the new varieties.

If anticipatory and reactive measures are substitutes, on the other hand, anticipatory adaptation may reduce the need for subsequent reactive action. In that case, additional anticipatory measures can be put in place to compensate for the absence of reactive adaptation. For example, protecting a certain stretch of coast may reduce the inclination of people at other stretches to adapt because they expect the government to help them out. The balance between anticipatory/planned and reactive/autonomous adaptation thus depends on the exact relationship between the particular measures under consideration.

3. The timing of adaptation measures

It is assumed by some that specific measures to adapt to climate change will not be necessary for several decades (e.g. Goklany, 1995).[3] While this may apply to some specific types, or perhaps even the majority of investments, the question remains as to how the optimal date of implementation should be determined in general.

3.1. The optimal investment timing

In a cost–benefit set-up, an investment should be delayed as long as the benefits of delay (avoided investment costs) are greater than the associated costs (higher climate change damages). For example, suppose an adaptation investment of C^N now leads to unmitigated damage of d_0^N in period 0, and a stream of partially mitigated damages d_t^N from period 1 onward ($t = 1,2,\ldots$).[4] If r is the discount rate, the net present value damage (NPV D^N) associated with this investment is:

$$\text{NPV } D^N = C^N + d_0^N + \frac{d_1^N}{(1+r)} + \frac{d_2^N}{(1+r)^2} + \cdots + \frac{d_t^N}{(1+r)^t} + \cdots \quad (1)$$

In comparison, postponing adaptation (i.e. doing an investment of C^L one period later) would lead to unmitigated damages in periods 0 and 1 (denoted d_0^L and d_1^L, respectively), and partially mitigated damages d_t^L thereafter. This delay would be preferable if:

$$C^N \text{-} \frac{C^L}{(1+r)} > (d_0^L \text{-} d_0^N) + \frac{(d_1^L \text{-} d_1^N)}{(1+r)} + \frac{(d_2^L \text{-} d_2^N)}{(1+r)^2} + \cdots + \frac{(d_t^L \text{-} d_t^N)}{(1+r)^t} + \cdots \quad (2)$$

[2] Recall that climate change is believed not to threaten global food supply (Reilly et al., 1996). If it were, there may be a case for agricultural subsidies to keep food prices low and maintain agricultural know-how. Income subsidies, however, would do, and avoid distorting price signals for adaptation.

[3] Yohe (1991) concluded that 'planning to take early action' to adapt to climate change is preferred.

[4] For simplicity, we assume that the project is infinitely lived.

The left-hand side of this equation denotes the cost savings (i.e. the benefits) from the delay, and the right-hand side the increase in damage over time (i.e. the costs of the delay). In the easiest case, where there is no change in investment costs and the delay has no lasting effects beyond period 1,[5] the trade-off is simply between the cost of an additional period of unmitigated damage and the return, r, earned on the capital while implementation is delayed. Delay is then worthwhile if:

$$rC > d_1^L\text{-}d_1^N \quad (3)$$

However, in other cases C^L may be greater than C^N, for example, if a device has to be retrofitted to capital installed in period 0; or it may be smaller, say, because of technical progress. It is also possible that delay has irreversible effects that cannot subsequently be reversed. For example, a cultural sight in a coastal city may be irreparably damaged in a storm before protection measures are in place. In all these cases, the decision on timing should be guided by the more comprehensive rule, and it is unclear how long adaptation investments can be postponed. What can be said, though, is that early adaptation is more likely to be relevant for long-lived investments, measures with a long lead time, and measures where subsequent retrofitting would be expensive.

3.2. Uncertainty and extreme weather events

Uncertainty and the effect of weather extremes further complicate the timing decision. Adaptive structures, as most climate-sensitive investments, tend to be designed with respect to weather extremes—i.e. the tails of the probability distribution. If we think of weather extremes as the exceedence of a certain threshold (say, temperatures above 35°C), then weather extremes may change much faster than weather means. This is a basic given in probability theory (e.g. Katz and Brown, 1992) and demonstrated in many studies (e.g. Knox, 1993; Kwadijk and Middelkoop, 1994; Downing et al., 1996).[6]

Thus, it is quite possible that changes in weather extremes, such as crossing certain thresholds, will be noticed much earlier than changes in mean climate. Natural resources will most likely be coping with changes in weather extremes before there is any consensus about changes in mean climate. This implies that we may well be witnessing climatic changes over the next decades. Indeed, some empirical studies find changes in extreme weather for the recent past—for example, precipitation intensity in the USA in the last century (Karl et al., 1995 Karl et al., 1996)—although attribution to the enhanced greenhouse effect is problematic. Therefore, weather-sensitive investments that are made now and that are meant to remain in function for a couple of decades should take notice of a possible change in climate.

4. Adjustments in the capital stock

In a majority of cases, adaptation will probably not involve investments in climate change-specific structures, but the replacement of one type of capital by another. How does the possibility of future climate change affect investment decisions?

4.1. Climate change and capital productivity

Investments in climate-sensitive capital need to take into account the entire climatic future of the investment. This is specially the case for the design of longer-lived investments (National Academy of Sciences, 1992). Also, climate change needs to be duly considered in the design of investments that are sensitive to faster-changing weather parameters such as flooding. Although conceptually distinct, the two criteria come together in practice.

Climate change matters if the weather parameters to which the investment is sensitive change significantly during the lifetime of the investment,

[5] That is, $C^N = C^L = C$ and $d_t^N = d_t^L$ for $t > 1$. Also note that damage in period 0 remains unmitigated in both scenarios, i.e. $d_0^L = d_0^N$ in any case.

[6] Note that extremes may change either way—i.e. become worse or better. Note also that composite extremes (e.g. runs of dry or wet years) may change faster still than single extremes.

or may change with a large enough probability.[7] Consider an investment in a weather-sensitive project, say in water resources or agriculture. The planned piece of infrastructure or machinery will be designed for a certain range of weather conditions, under which it can be trusted to perform properly. However, if weather deviates too much from normal, performance declines. In really extreme weather situations, functioning breaks down completely and damage may be done. As climate starts changing, the actual weather regime will increasingly differ from the design weather regime; that is, anomalous and extreme weather will occur ever more frequently, and, as a result, the performance of the investment decreases until it eventually becomes unsatisfactory.

The challenge thus is to keep the design of the capital stock in tune with prevailing climate conditions, taking into account that these conditions are likely to change continuously, but in an uncertain way. This can either be done by replacing capital more frequently, or by increasing the range of weather conditions under which the capital stock (can be made to) perform(s) well.[8]

4.2. Increasing capital turn-over

The decision about the optimal replacement time for capital is governed by the same basic rule as that on investment timing (see above equations). Capital is worth replacing if the costs of non-replacement (in the form of a lower performance) are higher than the benefit of postponed investment costs (in the form of lower capital needs). Since climate change will increase the costs of delay (by reducing the performance of existing capital), the economic lifetime and perhaps the technical lifetime of capital will be shortened.[9]

Evidently, increasing capital turn-over raises capital costs, relative to the lifetime output of the equipment. Nevertheless, the option may be attractive for existing capital, which may be relatively difficult to retrofit, or for relatively short-lived capital. Increased turn-over could also be interesting for equipment that is moveable at reasonable cost, where a second-hand market could develop over different climate zones.

In such situations, the leasing of capital goods may become more attractive than buying, as leased capital can be replaced relatively quickly, and the lessor can reduce the risk by doing business in a variety of climates, shifting technologies from one location to another while holding climate approximately constant. At the same time, doing business in a variety of climates increases experience with the performance of equipment under various circumstances, thus improving the price/performance ratio. Large enough companies may seek such diversification internally.

4.3. Increased flexibility and robustness

Alternatively, capital can be made more robust and systems more flexible, so that they perform under a wider range of climate regimes. For example, the capacity of water storage systems can be increased in anticipation of future droughts, coastal protection measures can be strengthened to withstand more severe storms and floods, or equipment can be designed to allow for the possibility of mid-lifetime adjustments. Increasing the flexibility or robustness of capital of course comes at a cost. Typically, the greater the range of

[7] Note that it is *predicted* climate change that matters. Current weather follows a certain probability distribution, with a certain mean and variance. Suppose that the enhanced greenhouse effect only changes the mean, by an uncertain amount. Then, in the perception of the investor, not only the mean changes (because of climate change), but also the variance (because the mean change is uncertain). The mean could change either way, but the variance necessarily increases due to the additional uncertainty. To a forward-looking decision maker it is as if weather has become more variable, with damaging extremes occurring more often. This additional uncertainty alone is sufficient reason to adjust the design of the investment.

[8] Matalas (1997) in contrast argues for a 'wait and see' approach as the best way to address uncertainty about the future. He concludes that it is best to delay making important and irreversible investments.

[9] Rogers (1997) implies that taking into account faster growth in demand for water could lead water-resource planners to tap new reservoirs in shorter time intervals. Reductions in supply because of climate change could have the same effect as increases in demand.

acceptable climates, the higher the necessary investments and/or the lower the overall performance. On the other hand, precautionary adjustments in design will often be cheaper, even under uncertainty, than running the risk of premature scrapping or expensive retrofitting. This will particularly be the case for long-lived, quasi-irreversible investments like irrigation and sanitation systems, bridges, or dams. The trade-off is again governed by the basic equations above.

Which option, or mix of options—accelerated capital turn-over or increasing the tolerance to a wider range of climatic conditions—is chosen ultimately depends on the relative costs of each alternative, and may vary from case to case. However, since adjustments in design have to be decided ex ante, whereas replacement decisions can be reviewed continuously, early adaptation efforts are likely to focus on increasing the flexibility and robustness of systems to changes in climatic conditions.

In either case, as weather conditions become more uncertain, the uncertainty about the performance of climate-sensitive investments will also increase. In well-functioning markets, this additional risk will be translated into a higher required return on such investments. In addition, insurance premiums may rise, or insurance may be withdrawn (Tol, 1998), also reducing returns. As a result, climate-change-sensitive projects will become more difficult to finance. This in itself is, of course, an adaptive measure and (provided financial markets are well informed) helps to reduce society's exposure to climate change risks.

5. Planning

The previous sections focus on physical investments. The same arguments made above essentially also hold for long-term plans, such as those of coastal zone development, drought contingency or sustainable development. These plans need to take account of the fact that weather, and hence crop yield or tourist flows, may well differ in the future.

Like long-term investments, plans can be adjusted to make the outcome more robust to climate change, and to increase the flexibility of systems. For example, coastal zone development plans can be adjusted by discouraging development of coastal areas likely to be vulnerable to sea level rise. Or, they can be used to set aside buffer zones that would allow natural systems to migrate. Also, plans may need to be revised more frequently to account for new information on climate change (which is similar to shortening the life of capital investments).

Plans are, by definition, forward looking. They put individual investment projects into a programmatic context, and, unlike investments, they can be adjusted with minimal loss of capital. At the same time, changing plans can have significant effects on capital investments. Planning is therefore an important instrument of anticipatory adaptation.

6. Research

Another important instrument of anticipatory adaptation is research and the dissemination of information. Research can improve adaptation by providing more reliable information about climate change and its impacts, but also by developing and testing improved adaptation options and technologies.

The information needs for adaptation may require a different orientation of current knowledge, which is applicable to a wide variety of climates but at the same time assumes climate to be constant instead of variable and changing. Consider, for example, a farmer's decision on the crop varieties to plant for the following season. Under climate change, farmers will gradually have to shift to more heat-tolerant crops. These crops may have lower yields than less heat-tolerant crops in cooler weather. Given that there will still be year-to-year variability in climate, how should farmers react to an extremely warm year? Should they assume that the following year will also be warm, that the weather will go back to recent 'normals', or recent normals plus an increment? With stationary climate, farmers can base planting decisions on long-term means and variances in climate. With changing climate, these statistics may no longer be useful.

As the example illustrates, gaining better insights into climate change on a decadal scale and into long-term regional weather patterns is essential for efficient adaptation, provided that the information reaches the proper people in a timely, understandable and reliable manner. Skills in long- and short-term weather forecasts are increasing (e.g. ENSO, monsoon; National Weather Service, 1997), but short-term climate forecasts are still in their infancy. Further research on these matters may be prudent, particularly since success in science often takes a long while.

It may also take a while to convince potential clients of forecasts of the usefulness and reliability of the information provided. Successes with long-term weather forecasts may help. Related to this, decision makers need to be (made) aware of the fact that the climate is changing. Besides forecasts, trends in observations may be helpful, not only of temperature and precipitation, but also of selected indicators which are more appealing to laypersons. Examples of such indicators are blossom dates (for agriculture), snow days (for winter sport) and flood heights (for water management). Thus, it is important that information dissemination networks, such as agriculture extension services, provide data on trends on observed changes in climate and other indicators.

As we are gradually moving out of the realm of experience, research will have to point out what the weather regime is likely to be and how infrastructure or machinery will behave under it. The former is likely to be the task of numerical and statistical weather and climate forecasting. The latter can be done, for example, through research on spatial and temporal analogues. Additional engineering research may also be needed, as well as research on how to deal with the increased weather uncertainty in short-term business or investment decisions.

7. The role of government

Some authors, most prominently Mendelsohn (1997), have argued in favour of autonomous adaptation as the most efficient way to mitigate the impact of climate change. There can be no question that individuals will undertake every effort to adapt to climate change. However, they will do so within the confines of the informational, budgetary and other constraints they face. For autonomous adaptation to be effective, and to avoid maladaptation, certain preconditions therefore have to be met. Individuals have to have the right incentives, resources, knowledge and skills to adapt efficiently.

Providing a conducive environment for adaptation, including precautions that adaptation by one group does not cause harm to another, is generally regarded as the role of the state. In addition, many adaptation options (e.g. coastal defence, education) are widely considered to be a task of government. What should be the role of the state in adaptation?

7.1. Policy environment

Perhaps the main role for government will be to provide the right legal, regulatory and socio-economic environment to support autonomous adaptation.

Having the ability to adapt requires that there is room to change behaviour. Changing behaviour may be constrained by law, politics, morality or custom. Crop management practices, particularly in subsistence farming, are often guided by custom, which is sometimes enshrined in moral or religious codes (an historical example is the extinction of Christian Norwegian settlers on Greenland; Lamb, 1965). Behaviour and customs are difficult to change. This could be overcome by educating people about the risks that current behaviour and customs may pose under climate change and how they can modify their behaviour to better prepare for climate change. A generic form of adaptation is to encourage changes in behaviour through education and outreach on the risks of climate change and coping strategies.

Actors only adapt insofar as their change in behaviour results in a change in welfare. Providing the right incentives is therefore key. When market signals are distorted, what is rational for an individual may no longer be rational for society. People under- or overadapt. An example is price or income subsidies in agriculture, in which crop yield changes do not necessarily translate into income changes. Without changes in income, farmers may not adjust their behaviour, such as changing the varieties of crops they plant. Fixed allocations of water resources may lead to a similar lack of incentives to adapt. Without observing a change in price or allocation, people will have little incentive to change their behaviour. Another role of government will be to stimulate incentives to adapt quickly and rationally to climate change—for example, by removing legal and economic distortions of free markets.

7.2. Market imperfections

Adaptation requires increased investments in research, more suitable capital and the mitigation of risk (i.e. insurance, reserves, diversification). Economic theory recommends that the government's involvement in these activities be limited to circumstances where markets cannot be expected to work properly, for example, because there are natural monopolies or externalities or in the case of asymmetric information. Government intervention may, for instance, be warranted if the increased use of irrigation water by adapting farmers causes external costs by further reducing depleted supplies.[10] Government involvement may also be needed to encourage long-term investments or to improve access to capital markets for small borrowers. Imperfect information often prevents small borrowers from obtaining credit to finance adaptation investments, especially if these investments have a longer pay-back time. Interventions will further be needed in cases where markets ignore the full social costs of an activity (e.g. land prices in flood-prone areas).

The provision of public goods is also a typical area of government involvement. Adaptive measures such as coastal protection and education are good examples of activities that are likely to remain in the public sector for this reason. Measures to mitigate the adverse impacts on ecosystems, for example, by opening up migration corridors, may be another case in point.

Research also has many features of a public good, but the case is less clear. Meteorological and climatological research, like other forms of basic research, has traditionally been government funded. Not all governments place equal priorities on this, however. Furthermore, because of climate change, the commercial value of such information will rise, and more of it may be provided by the private sector. Applied research to improve the technical and economic performance of investments under different climates could also be mostly privately funded, with the state providing the right incentive framework—for example, by guaranteeing intellectual property rights. An exception may be cases where weather performance is only a minor purchasing criterion, or where individual agents are too small to perform their own research (e.g. subsistence farmers). In such cases, the government may step in and advise on investment and management decisions, perhaps in cooperation with an NGO, or encourage the formation of 'research cooperatives'.

7.3. Social policy

For a large number of people, climate change may cause considerable hardship. In addition to the adverse impacts themselves, adaptation measures, too, may be costly—for example, if marginally profitable activities become unprofitable and have to be given up. For more diversified companies, this may simply imply a change in portfolio or impacts may be eased through private insurance schemes or self-insurance. In some cases, though, climate change will threaten the livelihood of people. A social safety net will therefore have to be established to ease temporary hardship, for example, in the case of relocations. This will clearly be a role for the state, and may perhaps even require cooperation across national boundaries and between governments.

7.4. Related policy issues

A key concern in any government strategy will be the interlinkage between climate change and

[10] Note that market imperfections necessitate government intervention, but not necessarily the public provision of the good in question. For example, in the case of externalities, a corrective subsidy or tax would suffice.

other environmental and economic policy issues. Vulnerability to climate change is affected by such factors as economic and population growth, environmental policy in general and the non-climate change-related stress imposed on natural ecosystems in particular. Decisions on any of these areas therefore affect vulnerability and climate change should be a consideration when they are taken.

As an overall tendency, vulnerability may decrease as national income grows (Pearce et al., 1996; Tol, 1996). With growing income, health and educational standards will increase and the importance of climate-sensitive sectors such as agriculture may decrease. There will also be potentially more resources available to cope with climate change (e.g. build sea walls, flood control, relocate farmers). However, economic growth has to occur in an environmentally sustainable manner, or it will be in conflict with the need to reduce the mounting stress on the environment. Decreasing stress on climate-sensitive natural resources involves dealing with pressing local environmental problems such as air and water pollution, soil degradation and the protection of natural habitats. The key thus is to steer income growth into directions that reduce vulnerability to climate change rather than increasing it. Inter alia, this means limiting development in low-lying coastal areas, limiting fragmentation of forests, development in drought-prone areas, etc. Many of these measures may constitute good policy independent of climate change.

8. Conclusions

This paper discusses elements of an optimal strategy to climate change. Given the long time-span and the great uncertainty, the intuitively optimal current adaptation policy may be to enhance the flexibility or robustness particularly of long-term, quasi-irreversible investments (e.g. long-lasting infrastructure) and to intensify information and its use. Partly, these are no-regret measures.

More specifically, our analysis points to the following types of anticipatory adaptation policies that may already be considered, or at least studied, now:

- Long-term weather-sensitive capital under construction needs to be designed such that it is robust to a wider range of weather conditions than the current, or such that it can be adjusted to withstand different weather regimes.
- Existing long-term weather-sensitive capital may be depreciated faster, to set aside funds to replace it earlier than initially anticipated, or to adjust it so as to withstand a different weather regime.
- Research should be conducted on buildings, infrastructure, crops etc. that are better suited to perform well under the range of weather conditions that may occur under the enhanced greenhouse effect.
- Research should also be conducted to narrow the range of uncertainty about regional climate change over the typical lifetime of investments.
- Institutions should be built to ensure that the results of such research reach the relevant actors, and that they have the incentives and abilities to act accordingly. Two examples of such policies are improved and permanent education, and removing distortions of product and factor markets (e.g. price subsidies, access to micro-credits).
- The ability to adapt depends to a large extent on the initial ‘health’ of an actor; policies aimed at overall development or reduction of other stresses than climate change would increase the ability to adapt.
- Long-term plans such as sustainable development plans, coastal development plans and drought contingency plans should be revised to incorporate climate change. For example, sustainable development plans may not account for the possibility that crop yields change, or that farmers change crops or even location.
- Trends that will most likely make it harder for future generations to cope with climate change should be halted or reversed. Development of low-lying coastal areas and river flood plains and fragmentation of habitats may have a number of negative consequences under current climate. These trends will most likely also make future adaptation more difficult (Smith, 1997).

- Burden-sharing and insurance schemes need to be designed to cover the unavoidable mishaps that will occur in an uncertain climate future. Such schemes should on the one hand protect individuals and companies from falling into a high-impact/no-resources-left-to-adapt trap, but on the other hand preserve the incentive to adapt.

These types of adaptation are very general. Numerous ways exist to implement and combine them. Which way is chosen may differ from situation to situation. Adaptation strategies that work well in a coastal zone may fail in agriculture; a beneficial strategy for country A may be counterproductive in country B. The generic framework sketched in the above thus needs to be translated to the field level. A wide variety of decision support tools is available to support decision makers in this task.

In terms of analysis, an important task is to better understand how well reactive adaptation will work. Adopting a methodology that portrays how people will likely adapt to climate change will help in identifying the costs and shortfalls of reactive adaptation. This information can then help in designing the anticipatory strategies that will soon be needed.

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