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Adaptation in integrated assessment modeling: where do we stand?

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Abstract Adaptation is an important element on the climate change policy agenda. Integrated assessment models, which are key tools to assess climate change policies, have begun to address adaptation, either by including it implicitly in damage cost estimates, or by making it an explicit control variable. We analyze how modelers have chosen to describe adaptation within an integrated framework, and suggest many ways they could improve the treatment of adaptation by considering more of its bottom-up characteristics. Until this happens, we suggest, models may be too optimistic about the net benefits adaptation can provide, and therefore may underestimate the amount of mitigation they judge to be socially optimal. Under some conditions, better modeling of adaptation costs and benefits could have important implications for defining mitigation targets.

1 Introduction

We know that in many areas of social life—automobile safety, for instance—risks are substantially reduced through adaptive action. But we also know that adaptive behavior varies considerably between social agents, is not always "optimal," and

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can lead to perverse effects. For example, many people choose not to wear seat belts while driving, and many of those who do wear seat belts may compensate by driving faster (Adams 2006). In the last several years, researchers and policy-makers have devoted greater attention than before to the issue of adaptation within climate change policy discussions. The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) defined adaptation as adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts, to moderate potential damages or to benefit from opportunities associated with changes in climate (Smit and Pilifosova 2001). Adaptation may include reducing and transferring climate risks, as well as building the capacity make changes in the future.

As a consequence of this greater attention, adaptation policies exist, or are being developed, at a range of governance scales. Integrated analysis of adaptation can assess the costs, benefits, and uncertainties of these policies, and ought to be able to provide important insights for their development and implementation. Figure 1 presents in schematic form the relationship between damages associated with climate change and the costs and benefits of adaptation. In simple terms, adaptation reduces climate damage costs, but not to zero.

Integrated assessment models (IAMs) have become a common tool for assessing strategies to address climate change, including the costs and benefits of such strategies over time. In order to do so, these models typically combine knowledge from various disciplines in order to derive policy-relevant insights (Harremoës and Turner 2001). The models cover the cause and effect chain of climate change, including the economic activities that cause emissions, the effect of these emissions on atmospheric greenhouse gas concentrations in the atmosphere and ocean, the changes in temperature and other parameters from the increased concentrations, and the impacts of these changes on ecosystems and the economy. They analyze long time horizons—typically over 100 years—to suggest decisions to be made and strategies to be developed now. One challenge for modeling, and interpreting the results of models, is the great deal of uncertainty with respect to the costs of mitigation, climate damages, and climate adaptation (IPCC 2007; Parry et al. 2007).

Given the potential for adaptation policies playing a major role in influencing the costs of climate change—and as a consequence influencing the degree of climate change that policy-makers judge to be optimal or acceptable—it seems natural to

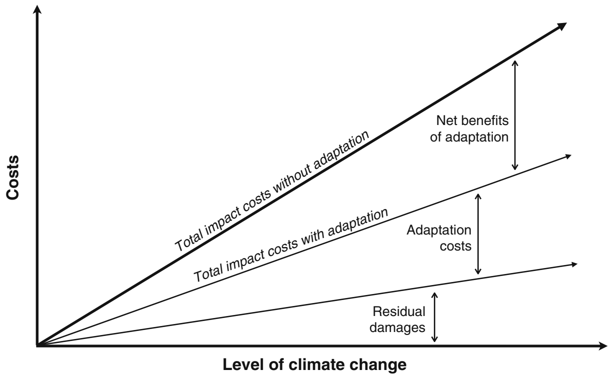

Fig. 1 Adaptation schematic from Stern (2007). The *total impact costs with adaptation* are the sum of *adaptation costs* and *residual damages*. The *net benefits of adaptation* are the amount by which these total costs are less than what they would have been in the absence of adaptation

include adaptation within integrated models. The first step in this direction has been to include assumptions about the amount of adaptation in the process of calculating the damages from climate change (Mendelsohn et al. 1994). Nordhaus and Boyer (2000, p. 4) describe the effect of this approach to calculating damages: "many of the earliest estimates ... were extremely pessimistic about the economic impacts, whereas more recent studies, which include adaptation, do not paint such a gloomy picture." Recent efforts have gone further towards making adaptation explicit by including adaptation as a specific control variable (de Bruin et al. 2009; Lecocq and Chalizi 2007). Still, there is broad agreement that more needs to be done to get adaptation better represented within IAMs (Stern 2007).

In this paper, we reflect on the direction that IAM modeling work has taken, and make suggestions for how it should proceed in order to provide advice to policy-makers that is on the one hand salient, and on the other hand not misleading. We draw special attention to the uses that IAMs can serve, and on the nature of policy processes that they reflect. We reach three main conclusions. First, we suggest that existing efforts to model adaptation overestimate the amount of adaptation that will occur and therefore also overestimate the benefits obtained from adaptation. This is primarily because they do not reflect the strongly disaggregated character of adaptation. Second, we suggest that the level of spatial detail necessary to identify the costs and benefits of adaptation measures may be more than is possible in globally oriented models, and more feasible in local or regional level analysis. Third, we suggest that the effects of including different adaptation scenarios within IAMs—the purpose of which is primarily to identify optimal mitigation pathways—is relatively minor compared to the range of uncertainty within these models. More work is necessary to verify this, but if correct then the valuable information learned from a better representation of adaptation within IAMs would not be the quantification of net benefits from adaptation, but rather the amount and distribution of adaptation costs.

2 Different IAMs and their treatment of adaptation

Very different categories of models exist within the general category of IAMs. These include process-oriented models with considerable physical detail—such as IMAGE (Bouwman et al. 2006), MiniCam (Edmonds et al. 1997), and MESSAGE (Messner and Schrattenholzer 2000)—and simpler models that focus on intertemporal cost–benefit analysis at a global scale. We focus on this latter group, because it is mainly in these models that economic consequences of adaptation have been dealt with. Models in this group typically have relatively little physical or economic detail (in order to make their calculations tractable), but instead derive estimates of both mitigation costs and climate damages at an aggregate scale. Important models within this type of integrated assessment model are DICE/RICE (Nordhaus and Boyer 2000), FUND (Tol 2002, 2005), MERGE (Manne and Richels 2004), and PAGE (Hope 2006). These models take steps to identify the potential, or even optimal, trajectories of mitigation levels, in which total climate costs are minimized and utility maximized, fulfilling the conditions that (i) marginal mitigation costs equal the sum of marginal residual damage plus marginal adaptation costs, and (ii) marginal residual damage costs equal marginal adaptation costs.

2.1 No adaptation

The first sets of analyses of the effects of climate change on human–environment systems began by exploring what would happen when anticipated climate change, such as in temperature, precipitation, and atmospheric CO_2 concentration, were used as inputs into models describing human systems sensitive to these climate variables (Parry and Carter 1989; Rosenberg 1981). Thus, if farmers in one region are growing wheat, damages would be estimated by using a crop model to assess how wheat yields change if temperature and precipitation change. This can be called the "dumb actor" approach, as it does not consider whether an actor could adapt, instead of simply accepting the climate damage. In the example provided here a farmer could shift from one type of crop to another, instead of continuing to grow wheat; shifting to maize in response to the change in climate could even raise profitability. Fairly quickly, researchers realized that this approach resulted in a worst case scenario, and that in all likelihood people would begin to adapt to climate change, thus reducing the level of damages (Rosenzweig and Parry 1994).

2.2 Implicit adaptation

The next generation of models, developed since the mid-1990s, implicitly assume the precise level of adaptation that would minimize climate damages. Tol and Fankhauser (1998) surveyed the literature in the late 1990s, and found that most models had come to consider adaptation implicitly, but not explicitly, the only explicit treatment being in the PAGE model (Hope et al. 1993). With the exception of the AD-DICE model, discussed below, this has not changed much since then. For a recent compendium of models that address adaptation, see Dickinson (2007).

How does the implicit consideration of adaptation work? In the area of agriculture, one focus sector of these models, this is done by taking a so-called "Ricardian" approach to land-use and production (Mendelsohn et al. 1994). This assumes that the production of different goods across society as a whole shifts, as the costs of inputs change, so as to continue to maximize the profits (or "rents") enjoyed by producers. The shift can occur either because an individual farmer decides to switch from wheat to maize, or because a maize growing farmer puts the wheat-growing farmer out of business; Ricardian models are not explicit about the process by which production systems change.

Econometric analysis of current and past land prices across regions with different values for key climate variables (e.g. temperature, rainfall) can suggest a statistical relationship between climate and rents. To estimate the climate damages, then, the models calculate rents under the new geographic distribution of climate inputs, based on the statistical relationships observed in the past. Outside of agriculture, it is also possible to include optimal adaptation in an ad-hoc manner. For example, to calculate the damages from sea level rise, one can calculate both the cost of lost property and infrastructure from flooding and the cost of preventing those losses by building dikes, and estimate damages as the lower of those two costs on the assumption that society will in fact build dikes if and only if doing so does minimize losses (Tol et al. 1998).

The DICE model originally based its damage estimates on Ricardian analysis, using data from the United States to calculate damages as a function of the degree of warming, and then applied that function globally. This came under criticism, since it was persuasively argued that other regions of the world would not enjoy the same opportunity to shift production, minimizing their damages (Cline 1996). To address this, the regional version of DICE, RICE, applies on a region-by-region basis either Ricardian analysis or a production function approach within a general equilibrium framework, which again assumes shifts in production to minimize losses. The newer versions of DICE, then, aggregate the regional results from RICE (Nordhaus 2008; Nordhaus and Boyer 2000). The approach for FUND is similar, developing damage functions from a large number of regional studies, each of which minimizes losses through adaptation wherever considered feasible. The other two IAMs we consider, MERGE and PAGE, are not based on this kind of bottom-up cost estimation, but rather generate damage functions by taking a weighted average of the results of other global IAMs, most importantly DICE/RICE and FUND, as well as global results published in the IPCC reports. With the exception of PAGE, all of these models, either directly or indirectly, assume optimal adaptation wherever they see adaptation as a possibility. Integrated assessment models designed for sectoral and regional studies are more detailed with respect to adaptation, but also typically attempt to model optimal adaptation (see for examples: Antle et al. 2004; Holman et al. 2005; Nicholls and Tol 2006).

It is important to note that Ricardian analysis has come under criticism, for two main reasons (Cline 1996). First, because it is a partial equilibrium (rather than general equilibrium) analysis, it does not consider changes in prices of different commodities as the entire production shifts. For example, it may be that the shifts in agriculture may require greater use of irrigation water. Even were the supply of irrigation water to remain constant under climate change, greater demand would increase its cost. This would have the effect of reducing rents, and increasing the estimated costs of climate change. Second, because the Ricardian approach ignores the process of shifting from one production system to another, it effectively ignores the frictional costs of doing so. As a thought experiment, consider that farmers in California and in the Netherlands have each figured out, over a long period of time, how to maximize their land rents given local climatic conditions, and entire production and distribution systems have co-evolved with this process. If they were to exchange climates, it would take a great amount of time and expense for them to adjust, and to enjoy the rents that the other is enjoying right now. Not only will each group of farmers need to learn new production methods, and supply chains need to be rebuilt, but the inherent uncertainty surrounding future climate change means that long-term investments cannot easily be analyzed and undertaken, as future climate change is unknown.

2.3 Explicit adaptation

The final way in which IAMs can treat adaptation is explicitly, namely by considering it as a control variable. The first model to do so was PAGE, which allowed a binary choice between no adaptation and aggressive adaptation (Hope et al. 1993). It suggested that aggressive adaptation could decrease initial climate damages by as much as 90% for economic impacts in OECD countries, 50% for economic impacts in the rest of the world, and 25% of the non-economic impacts. The estimated costs of those adaptation measures, however, has been criticized as being overly optimistic and at odds with empirical estimates (de Bruin et al. 2009). Combining their costs estimates and the estimates of the extent to which adaptation could eliminate damages, the authors reached the conclusion that a policy strategy for climate change ought to include adaptation. In turn, their conclusion that adaptation ought to be included in the modeling of a portfolio of policies has been widely accepted. Subsequent revisions to the PAGE model have not altered the basic structure of the model, or the basic parameter values (Hope 2006).

There has been surprisingly little progress, however, in including adaptation as a more nuanced control variable. Among global models, the AD-DICE model is the only example to date (de Bruin et al. 2009). The AD-DICE model, building on the DICE model, uses the existing DICE damage function, specifying damages as a quadratic function of temperature rise since 1900; parameter values are calibrated from a number of specific impact studies, each of which assumes a cost minimizing mix of adaptation and residual damage costs. Unlike DICE, AD-DICE then separates the damage function back out into the constituent elements—adaptation costs and residual damage costs—using the following restrictions in the calibration point of a doubling of CO_2-concentrations: (1) at the optimal level of adaptation, the sum of adaptation costs and residual damages correspond to the damages found in the DICE model itself; (2) at the optimal level of adaptation, adaptation costs make up 7–25% of the total damage costs (Tol et al. 1998); (3) the share of gross climate change damages avoided under optimal adaptation should be between 0.3 and 0.8 and (4) at the optimal level of adaptation, adaptation costs would comprise between 0.1% and 0.5% of GDP (Tol et al. 1998). Given that Tol et al. (1998) was a survey of a limited set of technological adaptation options, such as building sea walls to prevent coastal flooding, the costs and benefits of adaptation inherent in AD-DICE are based primarily on construction and engineering cost estimates. Additionally, they may now be out of date. From this calibration, the AD-DICE model develops an adaptation cost curve, reproduced in Fig. 2, which the authors suggest is implicit in the DICE model as originally developed and calibrated.

Figure 3 illustrates how this adaptation cost curve can then inform our thinking both with respect to the optimal level of adaptation, and the optimal level of mitigation. The left hand graph in Fig. 3 shows the adaptation cost curve, and also the corresponding residual damage cost curve, associated with a particular amount of warming, such as 2°C. The sum of these two costs is the total impact cost curve.

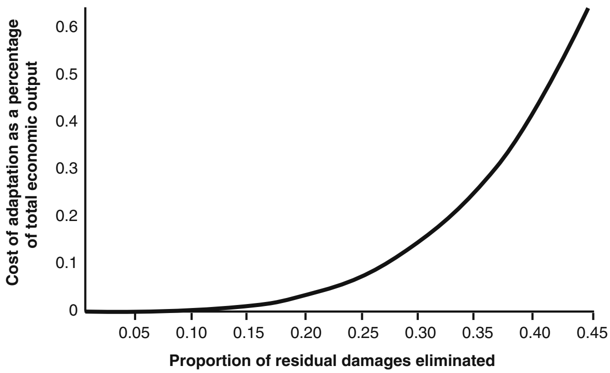

Fig. 2 Adaptation cost curve from de Bruin et al. (2009). The *horizontal axis* represents the level of adaptation, in terms of the proportion of the damages avoided through adaptive measures. The *vertical axis* represents the cost of that level of adaptation

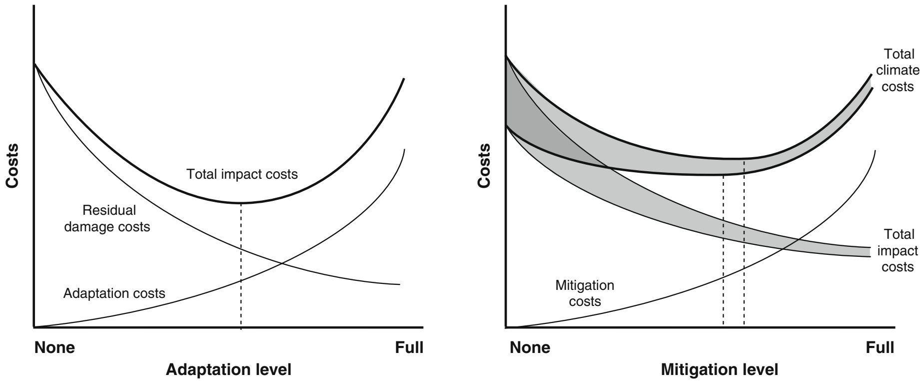

Fig. 3 Using the adaptation cost curve to identify optimal levels of adaptation and mitigation. The *left hand graph* assumes a fixed level of mitigation, and shows that the optimal level of adaptation—represented by the *dashed vertical line*—is that which minimizes the total impact costs. The fact that adaptation can vary implies a range of total impact costs associated with every possible level of mitigation, and this range is represented on the *right hand graph*. The sum of impact costs and mitigation costs in turn implies a range of total climate costs. The *right hand dashed vertical line* represents the optimal level of mitigation in the absence of adaptation, and the *left hand dashed vertical line* represents the optimal level of mitigation with optimal adaptation

The dashed line represents the optimal level of adaptation, which is where the total impact costs are at their lowest, for that amount of warming. The right hand graph shows what optimal adaptation implies for the choice of mitigation targets. There is a single mitigation cost curve, and moving from left to right along this curve brings higher mitigation costs but lower amounts of warming. Total impacts fall into a range, bounded by two curves. The lower curve represents the total impact costs attained through optimal adaptation, while the upper curve represents the total impacts costs when the level of adaptation is least optimal, either too little or too much. The width of the range will grow narrower with more mitigation, since that implies less need to adapt. Hence, total climate costs also fall into a range, again depending on the level of adaptation. The two dashed lines define the range of optimal mitigation targets. The optimal mitigation level is at its lowest when adaptation levels are optimal, and at its highest when adaptation is at its least optimal.

The results of the AD-DICE model are qualitatively similar to those of the PAGE model, in that they suggest that adaptation is an important policy option for limiting the total costs of climate change. However, the specification of the AD-DICE model allows further, quantitative, conclusions to be drawn, based on a maximization of total discounted economic output, with varying levels of both mitigation and adaptation over time as the control variables. Given the chosen model values, the model suggests that about one-third of the damages from climate change would in an optimal case be eliminated by adaptation. As a result, adaptation generates the majority of damage cost reduction before 2100, while mitigation generates the majority of damage cost reduction after 2100. The model indicates that the optimal mitigation effort with optimal adaptation is about one quarter less than the optimal mitigation effort in the absence of any adaptation: for instance, in 2050—under the DICE assumptions—it would be optimal to reduce emissions in 2050 by about 22%

from their business-as-usual level if there is no adaptation, whereas with optimal adaptation it is optimal to reduce emissions by only 16%. The authors suggest that the assumption of perfectly functioning markets, and a global adaptation function, may be a limitation of their model (de Bruin et al. 2009).

3 Modeling real adaptation processes

Optimal adaptation is not a good representation of the past, and probably is not a good representation of the future, because social and political constraints get in the way. As a paradigmatic example, the cost of protecting New Orleans from flooding that people considered to be inevitable has been estimated at up to $15 billion, for a system similar to that protecting the Netherlands (Fischetti 2006). But the choice to go ahead with such a system was never made. While inaction was progressing, Hurricane Katrina cost hundreds of lives, direct losses of over $150 billion (Burton and Hicks 2005), and indirect losses that were hard to measure, but estimated to reduce the growth of U.S. Gross Domestic Product for 2005 by between 0.5% to 1.3%, costing 400,000 jobs (Reed 2005). New Orleans is an extreme case, but nevertheless represents a well-defined problem in a wealthy country, where a single public expenditure could greatly reduce the risk, probably reducing the expected costs of climate change. Most adaptations are not so easy. In this section, we explain why.

3.1 Adaptation is mostly bottom-up

While both mitigation and adaptation involve actions of both public and private actors, the climate-related benefits of mitigation actions are enjoyed globally, while the benefits of adaptation accrue mostly to the person, organization, or community making the changes. As a result, mitigation decisions will involve top-down elements: governments agree on targets, and set policies in order to promote mitigation by private actors to meet those targets, decisions that private actors would not likely want to take in the absence of the policies. Adaptation, by contrast, is a more bottom-up driven process, in which private actors, local communities, regional and national governments need to take actions (Klein et al. 2007). Some adaptation is pro-active, such as when a homeowner decides to install air-conditioning in the anticipation of hot summers to come. Other adaptation is reactive, such as when a skier rebooks her holiday from a low elevation to high elevation resort in a year of poor snowfall. For both of these types of private adaptation, government action is often necessary in a supporting and coordinating role: for instance, to provide information, to increase benefits by a coordinated response, to regulate positive and negative side-effects from adaptation, or to provide financial support (Berkhout 2005). However, where there are broader social benefits to adaptation that markets will tend to underprovide, such as investments in science to provide better climate projections, provision of early-warning services and disaster relief, and the planning of climate-proof infrastructure, then the public sector will clearly play a more active role.

This distinction in the distribution of costs and benefits (locally versus globally) between mitigation and adaptation is fundamental when developing both predictive and normative models. For mitigation, we typically assume that targets are set centrally on the basis of a global assessment of climate damage and mitigation costs. Local circumstances may constrain (or enhance) the development and implementation of policies designed to achieve emissions reductions, but this will have little influence on mitigation targets themselves.

In the case of adaptation, however, the driving force for change is the assessment of local to national costs and benefits, with local conditions having a profound influence on the nature, costs and benefits of adaptive actions—whether pro-active or reactive. Two factors are important. First, more detailed information on the geographic distribution of costs and benefits, not averaged-out values, are relevant for informing adaptation actions and policies. Second, frictional costs can be large and possibly insurmountable. For example, community adaptations can include changes in spatial planning, water infrastructure, and flood prevention, involving long time scales and complicated negotiations between actors. In some cases national standards will set adaptation targets (such as requiring flood management plans or specifying the heights of protective barriers), but in the absence of such mandates, private perceptions and attitudes to risk, or uncertainty over the future private benefits of adaptation may lead to inaction. To say where adaptation *ought to* take place, one needs to know the spatial distribution of adaptation costs and benefits, and understand whether the net social benefits of adaptation, even if positive in the abstract, overcome the frictional private costs of achieving them. To say where adaptation *will* take place, we require knowledge, for instance, about risk perceptions, attitudes to coping and loss, and about the inertia of behaviors and 'stickiness' of institutions. In both cases, there is a far greater need for locally specific information than is needed for setting mitigation targets.

IAMs with a global focus that model adaptation using single damage curves have difficulties living up to this task. To make credible and reliable statements about adaptation in the future, one must consider the public policies necessary to support effective adaptation in light of the complexity of the system and the social and organizational learning that must first take place (Berkhout et al. 2006). Almost uniformly, these factors will act to restrain action to a level below what a central, "global" decision-maker would decide is optimal. To make a model that is not misleading in terms of being overly optimistic about the amount of adaptation taking place and hence the benefits of adaptation, we suggest that it is necessary to consider a few important aspects. We describe these in the remainder of this paper.

3.2 Adaptation does not occur in response to gradual changes in means

Most IAMs model damages as a function of changes in the global mean temperature, and implicit within these damages costs is a certain level of autonomous and concurrent adaptation. There are two important flaws with such an approach. First, the rate of climatic change is crucial to determining the extent to which adaptation can reduce losses; faster change can lead to greater perception of vulnerability (Patt and Gwata 2002), and yet can run up against constraints to learning (Berkhout et al. 2006). Second, most adaptations are made in response to the perceived risk of extreme events or the experience of the changing variability in climatic parameters (Negri et al. 2005; Thomas et al. 2007), neither of which are necessarily a linear function of change in the mean state (Emanuel 2005).

Many adaptation measures can be taken at relatively short notice and may not differ markedly from innovations and investments that would be made in the absence of climate change (Hertin et al. 2003). However, other forms of adaptation, such as the development of new seed varieties, the construction of large public infrastructure projects, and the implementation of new spatial planning approaches, can take decades. For these measures the role of public policy through investment in science, physical investment and regulation will have a critical role. While these may be influenced by economic welfare considerations, political and other factors are likely to play an important role as well. Moreover, the adoption of these measures by private actors will depend on variables such as rates of time preference. With high discount rates and high uncertainty about damages, and therefore uncertain returns from investment in adaptation, few private agents will make commitments to adaptation over the longer term. In modeling adaptation, then, it is important to differentiate between adaptations with immediate and adaptations with lagged benefits, since the latter will be more sensitive to discounting.

Extreme events and their potential impacts are gaining in importance in the policy debate on climate change. This is partly due to increasing empirical evidence about increased impacts resulting from altered intensities and frequencies of extremes such as cyclones and flooding (Parry et al. 2007), many of which are expected to increase in frequency or severity in many places (Solomon et al. 2007). In addition, recognizable adaptive behavior is more likely to be triggered by extreme, high impact climatic events, rather than by changes in mean conditions. This is because they reveal most clearly existing climate vulnerabilities. Yet there are very few economic studies that consider the processes of adaptation to extreme weather and climate variability (Wreford et al. 2007). At the same time, a great deal of research demonstrates that planned and anticipatory adaptation to extremes, such as the flood-proofing of infrastructure, is a classic case for which rational actor models perform poorly, as more detailed psychological study reveals (Grothmann and Patt 2005; Johnson et al. 1993; Kunreuther 1996; Zebisch et al. 2005). This is because of cognitive difficulties associated with low probability and high consequence events, as well as private actors' (often faulty) views about the obligation and capacity of the public sector. There are exceptions, of course: Dutch flood-control policies in anticipation of long-term projections of sea-level rise provide an example of how (in a top-down situation) science-based information can be accounted for in decision-making. Unfortunately, at the same time a large empirical literature exists that shows a poor track record of science-based assessment leading to "rational" planning by either public (Cash et al. 2006; Mitchell et al. 2006; Patt et al. 2007) or private (Irwin and Wynne 1996; Patt and Gwata 2002; Wynne 1996) actors.

3.3 Adaptation costs and benefits are scale dependent

Global economic models usually divide the world into large world regions, and deal with averages in those regions. The level of detail in impacts and responses at the local level and in specific economic sectors is low. Climate impacts are estimated by an aggregated damage function. While this function may be based on much more specific information—such as impacts on particular sectors—the associated dynamics are not captured within the IAM. As a result, the models treat adaptation to climate change as separate from background economic behavior. Impacts of and adaptation to climate change are highly variable over small distances and between groups, leading to interaction between actors and causing indirect effects on sector prices, which can only be captured by sector-level modeling. For an improved treatment of these issues, and hence to estimate adaptation costs more accurately, it would be desirable to develop further detail (and actors) in global modeling, and find ways to express geographic variability within the large regions defined in some of the global models in order to address the economics of adaptation. To be clear, we certainly do not recommend that this needs to be done in all models, as it depends on the purpose of the analysis, see Sections 4.1 and 4.2.

The vulnerability literature stresses the importance of local factors in estimating impacts, vulnerabilities and options for adaptation (Parry et al. 2007). As a result, most studies estimating both climate impacts and adaptation potential are at the local level. There is reason to believe that local economic studies do not scale up. A study by Aaheim et al. (2007) examined how an increase in the forest biomass affected the economic outcome for the forestry sector, when economic agents adapt in order to maximize profits and trade their products in the world markets. They found that when they examined this strategy at the local level, the profits increased. However, looking at the global level and assuming that additional biomass production would be a widespread phenomenon, the economic gains to private actors disappeared, because of an excess supply leading to decreasing prices. The benefits were captured by the biomass users as the prices went down. The forestry owners suffered a loss in the end. This pattern may not be unusual, and indeed is likely to be seen across a wide range of both adaptation- and mitigation-related decisions. We need more research to understand the complex way in which local adaptation aggregates to the global level (see Yohe et al. 2007).

In addition to identifying whether assumptions of constant prices remain valid when scaling up, three other issues related to scale dependencies of adaptation are perhaps even more important, and require further research. First, to what extent is the ability to substitute between input factors geographically dependent? Achieving optimal adaptation requires frictionless substitution (Cline 1996). In fact, fixed capital is in many cases immobile, both geographically and across sectors. Moreover, there is a time lag, in some cases a substantial one, between a local economic slowdown and full movement of the labor force. Second, what are the transaction and adaptation costs at different scales? Some activities are locally bounded, meaning that the output of a given sector cannot always be delivered easily anywhere within a region. The indirect effects of a change in one activity, triggered by climate change or any other similar factor, are higher in small local communities with one dominating sector than in larger communities with a diversified economy (Fujita et al. 1999). Third, how do adaptation costs add up? Costs related to extreme events may be large on a local level, but moderate if calculated for a country or region (Cairncross and Alvarinho 2005). Moreover, the indirect economic impacts of extreme events depend on the scale of the extreme event relative to the size of economic system that it hits (Stephen and Downing 2001). These costs are subject to local factors, such as measures implemented in advance to prevent, protect, and rebuild from damage. The motivation for implementing such measures is place-specific and depends on institutional, economic and political factors which cannot be easily accounted for in top-down modeling of economic impacts (although this represents a limitation to global models, it is not entirely obvious whether this also lead to a bias).

3.4 Non-market costs and benefits play a vital role

In order to compare mitigation and damage costs with each other, economic analyses attempt to monetize the value of climate impacts. There have been attempts to include non-market impacts in IAMs. Examples include the loss of biodiversity, enforced change of habits, impacts on unemployment and other social consequences (social exclusion), or even the value of a good winter (Parry et al. 2007). While the monetization of non-market mitigation benefits maps onto the adaptation domain, by not explicitly modeling adaptation one may seriously question whether IAMs have so far failed to consider the non-market costs of adaptation. Because these are local, they are much harder to estimate, and provide actors with healthy reasons to disagree and procrastinate.

For example, many studies suggest that an adaptation strategy for agriculturalists in many parts of Africa would be to switch from maize, which is fairly water intensive, to small grain crops such as millet and sorghum. A market analysis would suggest that under conditions of increasingly likely drought, average yields from the small grains would be higher, and the risks would be lower. Interviews with farmers, however, suggest that farmers resist this change, for a variety of reasons: for instance, alternatives to maize don't taste as good, and require more effort to grow. So while various organizations continue to promote small grains based on the analysis of numbers, farmers resist them based on personal preferences, and nothing changes (Patt and Schröter 2008). Their resistance is the result of non-market factors, which are not obvious to the outside analyst.

3.5 Information is seldom used optimally

The assumption of optimal autonomous adaptation implies that people act on the basis of the best possible information in a manner that maximizes the value of that knowledge. According to the standard economic value of information model (the cost-loss model), information such as a weather forecast or climate prediction is valuable if it would lead the decision-maker to change a decision from what it would have been in the absence of a forecast. They need to calculate the expected losses that they will incur for each choice option, given the probability distribution of weather parameters, which in turn necessitates them knowing the skill of the forecast (Katz and Murphy 1997). In fact, there is little empirical support to suggest that people do this (Stern and Easterling 1999), and a great deal to suggest that they do not (Patt 2007). Decision-makers simply do not make decisions in ways that maximize the value of the information, for a variety of reasons, some of which good policy can ameliorate.

Mitchell et al. (2006) present a model of environmental assessment effectiveness that posits that information needs to be salient, credible, and legitimate to decision-makers, before they will use it to change their minds. Numerous case studies lend empirical support to this proposition, and suggest some of the mechanisms by which information can be made more useful (Patt et al. 2006). Cash et al. (2006) suggest that it is necessary to involve local organizations as key stakeholders, in order to be assured of matching their needs. Patt et al. (2005b) showed, in a 5 year empirical study in Africa, that the use of scientific information for adaptation rose by a factor of five when the information was communicated by the researchers through a participatory system; this was a level of public investment in the communication of information that no government in Africa has consistently made (Patt et al. 2007). For all of these reasons, it is important to take into account the ways in which people actually do use information to make adaptation decisions. First, such a consideration is a prerequisite to designing effective policies that will increase the use of climate-related information to a level that approaches the optimal. Second, it will suggest that even with wise policies in place, the actual use of information is likely to be substantially lower than the optimum assumed by the cost-loss model.

3.6 Uncertainty is a defining feature of adaptation

Uncertainty dominates analysis of climate change (Schneider 2004), but may play an even larger role in adaptation than in mitigation analysis (Patt et al. 2005a). First, adaptation actions are more sensitive to the temporal and spatial distribution of climate impacts, as well as socio-economic variables. Vulnerability and adaptive capacity will be determined primarily by the relative economic and social welfare of the groups exposed to climate risk. Second, behavioral factors related to the treatment of uncertainty and risk will play a larger role than for mitigation, given the more distributed nature of decision-making. Asymmetric attitudes to risks, bounded rationality and other well-known features of social and economic responses to uncertainty become important. Third, long-term climate trends to which adaptation must respond are sensitive to the mitigation pathway that society follows over the coming decades. Under such conditions, it is difficult to speak of optimizing behavior.

The IAMs reviewed in this paper aim to predict optimizing behavior to average changes in the climate, the economy, and technology. Some are beginning to consider issues of uncertainty, such as the PAGE model. This takes a stochastic approach using Monte Carlo simulation for varying climatological parameter values, and generates a probability distribution of future outcomes, accounting for climate-driven damage and adaptation costs, as well as baseline economic growth projections. However, none of the models treats either climate impacts or socio-economic development at a spatial scale that is fine enough to capture the regional differences in uncertainty associated with changing climate variability and extreme event risks. Likewise, none of the models considers the relationship between the scale of decision-making and the attitude towards risk. There may simply be no way we can model real responses to actual or anticipated climate damages, partly because social responses to uncertainty and risk are complex, and depend on framing and other factors that are very difficult to predict (Kahneman and Tversky 1979). But the net effect of uncertainty is to increase the value and attractiveness to adaptation planners of waiting for more information; unless models incorporate this effect, they will overestimate the scale and pace of adaptation.

4 Discussion

Integrated assessment models have been important tools providing information for the design of climate change mitigation policies. In any model of processes as complex as those leading to climate change, its impacts and adaptive responses by people and organizations, significant simplifications must be made. As we have shown, however, the simplifications usually made when modeling impacts of and adaptation to climate change all lead to a bias in a particular direction, namely of underestimating the difficulty of adaptation, and hence overestimating the net benefits. This could compound the problem, suggested by some studies, that impacts themselves are underestimated (Parry et al. 2007). In this final section, we offer suggestions for moving forward.

Central to consideration of *how* to model adaptation within IAMs is the underlying issue of *why* to model adaptation. The literature suggests that there are two reasons for modeling it (Parry and Carter 1998; Schröter et al. 2005), and we suggest that each reason carries different implications for how one should do it.

4.1 Modeling adaptation to support adaptation

The first reason to model adaptation is to design successful adaptation strategies. When facing a choice between different adaptation options, including not adapting, the decision-maker may want to choose the option with the greatest net benefits. In some cases this is fairly simple and straightforward, and simply an estimation of private costs and benefits is necessary (e.g. deciding to buy an air conditioner for hot weather). In more complicated cases, however, there may be interactions between public policies and private adaptation, or between different public policies. For example, a public policy to provide better information about likely climate changes will help private actors reach more accurate conclusions about the costs and benefits of different options. In this context, one would need to consider the costs and benefits of the private actors, as well as an appraisal of the net societal benefits from the sum of private actors' adaptations. Providing information as public policy only makes sense if the costs do not exceed the benefits across all private actors, implying that one also needs to estimate how many private actors are likely to respond to public provision of information (see Patt et al. 2007).

Policy makers planning adaptation strategies need information. They need to know what the range of potential climate impacts will be at the scale that they are working, what other actors—private actors, and other public actors—might try to do to adapt, and given these potential futures, what the possible costs and benefits of their own policy options could be. There are models and decision-support tools aimed at informing specific decisions, such as what crops to plant (Prato 2008), or how much self-insurance and risk financing to implement (Hochrainer 2006; Mechler et al. 2006), and these are increasingly incorporating uncertainty about possible climate futures. These can provide extremely useful information to both private and public decision-makers, when embedded in a participatory assessment and communication process. To serve decisions being made at the global scale, there are estimates being made of the adaptation financing requirements for developing countries, which necessarily identify particular adaptations as appropriate or feasible (UNFCCC 2007).

Right now, the state of the art of adaptation in IAMs, such as AD-DICE, is that the costs of adaptation are balanced with the residual damages. They identify an optimal level of adaptation, as a function of temperature. We think the information they offer for concrete adaptation policy strategies is limited, for two reasons.

First, it is easy to underestimate and difficult to quantify the range of potential climate impacts at the local scale, particularly if one begins to look more than 30 years in the future, when current mitigation policies begin to have an influence on future climate impacts. An adaptation planner has to try to prepare for the world as she predicts it, and if she is optimistic about how much mitigation will occur, then the scenarios that incorporate no mitigation are simply not salient to her. Therefore, it is essential to develop scenarios of future climate impacts that include a range of potential mitigation strategies, something not found in the current range of global scenarios used by the IPCC (Solomon et al. 2007), and to downscale these with regional models. The next IPCC report and the modeling teams supporting it will likely go further in this direction (Moss et al. 2008), but even with a wider range of scenarios, it will be difficult to gain more than qualitative guidance on local changes in extreme event risk into the future.

Second, public decision-makers in the area of adaptation face the challenge not of setting targets for adaptation, but primarily of coordinating and supporting the activities of other public agencies and of private decision-makers. This is especially so if, as we have argued, most adaptation is bottom-up. In that case, the idea that there is an optimal level of adaptation that they can achieve is misguided. The uncertainty associated with private adaptations into the future is even greater than that associated with climate impacts themselves. Probably the only way to explore what private actors will do is to engage in a stakeholder driven process of dialogue, although this has its own complications (Hedger et al. 2006). Global cost benefit models can contribute to that process, but they can neither replace it nor generalize its outcomes.

There is an important role for models and decision-support tools in the adaptation planning process, by both private and public actors. These models and tools, however, are probably not of a character similar to the global cost–benefit IAMs we have discussed here. The models needed for this would be much more detailed, and most likely specific to a sector or region. Linking the information between the global IAMs and the specific regional or sectoral models—those designed to address adaptation questions—is an area where a great deal of work is needed.

4.2 Modeling adaptation to guide mitigation

The second reason to model adaptation is to capture the role of adaptation in the discussion of meaningful mitigation targets. The fundamental question that IAMs can help answer is how sensitive is the choice of an optimal or appropriate mitigation target is to the range of potential future adaptations. The arguments we have made in Section 3 can refine the lessons we can learn from AD-DICE and PAGE, the two models that do explore the sensitivity of mitigation targets to adaptation levels.

As we showed above, the AD-DICE model suggests that varying adaptation between nothing and its optimal level moves the optimal mitigation target from a 22% to a 16% reduction from baseline emissions—which are assumed to have grown substantially from 1990 onwards—by 2100. This may seem significant, but it is marginal compared to the range of targets that policy makers are now considering. For example, the Stern Review suggested that it would be sensible to achieve a 500–550 ppm stabilization scenario, and this implies reductions from 1990 emissions of more than 50% by 2100, and even greater departure from the AD-DICE 2100 baseline emissions. The European Union has adopted a target of 2°C total warming, and this implies reductions from 1990 emissions of more than 80% by 2100. These targets respond to a framing of the climate problem not as one of economic optimization, but of risk management (Barker 2008). Meanwhile, the arguments we made in Section 3 suggest that the approach taken in AD-DICE probably overestimates the net benefits of adaptation. If this is so, then the potential to reduce climate impact costs through adaptation is less than AD-DICE represents. As the estimates of the net benefits that society can achieve through adaptation fall, so too does the sensitivity of the mitigation target. In this case, modeling adaptation accurately—implying lower levels of adaptation—reduces the effect of adaptation on the optimal mitigation pathway.

But there is an important caveat to this argument, and that stems from the degree of uncertainty that currently pervades estimates of total impact costs (Yohe et al. 2007). It may well be that IAMs consistently underestimate the magnitude of the climate problem, and so underestimate the benefits to be obtained through wise adaptation. Figure 4 illustrates the effect that this could have on mitigation, and the role that adaptation would then play. The lower two curves, copied from Fig. 3, show the range of total climate costs according to the level of adaptation, and reveal a range of optimal mitigation targets contingent on that adaptation level. The dashed curve shows where, within that range, realistic levels of adaptation may actually put us, and the dashed vertical line reveals the corresponding optimal mitigation target. The upper two curves, however, redefine the total climate cost range given a higher estimate of damages associated with any particular level of warming. In this case, not only is the optimal level of mitigation higher, but the sensitivity of that optimum

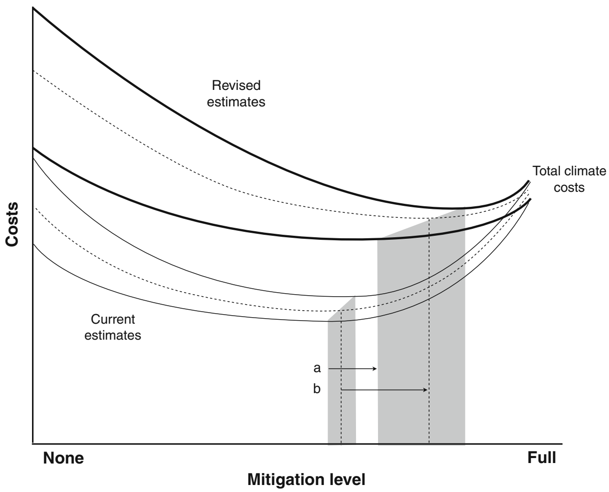

Fig. 4 Sensitivity of mitigation target to adaptation and to different estimates of the magnitude of the entire climate problem. The total climate costs are as in Fig. 3: the *low solid curve* represents the case with optimal adaptation, the *dashed middle curve* represents possible adaptation, and the *high solid curve* represents no adaptation. If the total damage costs were to be revised upwards, then this would have the effect of shifting the range of adaptation-contingent optimal mitigation targets. *Arrow a* represents the shift in optimal mitigation targets if one assumes optimal adaptation, while *arrow b* represents the shift if one assumes possible adaptation. The relative lengths of the *two lines* depends highly on the shapes of the total climate cost curves, but in this case *arrow b* is much longer than *arrow a*

is also greater to the level of adaptation society can achieve. Here, the attempt to model adaptation more accurately, in line with the suggestions we have made in Section 3, becomes important. Knowing how much adaptation society can actually achieve would influence, to a great deal, how far the optimal mitigation target ought to shift as a result of revised estimates of the seriousness of the climate problem. This is so even while realizing that the role of IAMs here is more to explore the range of outcomes than to provide exact numbers, given the uncertainties and value judgments that are involved.

4.3 Conclusion

The efforts to make adaptation costs more explicit in IAMs may be extremely important for improving the political salience of those model results, and with that their usefulness and importance (Mitchell et al. 2006). More explicit attention to the process of adaptation is vital for several reasons. One of them is to inform policy makers on what levels of adaptation are appropriate. For this task, however, IAMs may not be the best tool. However, for the question of how adaptation may interact with mitigation strategies, and in particular how it influences the level of mitigation, IAMs are the right tool. Assuming that the estimates of adaptation costs and total climate damages that have been used to calibrate AD-DICE are correct, their results suggest that different adaptation strategies have a relatively limited effect on the optimal level of mitigation. On the other hand, if the total climate damages are higher than those used to calibrate existing models, different adaptation strategies could influence the mitigation target to a much higher degree. However, we also claim that current IAMs over-estimate the level of adaptation and under-estimate the cost. While adaptation could play a more significant role in reducing the impacts of climatic change, such adaptation is likely to be more difficult and costly than current models suggest. Given these crucial uncertainties, it is vital to improve the representation of adaptation within IAMs, in particular by addressing the special characteristics of adaptation that we have discussed: the highly disaggregated nature of vulnerability and adaptive response; the importance of extreme events as triggers for adaptation; the scale dependence of adaptation; the role of non-market values; the non-optimal use of information by agents; and the central role of uncertainty in shaping private adaptation action.

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