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ENVIRONMENT WORKING PAPER NO. 23

PLAN OR REACT? ANALYSIS OF ADAPTATION COSTS AND BENEFITS USING INTEGRATED ASSESSMENT MODELS

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ABSTRACT

Financing for adaptation is a core element in the ongoing international negotiations on climate change. This has motivated a number of recent global estimates of adaptation costs. While important from an agenda setting perspective, many of these estimates nevertheless have a number of limitations. They are typically static (i.e. estimated for one specific year), do not differentiate between investments in various types of adaptation or quantify the resulting benefits, and are delinked from policies and investments in greenhouse gas mitigation.

This report examines adaptation and mitigation within an integrated framework. Global and regional costs of adaptation are assessed dynamically and the resulting benefits are also quantified. This is accomplished by developing a framework to incorporate adaptation as a policy choice variable within three Integrated Assessment Models (IAMs): the global Dynamic Integrated model of Climate and the Economy (DICE), the Regional Integrated model of Climate and the Economy (RICE), and the World Induced Technical Change Hybrid (WITCH) model. In addition to reactive adaptation, the framework developed here also takes into account investments in adaptation “stocks” such as coastal protection infrastructure, as well as investments in building adaptive capacity.

This report presents the first inter-model comparison of results on adaptation costs using the emerging category of adaptation-IAMs. Results show that all types of adaptation options are important in offsetting some of the adverse impacts of climate change. In terms of timing, investments in building adaptation stocks become effective with a time delay, and should ideally be implemented early, while reactive forms of adaptation become increasingly necessary as climate damages increase and the returns from preventive investments in adaptation stocks become limited. However, the total costs of climate change are the lowest when both mitigation and adaptation are undertaken in conjunction. Any least-cost policy response to climate change will need to involve substantial amounts of mitigation efforts, investments in adaptation stock and reactive adaptation measures to limit the remaining damages.

JEL Classification: Q50, Q54, Q59

Keywords: Integrated Assessment Modelling, Adaptation, Adaptive Capacity, Climate Change

RÉSUMÉ

Le financement de l’adaptation est un élément essentiel dans les négociations internationales qui se poursuivent concernant le changement climatique. C’est ce qui explique pourquoi un certain nombre d’estimations des coûts de l’adaptation au niveau mondial ont été établies récemment. En dépit de leur importance pour la définition de programmes d’action, beaucoup d’entre elles présentent toutefois plusieurs carences. Elles sont généralement statiques (c’est-à-dire calculées pour une année précise), elles ne font pas de différence entre les investissements en fonction du type de solution d’adaptation ou ne chiffrent pas les avantages qui en découlent, comme elles ne se rattachent pas non plus à des politiques ou à des investissements visant l’atténuation des émissions de gaz à effet de serre.

Ce rapport étudie l’adaptation et l’atténuation dans un cadre intégré. Les coûts mondiaux et régionaux de l’adaptation font l’objet d’une évaluation dynamique, et les avantages qui en résultent sont quantifiés. A cet effet, on a créé un cadre pour tenir compte de l’adaptation sous la forme d’une variable exprimant le choix stratégique dans trois modèles d’évaluation intégrée : le modèle mondial DICE (Dynamic Integrated model of Climate and the Economy), le modèle régional RICE (Regional Integrated model of Climate and the Economy) et le modèle WITCH (World Induced Technical Change Hybrid). Ce cadre ne prend pas seulement en considération l’adaptation réactive, mais aussi les investissements dans les “stocks” de biens d’équipement à vocation d’adaptation, par exemple les ouvrages de protection des côtes, ainsi que les investissements visant à renforcer la capacité d’adaptation.

Ce rapport présente la première comparaison des résultats du calcul des coûts de l’adaptation obtenus à l’aide de différents modèles, en s’appuyant sur la nouvelle catégorie de modèles d’évaluation intégrée appliqués à l’adaptation. Ces résultats font ressortir que tous les types de solutions d’adaptation envisageables sont importantes pour contrebalancer certains effets préjudiciables du changement climatique. Quant à leur échelonnement dans le temps, les investissements dans la construction de biens d’équipement à vocation d’adaptation produisent des effets après un certain temps, aussi faudrait-il dans l’idéal les mettre en œuvre rapidement, tandis que les formes d’adaptation réactives deviennent de plus en plus nécessaires au fur et à mesure que les dommages dus au climat augmentent et que les rendements des investissements effectués à titre préventif dans des équipements à vocation d’adaptation se réduisent. Il n’en demeure pas moins que les coûts totaux de l’adaptation sont les plus faibles quand des actions d’atténuation et d’adaptation sont mises en œuvre de façon conjuguée. Toute politique climatique guidée par le principe du moindre coût devra faire intervenir une somme considérable d’efforts d’atténuation, d’investissements dans des équipements d’adaptation et de mesures d’adaptation réactive pour limiter les dommages résiduels.

Classification: JEL : Q50, Q54, Q59

Mots clés : Modélisation de l’évaluation intégrée, Adaptation, Capacité d’adaptation, Changement climatique

FOREWORD

This report presents a synthesis of results from the OECD project on Modelling of Adaptation Costs using Integrated Assessment Models (IAMs). This work has been overseen by OECD's Working Party on Global and Structural Policies (WPGSP).

This report has been authored by Shardul Agrawala, Francesco Bosello, Carlo Carraro, Kelly de Bruin, Enrica De Cian, Rob Dellink and Elisa Lanzi. In addition to WPGSP delegates, the authors are grateful to Sam Fankhauser, Cécile Bordier, Maëlis Carraro, Jan Corfee-Morlot, and Helen Mountford for valuable input and feedback.

Further enquiries on ongoing work on Adaptation to Climate Change should be directed to Shardul Agrawala at the OECD Environment Directorate (Tel: +33 1 45 14 16 65; Email: Shardul.Agrawala@oecd.org).

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EXECUTIVE SUMMARY

Financing for adaptation is a core element in the ongoing international negotiations on climate change. Central to this policy imperative has been the need to get a better understanding of the costs of adaptation, particularly at the aggregate level. This has motivated a number of recent global estimates of adaptation costs. While important from an agenda setting perspective, many of these estimates nevertheless have a number of limitations. They are typically static (i.e. estimated for one specific year), do not differentiate between investments in various types of adaptation or quantify the resulting benefits, and are delinked from policies and investments in greenhouse gas mitigation.

This report examines adaptation and mitigation within an integrated framework. Global and regional costs of adaptation are assessed dynamically and the resulting benefits are also quantified. This is accomplished by developing a framework to incorporate adaptation as a policy choice variable within three Integrated Assessment Models (IAMs): the global Dynamic Integrated model of Climate and the Economy (DICE), the Regional Integrated model of Climate and the Economy (RICE), and the World Induced Technical Change Hybrid (WITCH) model.

This report presents the first inter-model comparison of results on adaptation costs from this emerging category of adaptation-IAMs. Global results are compared between the DICE and WITCH models, while RICE and WITCH are used for regional comparisons. The comparative nature of this assessment facilitates testing of the robustness of some of the policy relevant results, as well as offering a better understanding of some of the uncertainties involved, for example in the case of regional adaptation cost curves. This in turn can be used to inform policy makers and also to guide further work on data collection and model development.

The framework to model adaptation developed in this report is also more comprehensive than the one developed in an earlier OECD report that only considered adaptation as a “flow” variable, wherein all of its costs and benefits accrue just in one time period. Here, durable investments in adaptation “stocks” such as coastal protection infrastructure are also considered. Consequently, the dynamic aspects of adaptation, as well as the interactions between adaptation and mitigation, are much better addressed in the current framework. In addition, the adaptation variant of the WITCH model is used to distinguish between investments in building *adaptive capacity* and those used for adaptation actions that directly reduce the net climate damages. This is the first explicit treatment of adaptive capacity in economic modelling frameworks for assessing adaptation costs.

This analysis demonstrates that all types of adaptation options are important in offsetting some of the adverse impacts of climate change. These range from autonomous, reactive measures, such as the use of air conditioning, to anticipatory investments in adaptation stock, for instance in coastal protection. They also include investments, for example in social protection programmes, which can contribute to enhancing adaptive capacity. The costs and the policy mix of these investments, however, vary considerably across regions, over time, and depend upon the level of mitigation as well as assumptions about climate damages and discount rates.

The two regional adaptation-IAMs developed for this study, AD-RICE and AD-WITCH, show a number of consistent trends in regional adaptation cost curves that plot the normalised costs of adaptation (as a per cent of GDP) against the “level of protection” achieved. The level of protection is a measure of adaptation benefits and refers to the fraction of climate damages that are offset by adaptation. The regional adaptation cost curves for the two models show that initial levels of adaptation can be achieved at very low normalised costs. Thereafter, investments in adaptation offer decreasing marginal benefits. The Indian sub-continent and Sub-Saharan Africa show the highest adaptation costs (in % GDP terms), followed by other low and middle income countries, as well as Western Europe. Meanwhile, Japan, USA and China fall at the lower end of spectrum in both models in terms of adaptation costs as a % of GDP, although the costs in absolute terms can be substantial.

These estimates of regional adaptation costs, however, are critically dependent on the climate damage functions used as inputs in the IAMs examined here. Although widely used in IAMs, currently available damage functions are based on limited information in terms of sectoral and geographic coverage. There is therefore an urgent need for a comprehensive effort by the climate research community to update information on regional damages that are used as inputs into such models to reflect more recent information from assessments like the IPCC Fourth Assessment Report.

Regional adaptation costs are also examined in this study as a function of time, in addition to the level of protection. Cost “snapshots” for the years 2050 and 2100 are presented that show the highest adaptation costs in the Indian sub-continent and Sub-Saharan Africa. The range in cost estimates across the two models, however, is quite significant. For example, for the Indian-sub continent the adaptation costs range from about 0.15 to 0.50% of GDP for the year 2050, and from about 0.7% GDP to 1.4% GDP in the year 2100. For Sub-Saharan Africa the corresponding ranges are from 0.25% to 0.40 % of GDP in 2050 and from 0.5% to 1.4% of GDP in 2100.

These numerical adaptation cost ranges obtained from the comparison of only two models highlight the considerable uncertainties that underlie any estimation of adaptation costs. Other models, alternate parameterisations of regional climate damages, as well as other frameworks for incorporating adaptation may well further expand this range of uncertainty. Specific numerical estimates on adaptation costs should therefore be interpreted with caution.

This analysis also concludes that, in terms of composition, the optimal mix of different types of adaptation will consist predominantly of investments in adaptation stock and/or adaptive capacity in most regions. This does not necessarily imply that fewer reactive or “flow” adaptation actions will be undertaken. Rather, investments in adaptation infrastructure and/or capacity might tend to be more expensive, and would therefore tend to dominate the adaptation budget.

One region where the two regional models diverge with regard to the optimal mix of adaptation investments is Sub-Saharan Africa. This is because a key component of climate change impacts in Africa is in the health sector. A pre-requisite for adapting to these impacts is investment in strengthening the underlying public health infrastructure. While AD-RICE treats such investments as stock adaptation, AD-WITCH considers it as “generic capacity” that is closely linked to development, and therefore outside the adaptation budget in the model.

These two differing perspectives underscore a very fundamental challenge facing international policy – how much of the adaptation deficit (such as lack of public health and other infrastructure) that is critical for the eventual success of many adaptation actions should be addressed as part of adaptation finance? Ultimately this is a matter of political choice, but adaptation-IAMs of the type developed in this report can be used as tools to illuminate the implications of alternate choices.

In terms of timing, meanwhile, the model results show that investments in building adaptation stocks and adaptive capacity become effective with a time delay, and should ideally be implemented early. As time goes by, however, the non-linear increase in climate damages would imply that there would be limits to what can be accommodated with preventive investment in adaptation stock. Greater expenditures in reactive adaptation would therefore become increasingly necessary, although even these reactive measures would reach their limits if climate damages continue to increase, highlighting the importance of mitigation.

Compared to OECD countries, non-OECD countries will need to allocate more resources as a share of their GDP to building adaptive capacity. This reflects their adaptation deficit as well as greater exposure to climate damages. According to this analysis, an optimal mix of adaptation investments would consist of almost equal expenditures in adaptive capacity and adaptation actions in non-OECD countries up to the middle of this century. However, as convergence in adaptive capacities is reached, investments in adaptation actions (as opposed to building capacity) will dominate for both non-OECD and OECD countries in the second half of this century.

Finally, this report shows that the total costs of climate change are the lowest when both mitigation and adaptation are undertaken in conjunction. Climate change costs are the highest under inaction, which is when neither mitigation nor adaptation is undertaken. This report also illustrates that the different climate policy options are both complements and substitutes: they are complementary in the sense that any least-cost policy response to climate change will need to involve substantial amounts of mitigation efforts, investments in adaptation stock and reactive adaptation measures to limit the remaining damages. These options are substitutes in the sense that they compete for limited resources, and investing heavily in one option will reduce the need for investments in the other.

1. Introduction

Adaptation has been increasingly recognised as an important complementary response to greenhouse gas mitigation to address the risks posed by climate change. Significantly scaled up financing for adaptation was key to the negotiations at the Fifteenth Conference of the Parties (CoP 15) to the United Nations Framework Convention on Climate Change (UNFCCC) and is a prominent element of the Copenhagen Accord. It also continues to be a core element in the ongoing international negotiations on climate change. Central to this policy imperative has been the need to get a better understanding of the costs and benefits of adaptation, particularly at the aggregate level. Consequently there has been considerable analytical effort in recent years in estimating the aggregate costs of adaptation (cf. UNFCCC 2007; Stern 2007; UNDP 2007; Parry et. al. 2009; World Bank 2010).

Previous work by the OECD was among the first comprehensive assessments of adaptation costs and benefits at global, national, sectoral and local levels (Agrawala and Fankhauser 2008). In examining the emerging literature on aggregate adaptation costs, this assessment identified a number of key limitations of global, multi-sectoral estimates that were primarily based on assessing the exposure of investments and flows to climate change impacts. Aggregation or scaling up of bottom-up estimates, meanwhile, posed problems with regard to double-counting and gathering data from a very limited (and often very local) evidence base.

The OECD assessment also concluded that aggregate cost estimates were not associated with a clear articulation of the benefits (i.e. reduced net climate damage) that might result from such adaptation investments. Stand-alone adaptation cost estimates also precluded analysis of the inter-relationships between adaptation and mitigation, and how the level of effort on one might influence the costs and benefits of the other. Questions such as these can only be addressed within the context of global integrated assessment modelling framework that has explicit treatment of climate damage, mitigation costs, as well as adaptation costs. While virtually all Integrated Assessment Models (IAMs) examine the trade-off between damage due to climate change and the costs of mitigation, these models have generally either overlooked adaptation entirely or treated it implicitly as part of the climate damage estimates.

A subsequent report by the OECD (de Bruin et al. 2009a) developed and tested a framework for the explicit incorporation of adaptation as a policy variable for two IAMs – the global Dynamic Integrated model for Climate and the Economy (DICE) and its regional counterpart, the Regional Integrated model for Climate and the Economy (RICE). These modified models – AD-DICE and AD-RICE – were then calibrated and used in a number of policy simulations to examine the distribution of adaptation costs and the interactions between adaptation and mitigation.

This analysis showed that to address climate change in an economically efficient way, the near term policy mix needs to include investments in both adaptation and mitigation, even though the latter will only lower climate damage in later periods. It also showed that both adaptation and mitigation can compensate to some extent for deviations from the efficient outcome that might be caused by the non-optimality of the other control option. The analysis also showed that the higher the current value of climate damage, the less important adaptation is as a policy option (de Bruin et al., 2009a).

At the same time, however, there were a number of key limitations of this first analysis. Adaptation was treated only as a “flow” variable, i.e. all the costs and benefits accrued in the same time period. While this may be valid for many adaptation actions, it is not realistic for investments in adaptation “stock” (such as coastal protection infrastructure) where the benefits will persist for decades into the future, if not more. Further, the IAMs that were used in the report to incorporate adaptation – the global Dynamic DICE and RICE - were themselves relatively simple, compared to other more sophisticated IAMs.

The present report addresses some of the limitations of the earlier analysis. Its specific contributions are as follows:

- A more sophisticated framework to model adaptation is developed that includes both investments in adaptation stocks and expenditures for reactive adaptation actions.
- This modified framework is implemented not only with DICE and RICE models, but also within the World Induced Technical Change Hybrid (WITCH) model that can explicitly models non-cooperative aspects of inter-regional relationships.
- The study of the tradeoffs between adaptation and mitigation are also improved thanks to the detailed structure of the energy sector in the WITCH model, which includes advanced low carbon technologies as mitigation options
- Besides stock and flow adaptation, the adaptation variant of the WITCH model (AD-WITCH) is also made to distinguish between investments in building adaptive capacity and for adaptation actions that directly reduce the net climate damage. This is the first explicit treatment of adaptive capacity in economic frameworks for assessing adaptation costs.
- Finally, this report offers the first inter-model comparison of results from the emerging category of adaptation-IAMs. Global results are compared between the DICE and WITCH models, while RICE and WITCH are used for regional comparisons. The comparative nature of this assessment facilitates testing of the robustness of some of the policy relevant results, as well as offering a better understanding of some of the uncertainties involved, for example in the case of regional adaptation cost curves . This in turn can be used to inform policy and also to guide further work on data collection and model development.

The rest of this report is organised as follows. Section 2 discusses key features and typologies for adaptation. It also discusses the concepts of adaptation stocks, adaptation flows, and adaptive capacity that underpin many of the subsequent results from the modelling analysis. Next, Section 3 provides an assessment of the treatment of adaptation so far within IAMs. Section 4 develops the framework for incorporating adaptation stock and flow modelling within the DICE/RICE and WITCH models. Section 5 compares the baseline scenarios of the three adaptation-IAMs to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) range. Section 6 compares the regional adaptation cost curves from the two regional models AD-RICE and AD-WITCH. Next, Section 7 unpacks the stock and flow components of the global adaptation cost curves from AD-DICE and AD-WITCH. The latter model is also used to analyse investments in adaptive capacity. Section 8 discusses the key results from the global policy simulations in treating adaptation and mitigation within an integrated modelling framework in AD-DICE and AD-WITCH. Finally, Section 8 concludes.

2. Characteristics and Scope of Adaptation

Adaptation consists of deliberate actions that are undertaken to reduce the adverse consequences, as well as to harness any beneficial opportunities, resulting from climate change. Even the most stringent mitigation efforts cannot avoid further impacts of climate change, which makes adaptation essential, particularly in addressing near term impacts. There are significant analytical and policy challenges associated with economic assessments of both mitigation and adaptation. However, the boundaries of mitigation measures are more clearly defined, and the literature on mitigation costs is much more comprehensive. Furthermore, there is a clear metric (reduction in greenhouse gas emissions) for assessing the effectiveness of such measures. In contrast, what does and does not fall within the purview of adaptation is much more ambiguous, the literature on adaptation costs remains relatively sparse and contested, and there are no accepted metrics for assessing the effectiveness of adaptation policies and measures (Agrawala and Fankhauser 2008).

2.1 What does adaptation involve?

A wide range of adaptation measures can be implemented in response to observed or anticipated climate variability and change. In general, adaptation measures offer the following possibilities to deal with climate risk (IPCC 2001, based on Burton 1996):

- *Bear losses*. All adaptation measures may be compared with the baseline response of "doing nothing" except bearing or accepting the losses. In theory, bearing loss occurs when those affected have no capacity to respond in any other ways (for example in extremely poor communities) or where the costs of adaptation measures are considered to be high in relation to the risk or the expected damage.

- *Share losses*. This type of adaptation response involves sharing the losses among a wider community. Such actions take place in traditional societies and in the most complex, high-tech societies. In traditional societies, many mechanisms exist to share losses among a wider community, such as extended families and village-level or similar small-scale communities. At the other end of the spectrum, large-scale societies share losses through public relief, rehabilitation, and reconstruction paid for from public funds. Sharing losses can also be achieved through insurance.

- *Modify the threat*. For some risks, it is possible to exercise a degree of control over the environmental threat itself. When this is a "natural" event such as a flood or a drought, possible measures include flood control works (dams, dikes, levees). For climate change, the major modification possibility is to slow the rate of climate change by reducing GHGs and eventually by stabilising GHG concentrations in the atmosphere (i.e. mitigation).

- *Prevent effects*. A frequently used set of adaptation measures involves steps to prevent the effects of climate change and variability. For example, in agriculture such measures include changes in crop management practices, such as increased irrigation water, additional fertiliser use, and pest and disease control.

- *Change use*. Where the threat of climate change makes the continuation of an economic activity impossible or extremely risky, consideration can be given to changing the use. For example, a farmer may choose to substitute a more drought-tolerant crop or switch to varieties with lower moisture. Similarly, crop land may be returned to pasture or forest or other uses may be found such as recreation, wildlife refuges, or national parks.

- *Change location*. A more extreme response is to change the location of economic activities. There is considerable speculation, for example about relocating major crops and farming regions away from areas of increased aridity and heat to areas that are currently cooler and which may become more attractive for some crops in the future.

- *Research*. The process of adaptation can also be advanced by research into new technologies and new methods of adaptation.

- *Encourage behavioural change through education, information and regulation*. Another type of adaptation is the dissemination of knowledge through education and public information campaigns, leading to behavioural change. Such activities have been little recognised and have

Table 1 provides representative examples of adaptation measures from specific sectors.

Table 1. Illustrative examples of possible adaptation measures (OECD 2009)

Sector	Type/category of adaptation	Example of adaptation options
Agriculture	*Share the loss*	Crop insurance
	Prevent the loss (structural, technological)	Investment in new capital
	Prevent the loss (market-based)	Removal of market distortions (*e.g.* water pricing); Liberalisation of agricultural trade to buffer regionalised losses
	Change use	Change crops, promote crop diversification Alter planting dates Alter farming practices
	Research	Development of heat- and drought-resistant crops
Coastal zones	*Prevent the loss* (structural, technological)	Coastal defences/sea walls Surge barriers Upgrade drainage systems, salt water intrusion barriers
	Prevent the loss (on-site operations)	Sediment management Beach nourishment Habitat protection (*e.g.* wetlands, mangroves)
	Prevent the loss (institutional, administrative)	Land use planning
	Change location	Relocation Set back areas
Water	*Prevent the loss* (structural, technological)	Loss reduction (leakage control; conservation plumbing) Capacity increase (new reservoirs, desalination facilities)
	Prevent the loss (institutional/administrative)	Water allocation (*e.g.* municipal *vs.* agricultural) Risk management to deal with rainfall variability
	Prevent the loss (market-based)	Water permits Water pricing
	Education/behavioural	Rational water use Rainwater collection
Health	*Prevent the loss* (structural, technological)	Air-conditioning Building standards
	Prevent the loss (institutional, administrative)	Improvements in public health Vector control programmes Disease eradication programmes
	Research	Research & Development (R&D) on vector control Vaccines Disease eradication

As is evident from the examples shown in the preceding discussion, the process of adapting to climate change is both complex and multi-faceted. It covers all aspects of society and consists of a wide range of behavioural, structural and technological adjustments (OECD, 2008). A number of overlapping typologies have therefore been proposed to classify the diversity of adaptation actions in terms of: timing (anticipatory vs. reactive), scope (short-term vs. long-term; local vs. regional); purposefulness (spontaneous vs. planned; passive vs. active), and adapting agent (private vs. public; human vs. natural systems).

2.2 Adaptation flows, stocks, and capacity

From an inter-temporal integrated assessment modelling perspective, it is important to distinguish between adaptation investments where both costs and benefits accrue in the same time period and those where initial investments offer benefits that extend beyond the time period when the costs were incurred (Lecocq and Shalizi 2007). In modelling jargon, the former can be termed “flow” adaptation and the latter “stock” adaptation.

Flow adaptation generally falls within the category of reactive actions such as changes in agricultural practices, energy expenditures for space heating and cooling, and treatment of climate related diseases. It can also include public expenditures, such as in disaster relief and recovery. In such cases no cumulative build-up of investments is needed. At the same time, flow adaptation can also include certain planned, proactive measures with benefits that persist for some time but not long enough to spill over to subsequent time periods. A classic example in this case would be beach nourishment.

Stock adaptation, meanwhile, is characterised by a build-up of investments in capital goods aimed at reducing the net damage from climate change. Investments in coastal protection infrastructure such as sea walls, water storage and irrigation facilities, disaster early warning systems, are all examples of stock adaptation that require upfront investments that then offer a stream of benefits well into the future.

It is important to distinguish between stock and flow adaptation for several reasons. First, from an economic perspective the time lag between costs and benefits will change the optimal time profile of adaptation. Distinguishing between stock and flow adaptation within an integrated assessment modelling framework will also affect the optimal mix of adaptation and mitigation. This optimal mix depends crucially on the discount rate, as the cost-to-benefit time lag of mitigation is (much) larger than that of adaptation. The discount rate will thus influence what the optimal mix at any moment in time is, and how this optimal mix changes over time. Furthermore, the discount rate will also affect the optimal mix of both forms of adaptation: high discount rates have a much stronger effect on stock adaptation than on flow adaptation, as the future benefits of the stock adaptation have to be discounted. Second, stock adaptation includes the investment of funds for the build up of capital stock. This may be a large constraint when adapting to climate change, especially in poorer regions. Adaptation of the reactive private nature will more likely take place, whereas proactive public adaptation may be limited, as many regions do not have the funds to build up large infrastructures. Distinguishing between these forms of adaptation can help us understand how severe such adaptation limits will be. Finally, it is possible to understand the importance of the role the public sector, which is more directly involved in stock adaptation.

Stock and flow adaptations are in fact closely intertwined. Any sector is likely to have a combination of both flow and stock measures. For example, while changes in agricultural practices in response to climatic conditions are a flow adaptation, investments in irrigation or water storage are examples of stock adaptations in the same sector. Furthermore, the efficacy of many flow adaptation activities would depend at least in part on the adaptation stock available. Changes in crop practices, for example, might be constrained if sufficient irrigation is not also available. Flow and stock adaptations can also substitute each other to a certain degree, but are certainly not perfect substitutes.

Besides stock and flow, another relevant distinction is between investments in adaptation *actions* that directly help reduce the adverse consequences of climate change impacts (or help capitalise on beneficial opportunities) from investments in adaptive *capacity*. The IPCC Fourth Assessment defines adaptive capacity as “the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damage, to take advantage of opportunities, or to cope with the consequences" (IPCC 2007). Adaptive capacity is vital for effective adaptation responses, and therefore another component of the adaptation "bill". Again, investments in adaptive capacity and adaptive actions can substitute each other to a certain extent, but are not perfect substitutes. Insight on the linkages between investments in developing adaptive capacity and adaptation actions themselves would be another avenue for analysis using integrated assessment models.

3. Climate Change Adaptation within Integrated Assessment Models (IAMs)

Climate change involves many interrelated processes belonging to different disciplines. Human activity contributes to greenhouse gas (GHG) emissions; atmospheric, oceanic and biological processes link these emissions to atmospheric concentrations of GHGs. These concentrations influence climatic and radiative processes to result in changes in climate. These changes in climate result in biophysical and socio-economic impacts.

Integrated Assessment Models (IAMs) represent the above mentioned component processes as well as associated policy responses to climate change within a formalised modelling framework. An important advantage of such models compared to the usual integrated assessment is the imposition of common standards. The underlying assumptions of an assessment can be compared with other models. Moreover, these models can be used widely and are adaptable as new knowledge in the related disciplines becomes available. The main disadvantages of IAMs are that they may force a more precise representation than the underlying knowledge allows, may impose inappropriate restrictions and may aggregate results. IAMs are also weak in representing policies and decentralised decision-making, which is particularly relevant within the context of adaptation.

3.1 Treatment of adaptation in IAMs

Virtually all existing IAMs focus on the trade-off between damage due to climate change and the costs of mitigation. Adaptation, however, is either ignored or only treated implicitly as part of the damage estimate (Fankhauser et al. 1999; Fisher et al. 2007). This means that adaptation is not modelled as a decision variable that can be controlled exogenously. It is sometimes argued that adaptation is, in fact, not a decision variable for a region. This is because adaptation is often viewed as primarily a private choice and, as such, not in the hands of the policy-makers of that region (Tol 2005). However, besides the fact that many forms of adaptation are public, even private adaptations still involve decisions taken within a region, even if not by the leaders of that region. Public policy frameworks also influence private decisions. One may also argue that, under certain assumptions, the socially optimal adaptation coincides with the adaptation provided by the market (see for example, Mendelsohn 2000). This, however, is unlikely as companies and households lack information on the effects of climate change and adaptation options, and adaptation sometimes entails large-scale projects that the market cannot provide.

Therefore, in order to fully understand the effects of climate change and climate change policies, adaptation does in fact need to be considered and modelled as a policy variable. Hope et al. (1993) is the first paper that models adaptation within an IAM. Using the Policy Analysis for the Greenhouse Effect model (PAGE), the authors look at two adaptation policy choices, namely no adaptation and aggressive adaptation. The benefits of adaptation used in PAGE are much higher than found elsewhere in the literature (c.f. Reilly et al. 1994, Parry et al. 1998a/b, Fankhauser 1998, Mendelsohn 2000). Not surprisingly, Hope et al. (1993) find that an aggressive adaptation policy is beneficial and should be implemented. Although this analysis takes a step in considering adaptation and how it may be implemented into IAMs, the simulations convey little about the dynamics of adaptation or the trade-offs with mitigation. Furthermore, adaptation is not a continuous choice, but a discrete variable in their analysis; and it is a scenario variable rather than a choice variable. Although later versions of the PAGE model have been developed, the specification of adaptation is largely unchanged (Hope 2006, 2009).

A more recent and detailed paper where adaptation is explicitly modelled is the FUND model of Tol (2008). Coastal protection is treated as a continuous decision variable, based on Fankhauser (1994), and gives insights into adaptation dynamics. The analysis shows that adaptation is a very important option to combat the impacts of sea level rise. Furthermore, in this model, mitigation and adaptation need to be traded off as more mitigation will lead to fewer resources available to invest in adaptation. Tol concludes that too high a level of abatement may actually have adverse effects as less adaptation may be undertaken. A lower level of adaptation may in turn lead to more net climate change damage. The study also concludes that optimal investments in adaptation increase over time. Although adaptation is explicitly modelled as a decision variable, the treatment of adaptation in this analysis is only limited to coastal protection.

3.2 Recent developments in incorporating adaptation as a decision variable in IAMs

While adaptation was not explicitly incorporated in other existing IAMs until very recently, at least some of these models can be potentially modified to treat adaptation as a decision variable. Three criteria can be used for screening for such candidate models from amongst the over 30 previous IAMs that currently exist.

- First, only *global* IAMs, or models including several regions that together represent the globe, are considered. This is because a full analysis of adaptation/mitigation interactions would require a global analysis, given that the effects of mitigation measures will influence global damage. Therefore, specific regional integrated models are not considered.

- Second, the model should include *monetised* damage from climate change (i.e. the expression of damage in monetary units). This is because monetisation offers a common metric to link the effects of the climate change on the economy and vice versa. The advantage of such IAMs is that they can deal with issues such as efficient allocation of abatement burdens and accepted damage, by specifying the costs and benefits of various abatement strategies. This excludes IAMs such as IMAGE that only have damage expressed in physical units.

- Third, the models should be *contemporary* (i.e. actively being used) and reasonably up to date with respect to the literature.

Only a very small subset of the 30 or so IAMs that were surveyed for this analysis fulfils all of the above criteria: DICE, RICE, MERGE, FUND, FAIR, PAGE, and WITCH.

The previous OECD report (de Bruin et al. 2009a) developed an explicit framework for adaptation within the global DICE model and the regionalised RICE model, building upon the work of de Bruin et al. (2009b). DICE and RICE are both well established, publicly available, and also among the simplest IAMs. Furthermore, many of the other candidate IAMs mentioned above have monetised damage functions that are extracted from DICE/RICE.

As previously noted, however, adaptation was only modelled as a “flow” variable in this first report, which was not realistic for investments such as coastal protection and water storage infrastructure.

The current report therefore develops a more elaborate stock and flow framework for adaptation within the DICE/RICE models. The adaptation stock and flow framework, with an additional component of adaptive capacity, is also implemented in the more complex WITCH model. In addition to the individual model results, this report therefore also offers an opportunity for inter-model comparison of results. The following sections outline the respective frameworks and data used, and provide a comparative analysis of the key results.

4. Stock and Flow Modelling of Adaptation in DICE/RICE and WITCH Models

This section will first provide a brief overview of the three IAMs used for this analysis: DICE, RICE and WITCH. Next, the section outlines how adaptation is incorporated into these models, and the data that has been used to do so. More detailed technical descriptions are provided in the Annexes to this report.

4.1 Model description

The *DICE* model was originally developed by Nordhaus and updated most recently in 2007 (Nordhaus 1994, 2007). It is a dynamic integrated model of climate change in which a single world producer-consumer makes choices between current consumption, investing in productive capital, and reducing emissions to slow climate change. In each time period, consumption and savings/investment are endogenously chosen subject to available income and reduced by the costs of climate change.

The *RICE* model is the regional version of DICE (Nordhaus and Yang 1996; Nordhaus and Boyer 2000). It is a growth model in which each region produces using labour, capital, and energy inputs. The RICE model does not have an explicit mitigation variable, but mitigation is incorporated explicitly in specification of the carbon energy inputs.

The *WITCH* model is a hard-linked, energy-economy-climate model designed to deal with main features of climate change (Bosetti et al. 2006, Bosetti et al. 2007, Bosetti et al., 2009). While sharing the same overall structure as DICE and RICE, WITCH introduces several new features. It explicitly considers non-cooperative behaviour among regions.[1] Regions interact through the presence of environmental externalities, as well as other economic channels such as the international energy market and international technology spillovers. Hence, forward-looking regional planners maximise their intertemporal welfare taking into account interactions with other regions. A cooperative solution can also be implemented in which a world central planner internalises all externalities by maximising the weighted sum of regional utilities. The bottom up characterisation of the energy sector includes several types of technologies, including breakthrough technologies whose penetration rate is driven by innovation. WITCH includes dedicated R&D investment for enhancing energy efficiency, and for facilitating the introduction of innovative low carbon technologies.

DICE/RICE and WITCH share the same climate module that links greenhouse gases (GHG) emissions to GHG concentrations, and eventually to global mean temperature. A damage function translates the increases in temperature to GDP losses. The damages are region-specific in RICE and WITCH, and some regions can even experience net benefits from climate change. DICE, meanwhile, integrates global damages.

There are, however, a number of differences between DICE/RICE and WITCH, in particular in the way the models deal with mitigation and policies for the stabilization of greenhouse gases emissions is also different. Having a more disaggregated energy sector, and including technical change, and backstop technologies, the WITCH model has a higher number of mitigation options compared to DICE/RICE.

The two regional models RICE and WITCH also have different regional aggregations. RICE is divided in 13 world regions, based mostly on income levels. WITCH is divided in 12 world regions, based

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[1] This feature is also replicable in the RICE model at present.

on the similarities in the energy sector. Table 2 includes a description of the two models' regional aggregations.

Table 2. Regional aggregations of the AD-RICE and AD-WITCH models

Model	Region name and description
RICE	**USA**
	Western Europe
	Eastern Europe
	Japan
	China
	India
	Africa - Sub-Saharan Africa, except Namibia, and South Africa
	Low Middle Income Countries - Mexico, South Africa, Thailand, most Latin American and Caribbean countries
	Middle Income Countries - Argentina, Brazil, Korea, Malaysia
	Other High Income Countries - Australia, Canada, New Zealand, Singapore, Israel, high income island states
	Highly Industrialised Oil Exporting Regions - Bahrain, Brunei, Kuwait, Libya, Oman, Qatar, Saudi Arabia
	Low Income Countries – including countries from East Asia, South Asia, Central Asia, Middle East, Latin America
	Russia
WITCH	**USA**
	WEURO - Western Europe
	EEURO - Eastern Europe
	CAJAZ - Canada, Japan, New Zealand
	CHINA - China and Taiwan
	SASIA - South Asia
	SSA - Sub-Saharan Africa
	LACA - Latin America, Mexico, and the Caribbean
	KOSAU - Korea, South Africa, Australia
	TE - Transition Economies
	EASIA - South East Asia
	MENA - Middle-East

As the models have different regional aggregation the number of regions that can be compared between the RICE and WITCH is somewhat limited. The regions USA, China and (Western) Europe are virtually identical in the two models. Meanwhile, Africa in the RICE model essentially covers the countries included in the Sub-Saharan Africa region of the WITCH model. The two are therefore also comparable. Meanwhile, India in the RICE model is roughly comparable to South Asia region in WITCH that covers the Indian sub-continent. Further, the Latin America and the Caribbean (LACA) region in WITCH has considerable, but not complete, overlap with the Low-Middle Income (LMI) region of RICE. Other regional groupings in the two models are not comparable as the level of overlap is too limited.[2]

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[2] More details on the models are provided in Annex I.

4.2 Explicit modelling of adaptation stock and flow

Adaptation to climate change decreases the potential damage of climate change. This is the mechanism that is added explicitly in the three models examined here to develop their adaptation variants, i.e. AD-DICE, AD-RICE, and AD-WITCH. Gross damages are defined as the initial damages by climate change if no adjustments were made in ecological, social and economic systems. However, if these systems were to adapt, the observed climate damages would decrease. These "left-over" damages are referred to here as residual damages. Reducing gross damages, however, comes at a cost, i.e. the investment of resources in adaptation. These costs are referred to here as adaptation costs. Thus, the net damages are now represented as the sum of residual damages and adaptation costs.

The damage function in the integrated assessment models examined here increases exponentially with temperature, so that the higher the temperature, the higher the damage. This effect is stronger as higher levels of temperatures are reached. In the absence of adaptation, the damage is higher, and corresponds to the gross damage. The gross damage can be reduced when adaptation activities are undertaken. Depending upon the amount of resources invested and how effective adaptation is, a certain *protection level* will be achieved. The term "protection level" is a holdover from research in coastal zones, where the benefits of adaptation measures such as sea walls were quantified in terms of the level of protection they offered. In this report (and in other literature) the term protection level is used in a much broader sense to indicate the ratio of gross damages that are avoided as a result of the adaptation measure. With "full protection", all gross damage is reduced, and there is no residual damage. When, instead, no protection is undertaken, all of gross damages remain. In this case, therefore the grass and residual damages are the same. The protection level is expressed on a 0-1 scale, with 1 implying that 100% of the gross damages were avoided. Implicitly, it is assumed that there is decreasing marginal damage reduction of protection. That is to say that the more protection is used the less effective additional protection will be, meaning that efficient measures of adaptation will be applied first while less effective measures will be applied only later.

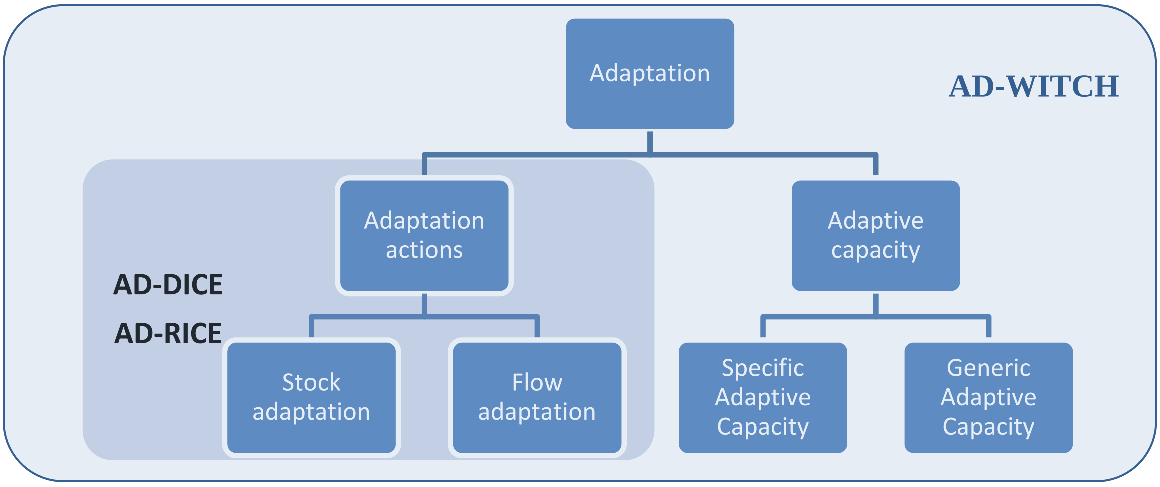
This overall rationale for incorporating adaptation was developed in a previous OECD report (de Bruin et al. 2009a), and applied to DICE and RICE models. However, as noted earlier, in the previous report adaptation was only considered as a "flow" variable, i.e. the costs and benefits of adaptation investments accrued in the same time period. In the present report a more comprehensive framework for adaptation is developed wherein both flow and stock adaptation are considered. Furthermore, the AD-WITCH model also considers the role of adaptive capacity in enhancing effectiveness of adaptation activities. This includes both *specific* adaptive capacity that specifically targets adaptation to climate change (e.g. investments in regional climate change impacts, R&D for drought resistant crops) as well as more *generic* capacity (improved sanitation and public health infrastructure) that is more broadly linked to development but will nevertheless contribute to enhancing the efficacy of downstream adaptation actions.

The adaptation costs, therefore, include resources invested in both stock and flow adaptation for these new versions of AD-DICE and AD-RICE. In the case of AD-WITCH, meanwhile, adaptation costs also include investments in building adaptive capacity, in addition to stock and flow actions.

Stock and flow adaptation are imperfect substitutes for each other. In the AD-DICE/AD-RICE model, these two forms are combined assuming that there is a certain substitution level between them. The combination of adaptation expenditures in the AD-WITCH model is more complex. In the framework developed for AD-WITCH it is possible to choose between investing in adaptation actions and/or building adaptive capacity. Within adaptation actions, meanwhile, it is possible to choose between stock and flow adaptation. These are considered to be substitutes. Adaptive capacity is then composed of generic and specific adaptive capacity, also considered to be substitutes. Generic adaptive capacity captures components not necessarily related to adaptation itself but to the economic development of a region. The level of development influences the possibilities to adapt, with richer regions having more possibilities and pre-existing human capital and knowledge to engage in adaptation activities. Specific adaptive capacity depends not only on forms of investment such as R&D and early warning systems, but also on institutional capacity. Both generic and specific adaptive capacities improve the effectiveness of adaptation. With regard to adaptation activities, these coincide with the stock and flow expenditures in the AD-DICE/AD-RICE models.

Figure 1 illustrates the different adaptation activities that can be undertaken in the AD-WITCH model, as well as the subset of activities that can be chosen in the AD-DICE/AD-RICE model. The decision-tree in the figure illustrates the distinction between the different types of activities, namely adaptation strategies and adaptive capacity. The former is then in turn divided between stock and flow adaptation, while the latter between specific and generic adaptive capacity.

Figure 1. Types of Adaptation included in the AD-DICE, AD-RICE and AD-WITCH models



In each time period, each region will chose an optimal level of flow adaptation, and optimal levels of investments in stock adaptation (and specific adaptive capacity). The choice of these variables determines the protection level, the residual damage, and the level of adaptation stock (and adaptive capacity).

There are a number of differences in the way adaptation has been incorporated into the models considered. While AD-DICE and AD-RICE assume that the level of GDP does not influence the capacity to adapt, AD-WITCH assumes that the level of GDP can also influence adaptation. Furthermore, AD-WITCH assumes that adaptation costs are given in dollars and adaptation benefits are given in percentage of GDP. This is likely to change the results as the level of adaptation will depend on GDP in different ways in the two models. The models also differ in the assumptions on the levels of substitutability between the different types of adaptation expenditure. In particular, AD-WITCH assumes lower possibilities to substitute. The exact effects of this assumption are hard to discuss as AD-WITCH has a more complex framework including nested substitution functions. Finally, there are differences in the parameters expressing the relationship between gross damage and temperature changes.

A more technical description of the framework used to incorporate adaptation in the DICE, RICE and WITCH models is provided in Annexes 3, 4 and 5.

4.3 Damage categories and stock and flow modelling

Climate change is not uniform throughout the world and its impacts are diverse and differentiated by region. Regions also differ for their intrinsic adaptive capacity. In general, developing countries are more vulnerable than industrialised countries.

The DICE, RICE and WITCH models all rely on the underlying climate damage function developed by Nordhaus and Boyer (2000). Further detail on this damage function and its various categories is provided in Annex 2. Some of the limits of this damage function and how they might influence the results in this report are discussed later in this paper in Section 6. The DICE2007 model, which is used here to develop AD-DICE, has updated global damage estimates that are significantly higher than those reported in Nordhaus and Boyer (2000). Comprehensive regional updates of the original damage estimates, however, have not yet become available. AD-RICE therefore retains the original Nordhaus and Boyer (2000) specification of climate damages. AD-WITCH, meanwhile, also considers new information coming from more recent literature on the different types of damages. All three adaptation-IAMs, however, also explicitly include information on sectoral adaptation costs and benefits that is used to calibrate these models. A key input to this is the assessment of adaptation costs and benefits previously conducted as part of this project (Agrawala and Fankhauser 2008).

The damage categories used in AD-DICE/AD-RICE and AD-WITCH are the same as in Nordhaus and Boyer (2000): Agriculture, Other Vulnerable Markets, Coastal, Health, Non Market Time Use, Catastrophic, and Settlements. These are explained in this section, with reference to the differences in data sources and assumptions between the AD-DICE/ AD-RICE and the AD-WITCH models. In AD-DICE/ AD-RICE expenditure for each damage category is also split in flow and stock adaptation. In AD-WITCH instead only the prevalent expenditure type is considered, so that some categories belong to flow adaptation, other to stock or adaptive capacity.

The ***Agriculture*** category refers to the damages in the agricultural sector due to climate change. The damage estimates are based on studies done on crop yield variation under different temperatures and precipitation. To assess the adaptation in this sector, regional estimates of adaptation costs and benefits developed by Tan and Shibasaki (2003) are used. The authors compute damages/benefits with and without adaptation for several world regions, but they only consider low cost adaptation measures. This type of adaptation action in agriculture can be classified as a flow activity. There are also investments in stock adaptation activities that can be done in agriculture, related to water supply and irrigation systems. These are also included in the agriculture category in the AD-DICE/AD-RICE model, but not in the AD-WITCH model where they are instead classified under water protection activities in the “Other vulnerable markets” category.

The ***Coastal*** category refers to the damages due to sea level rise. As the climate warms, the level of the sea rises. Adaptation options considered consist of either building sea walls to protect against sea level rise (incurring costs) or accepting the land loss (incurring residual damages). To estimate the adaptation in this sector AD-DICE/ AD-RICE use results from the FUND model (Tol 2007). This provides direct estimates of both optimal protection level as costs and benefits of adaptation for more than 200 countries in the world. The AD-WITCH model instead bases its estimates on the DIVA model, an interactive tool that makes it possible to perform an integrated assessment of coastal zones. In AD-WITCH expenditure to limit coastal damages is modelled as stock adaptation, as it requires mostly high investments for the construction of big infrastructures such as dams, or seawalls. This type of adaptation expenditure has very high efficiency. In AD-DICE/AD-RICE flow adaptation is also considered, and it is mostly relative to migration costs in response to the acceptance of the land loss.

The ***Health*** category refers to all damages incurred due to malaria, dengue, tropical diseases and pollution. Although heat- and cold-related deaths are also affected by climate change, they are not included here. In general, regions that are already vulnerable to such diseases also have large future damages, and thus developing regions tend to have the largest damages in this category. To estimate adaptation in this sector AD-DICE/AD-RICE uses the study by Murray and Lopez (1996) on which Nordhaus and Boyer (2000) base their estimates. This study assumes a level of adaptation based on general improvements in health care. AD-WITCH instead uses a study by Tol and Dowlatabadi (2001) which assesses the costs of the illnesses for different temperature scenarios. Both models also use from the WHO malaria report (WHO, 2008), which estimates the use of mosquito nets in various vulnerable regions. As this is mostly a reactive type of adaptation, in AD-WITCH it is modelled as a flow variable. In AD-DICE/AD-RICE, meanwhile, both stock and flow are considered, as in developing regions extra investments in healthcare infrastructure will be needed.

The ***Settlements*** category includes both human settlements and ecosystems. Both AD-DICE/AD-RICE and AD-WITCH start from the work of Nordhaus and Boyer (2000), but attempt to separate settlements from ecosystems. In this formulation settlements are assumed to have a higher adaptation potential than ecosystems, but they can adapt only at very high costs. The level of adaptation is low in developing regions, but higher in developed ones. In the AD-WITCH, this damage category is modelled as stock adaptation, as settlements adaptation requires the creation of new infrastructures.

The ***Other vulnerable markets*** (OVM) category refers to the effect of climate change on other markets. Nordhaus and Boyer hypothesise that the only significantly affected markets are energy and water. More energy will be needed in some regions for air conditioning whereas colder regions will need less energy for heating. Estimates for energy demand are based on recent literature (Fankhauser 1995, Mendelsohn 2000, Rosenthal et al. 1995, De Cian et al. 2007). Water use is also expected to increase, for example, due to increased irrigation needs. Estimates for water use are based on the work by Kirshen (2007), who proposes an estimate of the investment needed to meet projected water demand in 2030 consistent with IPCC B1 and A1 scenarios in eight world regions. In the AD-WITCH model the expenditure in space heating and cooling relative to the changes in energy demand is modelled as a flow variable, as changes in the use of heating and cooling devices will be reactive to the actual temperature. Water protection and use activities instead are modelled as a stock variable, as infrastructures are needed for consistently changing water use. In general, for this category, there are particular differences between industrialised and developed countries. Dryer, hotter regions will have more trouble adapting. Furthermore, developing regions may lack the infrastructure to adapt.

Non market time use is a more abstract category and refers to the change in leisure activities. Due to a change in climate, people's leisure hours will be affected. In colder regions, a warmer climate will lead to extra enjoyment of outdoor leisure activities. In warmer climates, however, leisure activities will be more restricted if the amount of extremely hot days increases. Most regions have benefits in this category. Estimates for this sector rely on expert judgment to estimate the adaptation variables. Most of the impacts in this category will be adaptation costs as people will adapt their leisure activities to fit the new climate. Most of the expenditure will be done reactively, so that in AD-WITCH this is modelled as flow adaptation.

The ***Catastrophic events*** category refers to the Willingness To Pay (WTP) to avoid catastrophic events.[3] These can be prevented through knowledge of the forthcoming disaster (early warning systems, scientific research, etc.). The main data source for this damage category is the study done by Adams et al. (2000) in which they find that early warning systems can be very effective for extreme events. However,

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[3] Note that although these are deterministic models and do not include an explicit treatment of probability, the estimates relative to the extreme event damage category take into account the uncertainty in the actual manifestation of these events.

this study is very specific, and only considers the use of early warning systems in Mexico and in the agricultural sector. Thus, the efficiency of adaptation expenditure in this category is limited to a low level. In AD-WITCH expenditure to limit the damages from extreme events is modelled as specific adaptive capacity.

The differences in assumptions between the models, what data they use for calibration, and how they distinguish between stock and flow adaptation in various damage categories are all very relevant for the results. Detailed data on the costs, effectiveness of adaptation expenditure, and aggregation of damages are provided in Annexes 4 and 5.

5. Results: Baseline Scenario Comparison

The baseline scenarios of the AD-DICE, AD-RICE and AD-WITCH models are important as baseline output and emission paths crucially affect the results, in particular the policy costs. In this section the baselines of AD-DICE, AD-RICE and AD-WITCH are compared with the common Special Report on Emissions Scenarios (SRES)[4] storylines developed by the IPCC. Comparisons are made along three projections: emissions, temperature change, and output. Projections of emissions are made to verify that the models predict the same levels of emissions in the baseline. Temperature change comparisons are used to verify that these emissions are translated into temperature change in the same range in AD-DICE, AD-RICE and AD-WITCH as they are in SRES. Finally, projections of output are compared to verify that the economic expectations given climate change are in the same range. These comparisons are shown in Figures 2, 3 and 4 respectively.

As can be seen from the figures, the AD-DICE and AD-WITCH models generally fall within the SRES range and are mostly similar to the B scenarios. Temperature and output estimates are particularly close to the B2 scenario. The AD-RICE model has lower estimates that fall at the bottom of the range. This is because the RICE model that is used to construct AD-RICE, unlike DICE and WITCH, has not been updated and reflects the lower economic projections from the late 1990's. It is important to bear in mind these and other differences when comparing the results, as they influence the role of adaptation particularly for what regards the climate change damages.

For the purposes of this analysis the interactions between adaptation and mitigation at a global level are examined by comparing results of AD-DICE and AD-WITCH, which are both based on more up to date information. Meanwhile, where regional specificity is required, results from AD-RICE are used in conjunction with AD-WITCH.

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[4] Climate models are usually run against scenarios that reflect different levels of human activity. The various SRES scenarios are based on different assumptions on future pollution, land use, and other driving forces. The A2 scenario reflects a divided world in which nations are self-reliant, economically oriented, and not environment-focused. The B1 scenario reflects instead a more integrated and ecologically friendly world in which there is resource-saving technical change, and a slower population growth. Finally, the B2 scenario is also ecologically friendly, but with less coordination between countries and more focus on local solutions.

Figure 2. Temperature in the models baseline scenarios compared to IPCC SRES

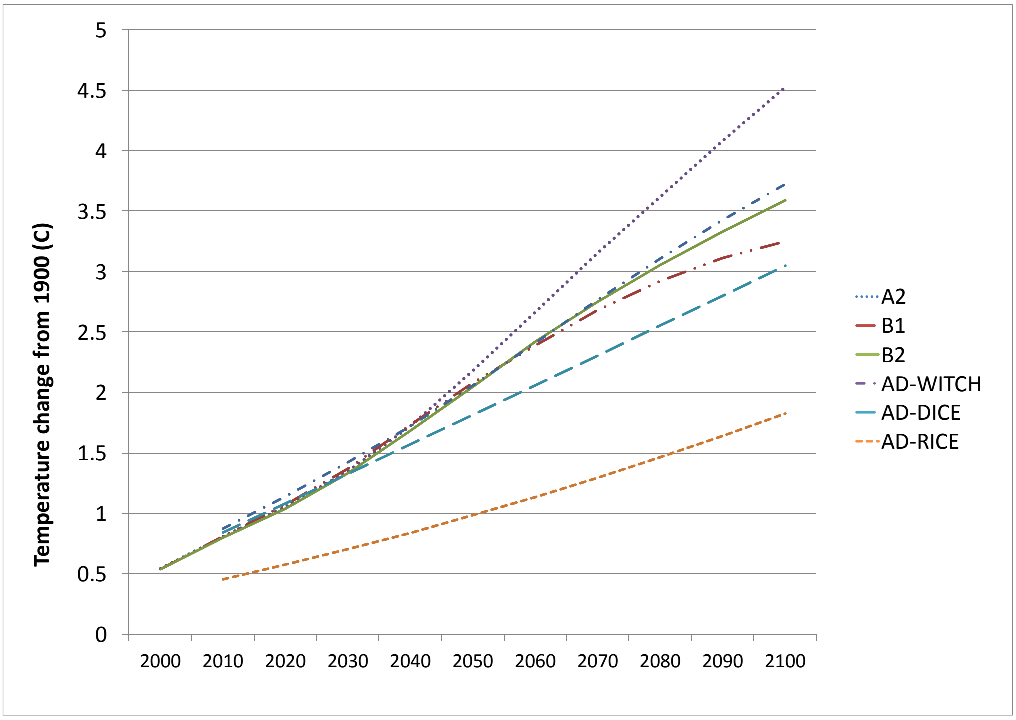


Figure 3. Emissions in the models baseline scenarios compared to IPCC SRES

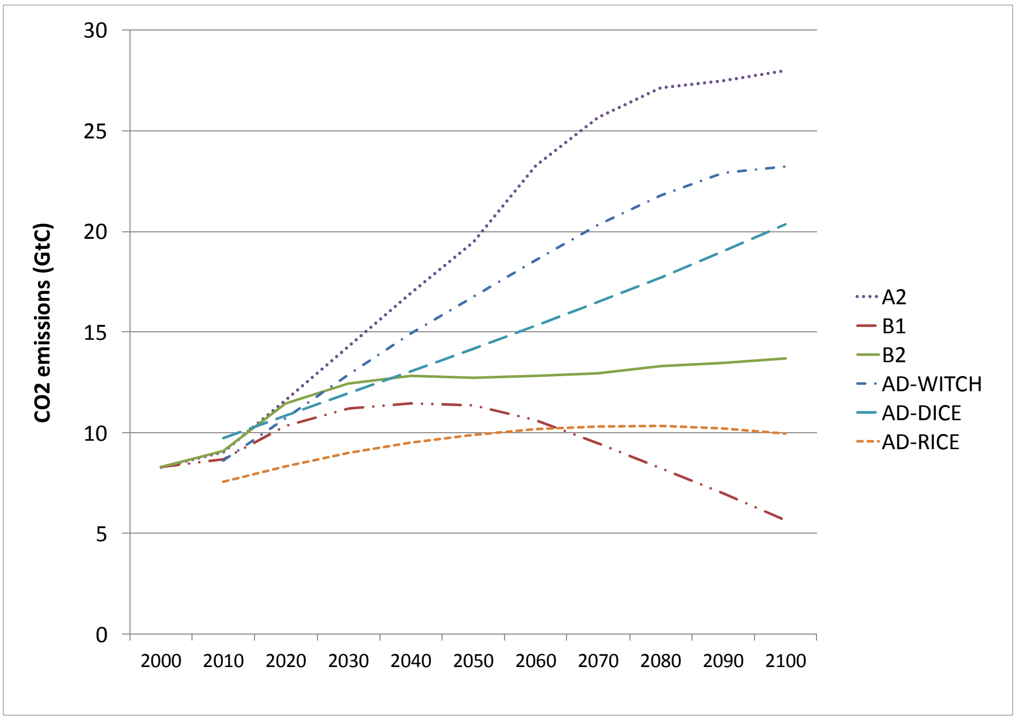
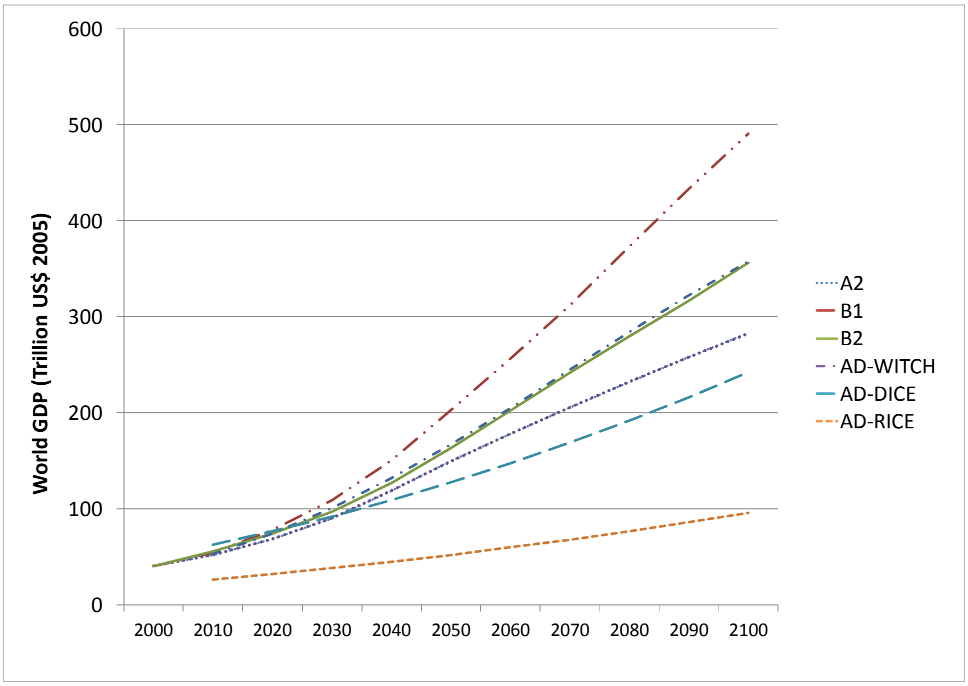


Figure 4. Output in the models baseline scenarios compared to IPCC SRES



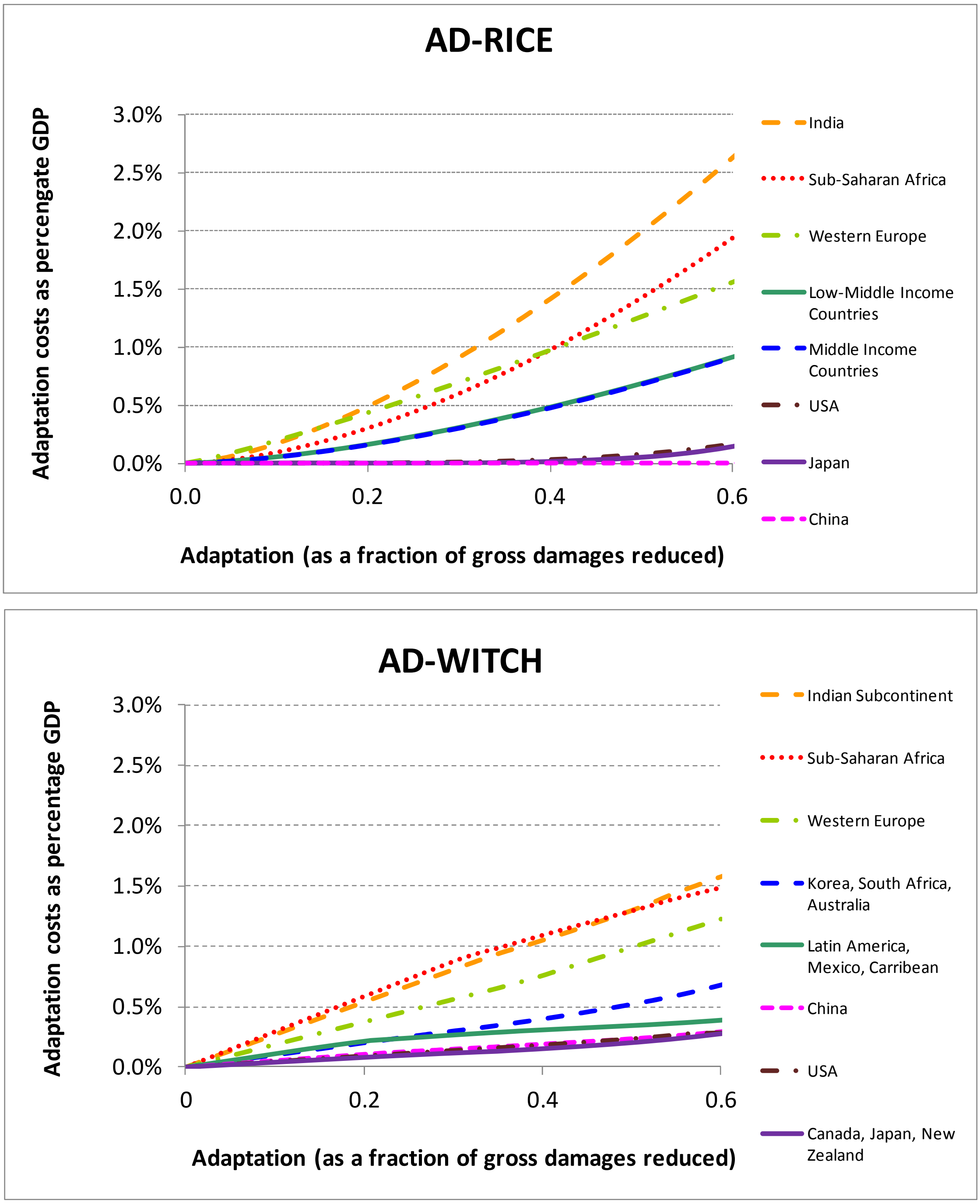
6. Results: Regional Adaptation Cost Curves

The use of the regional models AD-RICE and AD-WITCH allows estimating region-specific adaptation costs. In particular, it is interesting to study the regional *adaptation costs curves*. These illustrate the relationship between adaptation costs and the resulting benefits from reduced climate damages. The reduced climate damages are expressed here in terms of a parameter called “protection level”. The protection level refers to the fraction of climate damages that are offset by adaptation. Thus a protection level of 0.2 indicates that adaptation is able to offset climate damages by 20%.

The adaptation cost curves are region specific as they depend on the regional damages as well as the regional abilities to adapt to climate change. A major advantage of adaptation cost curves over many recent adaptation cost estimates is that they can provide a *dynamic* profile of adaptation costs. This is important, as projections of damages, mitigation and adaptation are expected to increase substantially over time. Further, the costs are mapped onto the benefits that might result from investing in adaptation. The other recent estimates generally do not quantify the benefits.

Figure 5 illustrates the adaptation cost curves from AD-RICE and AD-WITCH.

Figure 5. Regional Adaptation Cost Curves

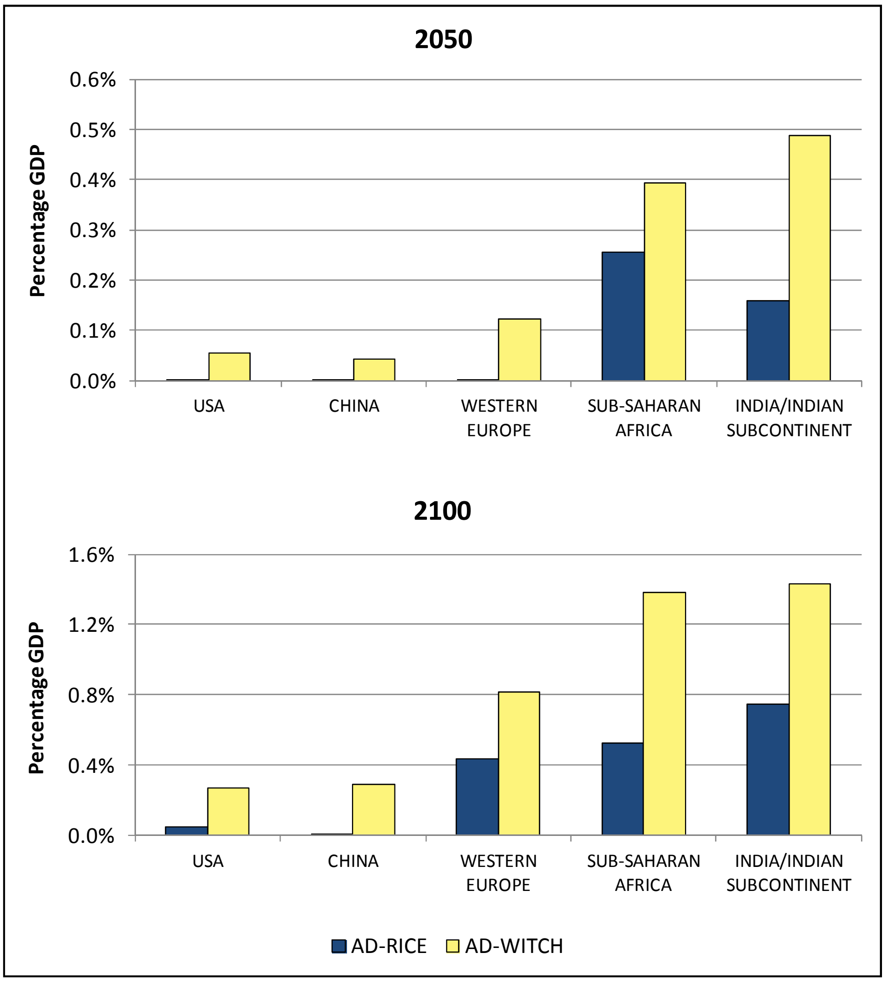


As shown in Figure 6, the normalised adaptation costs (as a percent of GDP) vary widely in the different regions but show reasonably consistent patterns for the two models. The regions with highest costs are the South Asia (India) and Sub-Saharan Africa. Meanwhile, Western Europe, South East and East Asia, Latin America and the Caribbean, Korea, South Africa and Australia, face intermediate normalised adaptation costs. Finally, three regions have particularly low adaptation costs, namely the USA, Japan and China in normalised terms, although the absolute costs would be substantial given the size of the GDP.

In addition to cost curves, regional adaptation costs can also be examined as a function of time (as opposed to the level of protection). As the optimal level of protection is determined endogenously for each region, different regions will achieve different levels of protection at any given time. Therefore, regional adaptation costs at any given time will be different from regional adaptation costs for a given level of protection. Figure 6 shows regional adaptation cost "snapshots" for the years 2050 and 2100 for five regions that are more or less comparable across the AD-RICE and AD-WITCH models: USA, China, Western Europe, Sub-Saharan Africa, and the Indian sub-continent. Again, the Indian sub-continent and Sub-Saharan Africa show the highest adaptation costs. However, in comparison with Figure 5 where AD-RICE costs tended to be higher for a given protection level, in this case costs tend to be higher in AD-WITCH. This is because the optimal level of protection undertaken for a given year is higher in AD-WITCH compared to AD-RICE.

The range in cost estimates across the two models is also quite significant. For example, for the Indian sub-continent, the adaptation costs range from 0.15 to 0.5% of GDP for the year 2050, and from 0.7% GDP to 1.4% GDP in the year 2100. For Sub-Saharan Africa the corresponding ranges are from 0.25% to 0.4 % of GDP in 2050 and from 0.5% to 1.4% of GDP in 2100.

Figure 6. Regional Adaptation Cost Estimates for 2050 and 2100



More than the specific numbers, these numerical ranges obtained from the comparison of just two models underscore the considerable uncertainties that underlie any estimation of adaptation costs. Other models, alternate parameterisations of regional climate damages, as well as other frameworks for incorporating adaptation may well further expand this range of uncertainty. Numerical estimates from these models therefore should be interpreted with caution.

In particular, results on the regional adaptation costs are critically dependent on the regional climate damage functions estimated by Nordhaus and Boyer (2000) that underlie the AD-RICE and AD-WITCH models. The damage functions in the IAMs used for this analysis are based largely on parameterisation developed by Nordhaus and Boyer (2000). These estimates have been partially updated for the DICE and WITCH models, but not for the RICE model. However, even the updated estimates (for example for the DICE 2007 model) have been criticised for underestimating climate change damages. A recent analysis by Hanemann (2008) on the USA suggests that the DICE model could underestimate damages by a factor of 4. Warren et al. (2006) also argue that results of IAMs are not fully reliable as they consider only a limited number of impact categories. These criticisms notwithstanding, other comprehensive damage estimates published in the peer-reviewed literature (e.g. Tol et al. 1998; Hope 2003; Mendelsohn et al. 2000) deliver results that are not significantly different from the estimates by Nordhaus and Boyer. A meta-analysis by Tol (2005) provides good insights into the uncertainties involved in damage estimates at the global level; clearly, the uncertainties are much larger at the regional level.

Higher climate damages in the underlying IAMs would affect at least two results in this analysis. First, achieving a certain level of protection under higher climate damages would involve higher adaptation costs. Therefore, in this case the adaptation cost curves will be higher at global and regional levels. Regions where the climate damages may have been particularly underestimated may therefore have higher adaptation cost curves than reported in this analysis. Second, higher climate damages would shift the adaptation mix towards more anticipatory investments, i.e. in building adaptation stock and adaptive capacity. In a similar way, higher damages would also affect the optimal adaptation and mitigation mix towards more investments in mitigation (see de Bruin et al., 2009a).

Despite these well-acknowledged limitations of existing climate damage functions, more comprehensive and up to date assessments of climate impacts and parameterisations of the associated damages that can be used within IAMs are not yet available. There is an urgent need for the climate impacts and modelling communities to develop this information. The potential for IAMs to inform policy relevant questions with regard to adaptation costs further adds to this urgency. Higher regional damages, in most cases, translate into higher regional adaptation costs. The differences in magnitude of adaptation costs between the models, meanwhile, come from differences in regional definitions, differing modelling philosophies, as well as differences in how adaptation is treated within the two models.

6.1 Components of the regional adaptation investment mix

Another dimension of regional adaptation costs relates to the regional mix of investments in stock and flow adaptation, which is illustrated in Figure 7.[5] As shown in this figure, investments in stock adaptation (and adaptive capacity) tend to dominate the mix of investments for both AD-RICE and AD-WITCH. This is not to say that (numerically) more stock adaptation actions will be undertaken. Stock forms of adaptation are generally more expensive and thus are more likely to constitute a bigger share of the adaptation budget. Again, this result highlights both the need for investing in adaptation infrastructure (and not just in reactive actions) as well as the need for explicitly incorporating such investments in any integrated assessment modelling work on adaptation.

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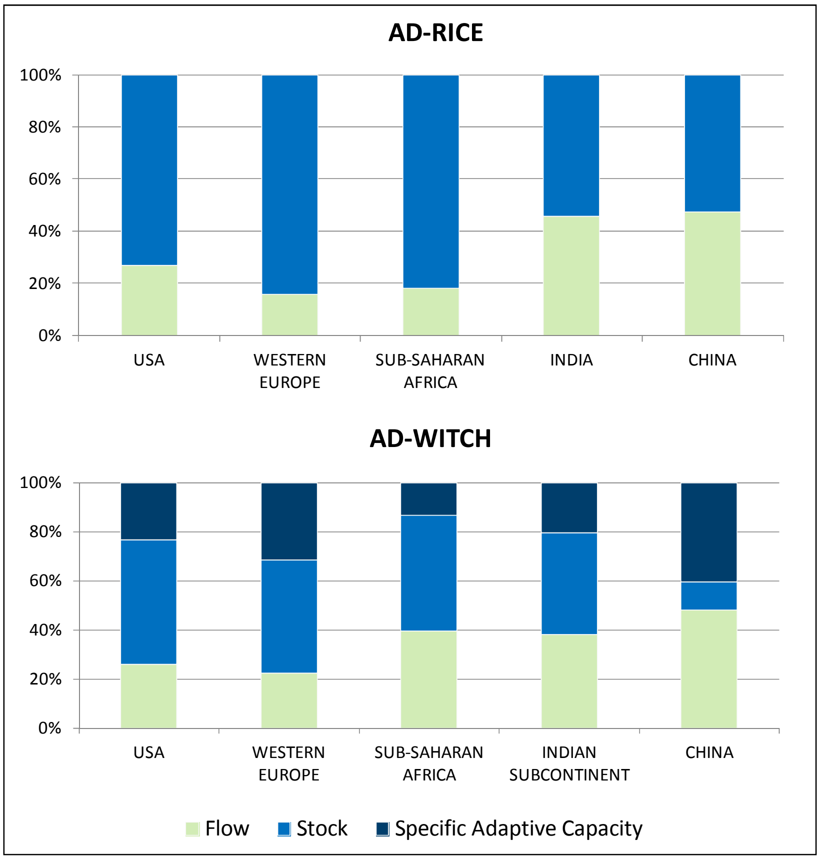
[5] At calibration point, for a 2.5 temperature increase.

Figure 7. Components of the regional adaptation investment mix



One region where the two regional models diverge in the optimal mix of adaptation investments is Sub-Saharan Africa. As shown in Figure 7, according to AD-RICE stock adaptation constitutes almost 80% of the adaptation budget. On the other hand, AD-WITCH only allocates 60% to investments in stock adaptation and adaptive capacity. This is because a key component of climate change impacts in Africa is in the health sector. A pre-requisite for adapting to these impacts is investment in strengthening the underlying public health infrastructure. While AD-RICE treats investments in building up basic public health infrastructure in Africa as stock adaptation, AD-WITCH considers it as a generic capacity or "core development" investment and therefore outside the adaptation budget.

These two differing perspectives underscore a very fundamental challenge facing international policy – how much of the adaptation deficit (such as lack of public health and other infrastructure) that is critical for the eventual success of many adaptation actions should be addressed as part of adaptation finance? Ultimately this is a matter of political choice, but adaptation-IAMs can potentially be used as tools to illuminate the implications of alternate choices.

7. Results: Composition of Adaptation Costs and the Role of Adaptive Capacity

This section details the composition of the evolution of the climate change costs and their components (gross damages, residual damages, adaptation expenditures) in AD-DICE[6] and AD-WITCH. This is

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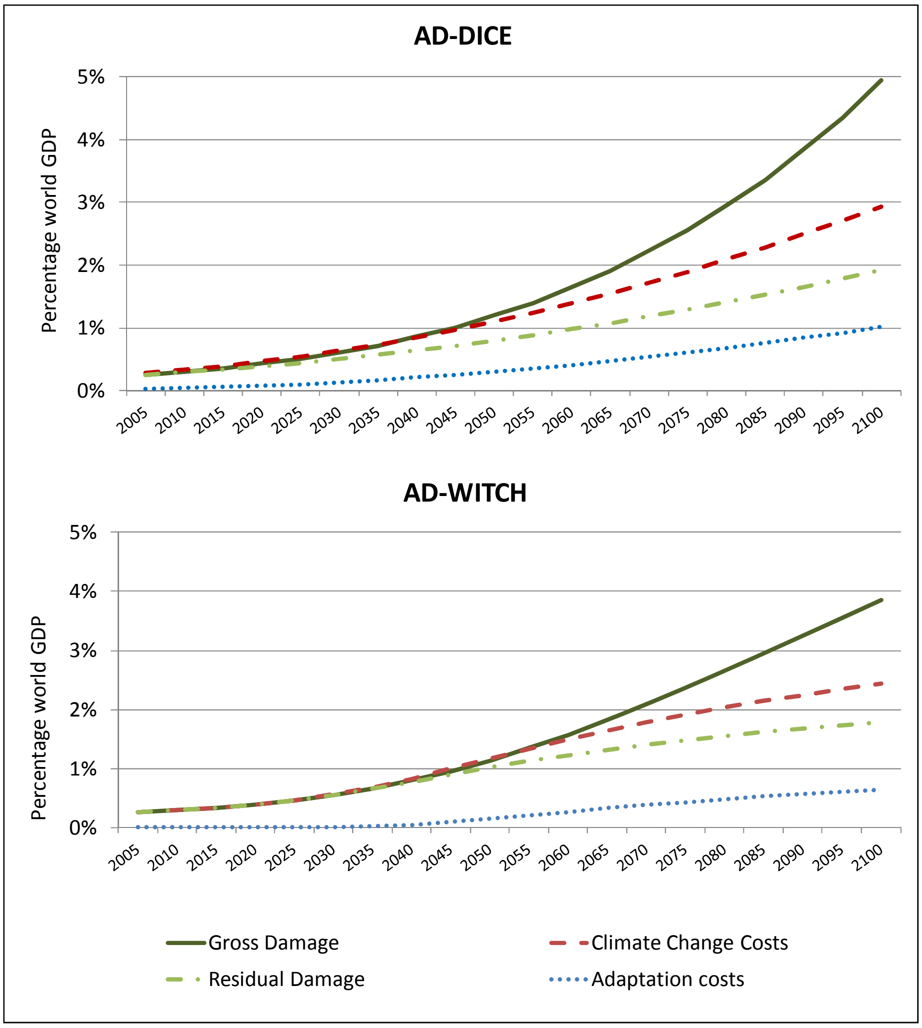
[6] While the AD-RICE model has been used for the study of regional adaptation costs, the AD-DICE model will be used for the global analysis. This choice is based on the fact that the DICE model has an updated dataset (from 2007), which is also more similar to WITCH, and thus more suitable for the comparison between the two models.

followed by a closer examination of the composition of the mix of adaptation expenditures between stock and flow adaptation in these two models. The final part of this section takes a closer look at investments in adaptive capacity, which is modelled explicitly in AD-WITCH. The scenarios examined in this section do not include mitigation. Adaptation-mitigation interactions will be examined in the following section.

7.1 The role of adaptation in reducing climate change costs in the absence of mitigation

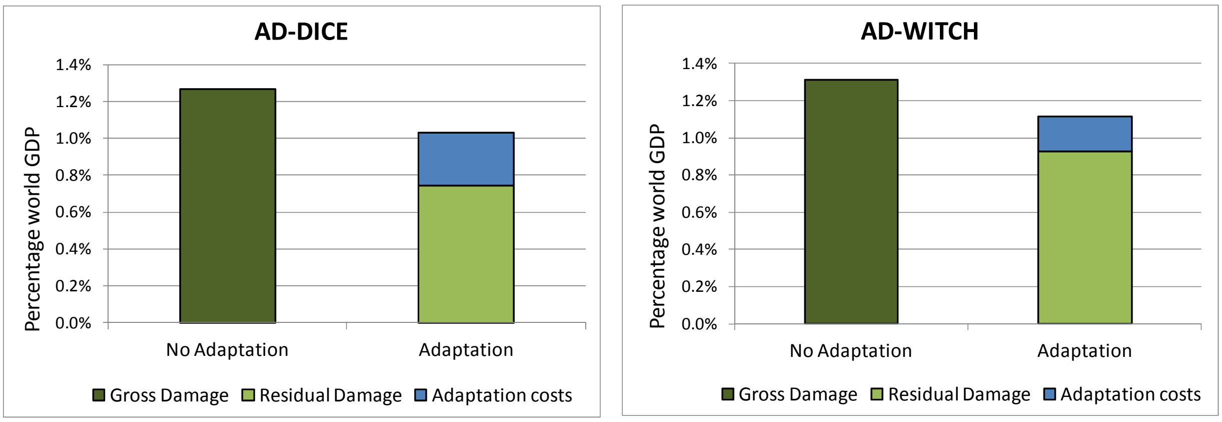
Adaptation can significantly reduce the damages resulting from climate change, even if it comes at a cost. Figure 8 shows the results from the "optimal adaptation, no mitigation" scenario in AD-DICE and AD-WITCH models. The gross damages (in the absence of adaptation) are higher than the "climate costs" i.e. the sum total of residual damages (in the presence of adaptation) and the costs of adaptation. The gross damages and the climate change costs in AD-DICE amount respectively to 5 and 3 percent of world GDP in 2100, whereas in AD-WITCH they are around 4 and 2.5 percent respectively.

Figure 8. Composition of Climate Change Costs under optimal adaptation and no mitigation



The Net Present Value (NPV)[7] of costs over the current century, as illustrated in Figure 9, show that overall climate change costs with no adaptation are higher (i.e. the NPV of gross damages is higher than the NPV of the sum of residual damages and adaptation costs). Investments will need to be made in earlier years, even though the benefits are only reaped in later periods.

Figure 9. Composition of Climate Change Costs in NPV under optimal adaptation and no mitigation



The costs of adaptation are 0.28 and 0.19 % of world GDP in the AD-DICE and AD-WITCH models respectively. The benefits from adaptation (calculated as difference in between the gross and net damages) are 0.51 and 0.38 % world GDP respectively. Therefore, the net benefits of adaptation are 0.23 % world GDP both in AD-DICE and of 0.20 % world GDP in AD-WITCH.

The benefit-cost ratio of adaptation is greater than 1 for both models (1.80 in AD-DICE and 2.03 AD-WITCH).[8] Thus adaptation is cost-effective in both cases, and in particular the benefits are approximately double of the costs. As a consequence of the reduction of climate change costs, adaptation also results in an increase in world output. Output increases by 1.4% in AD-DICE and by 0.5% in AD-WITCH. As more damages are reduced in AD-DICE, there is also a higher welfare gain in this model.

7.2 Composition of adaptation costs: stock, flow, and adaptive capacity

This section examines the relative importance and evolution of flow and stock adaptation, as well as specific adaptive capacity. These three components of adaptation costs can be expected to behave in different ways, as the different duration of the benefits influences the decision to invest. Figure 10 illustrates stacked investments in stock and flow adaptation and in specific adaptive capacity over time. The figure also shows snapshots of the relative contribution of the different types of adaptation expenditures for the years 2035, 2070, and 2100 to show how the mix changes over time.

As shown in Figure 10, the total adaptation costs build up slowly in the first few decades of this century but rise as climate damages increase in the latter half of the century. In the year 2100, the total adaptation costs range from 0.6 – 0.8 % of world GDP in the AD-WITCH and AD-DICE models respectively. Whereas in AD-DICE adaptation starts immediately, even if at low levels, in the AD-WITCH model it begins to emerge only after around 2025. This is a consequence of the assumptions on the adaptation costs over time in the models.

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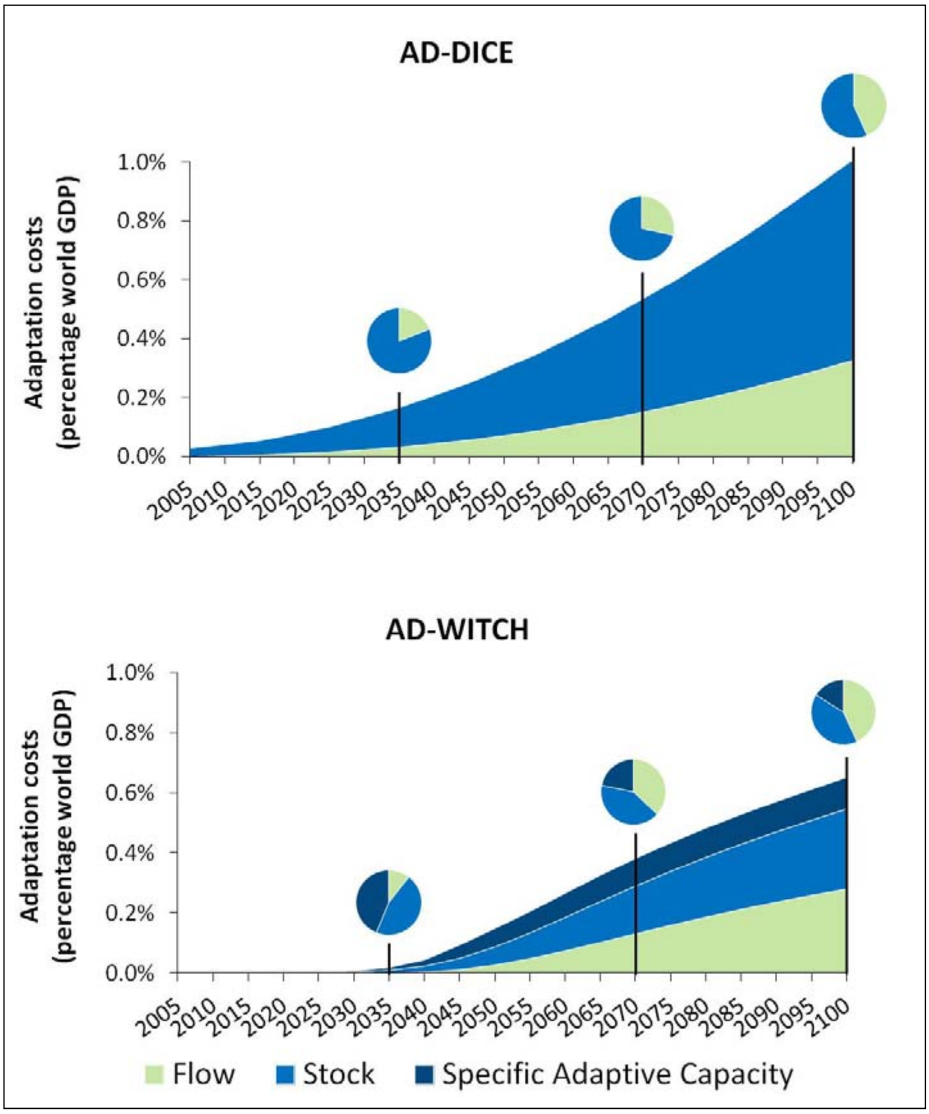
[7] The Net Present Value (NPV) is a method for evaluating the profitability of an investment or project. The net present value of an investment is the present discounted value of present and future cash flows.

[8] These benefit-cost ratios can be considered as an upper bound as they correspond to a no-mitigation scenario.

Both AD-DICE and AD-WITCH show similar patterns in terms of the overall mix of adaptation strategies. Both stock and flow forms of adaptation are important, although investments in stock adaptation (and specific adaptive capacity) tend to dominate for much of this century. There is also a difference in timing between stock and flow adaptation. Investments in stock adaptation start at an earlier date. This is because there is some time delay between the investments in stock adaptation and the realisation of benefits. As such they are anticipatory investments. Further, the benefits from stock adaptation last longer. For both these reasons it is reasonable to invest at an earlier date.

Figure 10. Breakdown of adaptation cost components



As illustrated by the pie charts embedded in Figure 10, stock adaptation constitutes almost 75% of the optimal adaptation mix for AD-DICE in the year 2035, and drops to about 55% by the end of the century. In the case of AD-WITCH, investments in stock adaptation and specific adaptive capacity constitute almost 90% of the optimal adaptation mix in the year 2035, dropping to about 55% by the end of the century. The prevalence of stock measures is also due to the higher cost of stock adaptation actions. However, it is necessary to point out that higher investments in adaptation stocks do not necessarily mean a higher number of adaptation actions of stock type. Stock adaptation actions are normally more expensive, therefore it is still likely that there are more flow adaptation actions despite the higher amount of investment in stock adaptation.

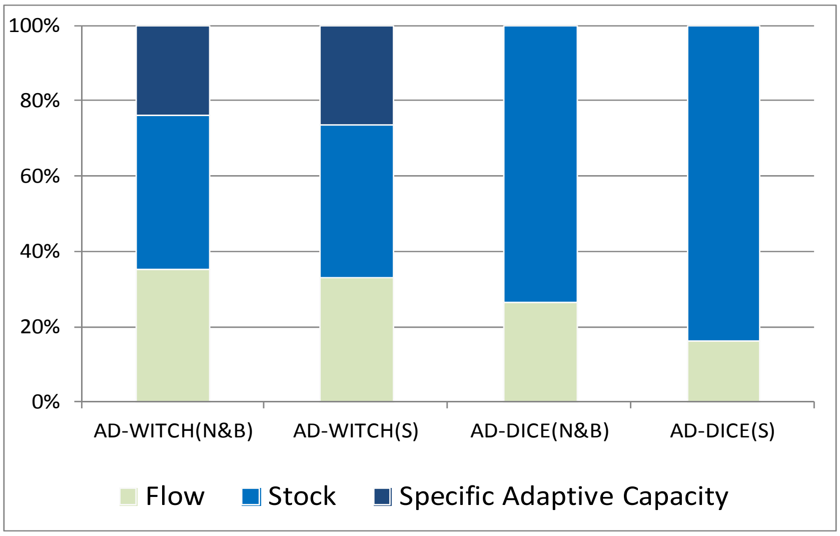
These results offer important pointers for allocation of adaptation financing. Specifically, sufficient upfront investments in adaptation infrastructure and in building up adaptive capacity should be important components of an overall investment strategy in addition to more reactive measures.

Box 1. Effect of alternate discount rates

The level and composition of adaptation costs depends upon the choice of the discount rate in the underlying models, specifically of the "pure rate of time preference" (PTP) that discounts the welfare of future generations relative to the present. The model formulations used in this report use the PTP proposed by Nordhaus and Boyer (2000) of 3 % declining over time, which has been criticised as being too high. Therefore a comparison is made here to check the sensitivity of the results by applying a very low PTP of 0.1 per cent, as proposed by Stern (2007).

Applying a lower pure rate of time preference makes the agents more far-sighted and therefore more likely to invest in stock adaptation and in building adaptive capacity that offer delayed benefits. This is illustrated in Figure 11 that shows the composition of adaptation costs (in Net Present Value) in AD-DICE and AD-WITCH under the high Nordhaus and Boyer (N&B) and low Stern (S) discount rates. Under the Stern discount rate, stock adaptation constitutes almost 82% of the adaptation costs in AD-DICE, an almost 20% increase compared to when the Nordhaus and Boyer discount rate is used. Likewise, in the AD-WITCH model, investments in stock adaptation and adaptive capacity under the Stern discount rate constitute almost 55% of the adaptation mix, a 10% increase compared to when the Nordhaus and Boyer discount rate is used.

Figure 11. Adaptation strategy mix for different models and discount rates



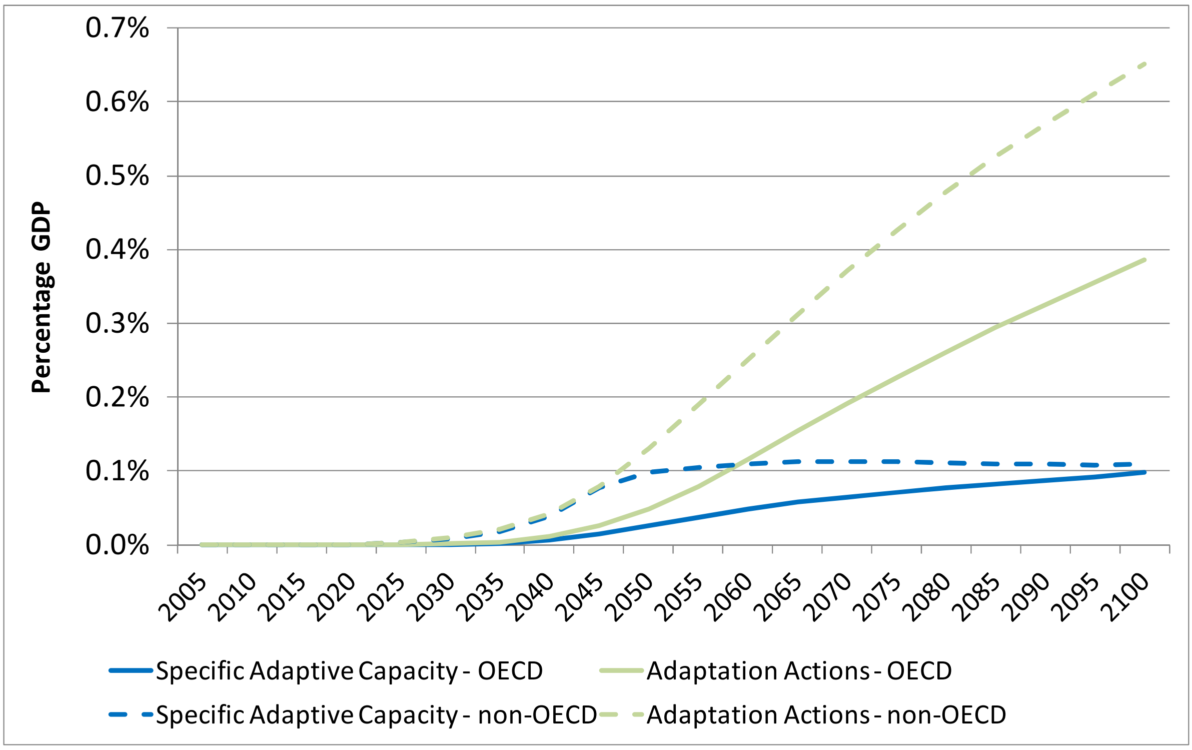
Lower discount rates would tend to skew investments away from reactive adaptation towards more proactive investments in building adaptation stock and adaptive capacity. Therefore, investments in adaptation stock and in building adaptive capacity behave more like investments in mitigation (as opposed to flow adaptation) due to the need for upfront investment and lagged benefits.

7.3 The role of adaptive capacity

An interesting addition of the AD-WITCH model is the further decomposition of adaptation costs into adaptation actions that directly reduce climate change damages and adaptive capacity. In particular, two forms of capacity are considered: generic and specific adaptive capacity. Generic capacity is meant to reflect the fact that countries with a higher level of development already have better safety nets, health infrastructure, telecommunications facilities, that also allow them to adapt more effectively to climate change. Specific adaptive capacity instead represents investments in the creation of capacity explicitly aimed at reducing the damages from climate change, such as investing in early warning systems.

While generic adaptive capacity does not account as a direct adaptation cost, it is interesting to compare investments in specific adaptive capacity as opposed to adaptation actions. Figure 12 shows the optimal allocation of resources between adaptation actions and specific adaptive capacity for OECD and non-OECD countries. Investments in both adaptive capacity and adaptation actions constitute a much higher share of GDP in non-OECD countries than in OECD countries. This is because OECD countries overall are less vulnerable to climate change given their higher levels of development and pre-existing levels of specific adaptive capacity (such as early warning systems). Further, an optimal adaptation mix in non-OECD countries will consist of almost equal investments in building adaptive capacity and in actions that directly reduce climate damages in the first half of the century. This reflects the considerable adaptation deficit as well as greater exposure to climate damages in these countries. However, once a sufficient level of adaptive capacity is built up, investments in adaptation actions (as opposed to building adaptive capacity) will dominate the strategy mix in both non-OECD and OECD countries in the second half of the century.

Figure 12. Adaptation actions and adaptive capacity: regional optimal mix



8. Results: Adaptation-Mitigation Interactions

A key motivation for including adaptation in IAMs, as mentioned previously, is that it permits the examination of the interactions between adaptation and mitigation. Both mitigation and adaptation help to reduce the risks of climate change. Mitigation – through the reduction in sources or the enhancement of sinks of greenhouse gases – reduces all impacts of climate change. Adaptation – through adjustments in human and natural systems – reduces the net impacts from changes in climate.

This section provides quantitative and qualitative insights on the interrelationship between mitigation and adaptation. In particular, the effects of mitigation on optimal adaptation patterns are analysed. The mitigation policy considered here is the stabilising CO_2-eq concentrations at 550 ppm (corresponding to a temperature of around 2.5 °C above pre-industrial levels at the beginning of next century).[9] This stabilisation level for mitigation is used purely for illustrative purposes to study the tradeoffs between mitigation and adaptation and should not be viewed as policy prescriptive.

In the AD-WITCH model, given the stabilisation target, investments in different energy technologies, physical investments, and R&D expenditure are chosen to minimize the costs of achieving this stabilisation. The possibility to invest in R&D, and the presence of more expensive mitigation technologies, makes costs higher and skewed towards the beginning of the century in the AD-WITCH model. Therefore, compared to AD-DICE, more early investments in mitigation take place.

In order to study the effects of such a mitigation policy and its interactions with adaptation expenditures, four different reference scenarios are examined in this report:

- **NO CONTROLS**: no adaptation and no mitigation (inaction scenario);
- **ADAPTATION**: scenario with optimal adaptation and no mitigation;
- **MITIGATION**: 550ppm stabilisation without adaptation;
- **ADAPTATION+MITIGATION**: 550ppm stabilisation with optimal adaptation.

The Adaptation + Mitigation scenario makes it possible to investigate the potential role of adaptation in the presence of a specific mitigation policy. This approach is consistent with the large majority of climate change policy studies, but it adds adaptation as a new variable. Here, optimal investments in adaptation are chosen, given the optimal mitigation portfolio to achieve the pre-specified 550ppm stabilisation target. Adaptation does not contribute to the achievement of the stabilisation target but it contributes to reducing the net climate damages and the total climate costs associated with such a stabilisation scenario.

Figure 13 illustrates the individual and joint benefits of mitigation and adaptation policies by comparing residual damage across the four scenarios.[10] The highest residual damage occurs in the case of complete inaction (i.e. no adaptation or mitigation). When only adaptation or only mitigation is undertaken, the residual damages are intermediate. Meanwhile, the lowest residual damages occur when adaptation and mitigation are used in conjunction. This highlights the complementarity between mitigation and adaptation that was also previously raised by the IPCC Fourth Assessment Report (Fisher et al. 2007).

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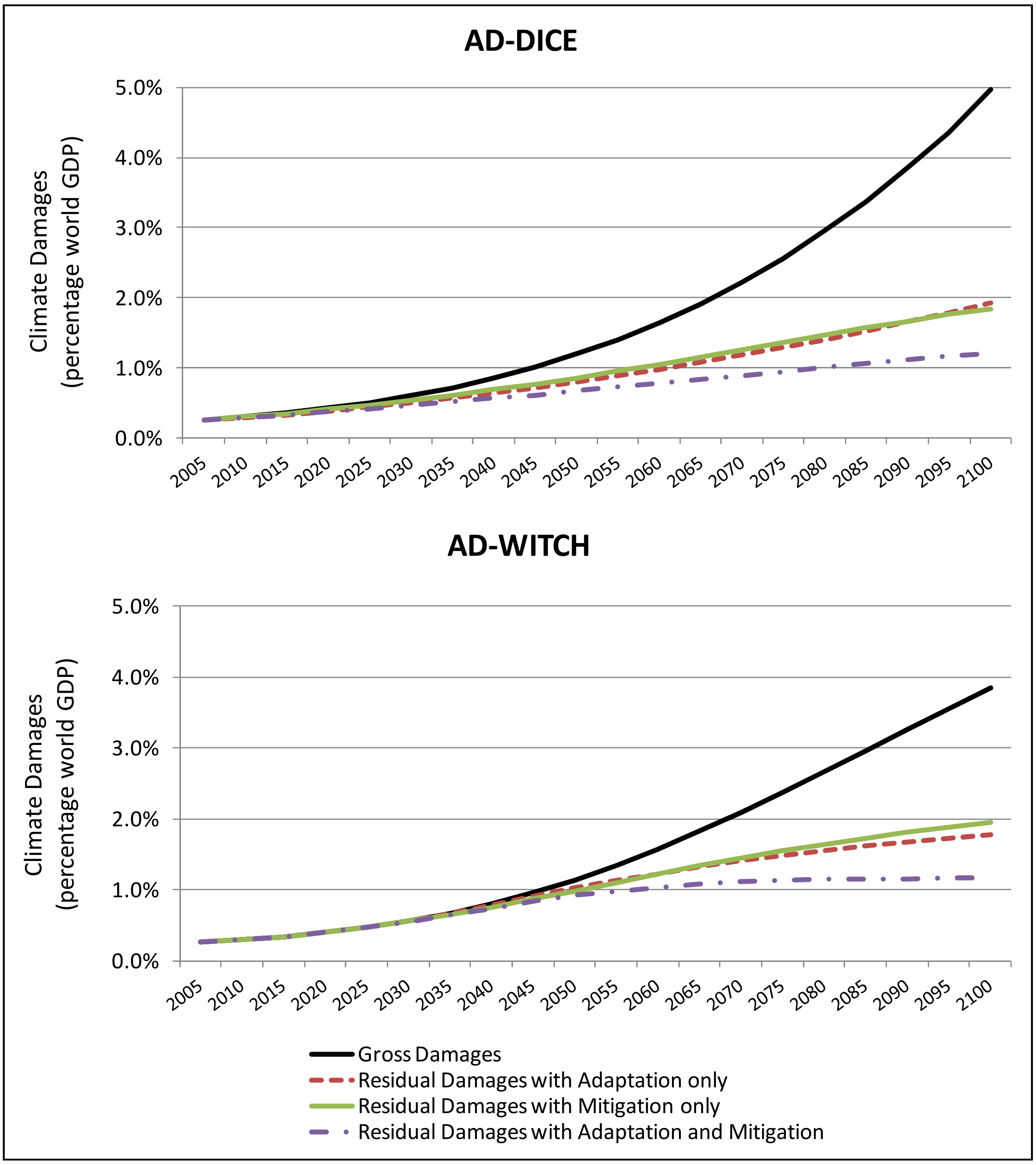
[9] The models are solved cooperatively, so that the 550ppm target is achieved though international cooperation.

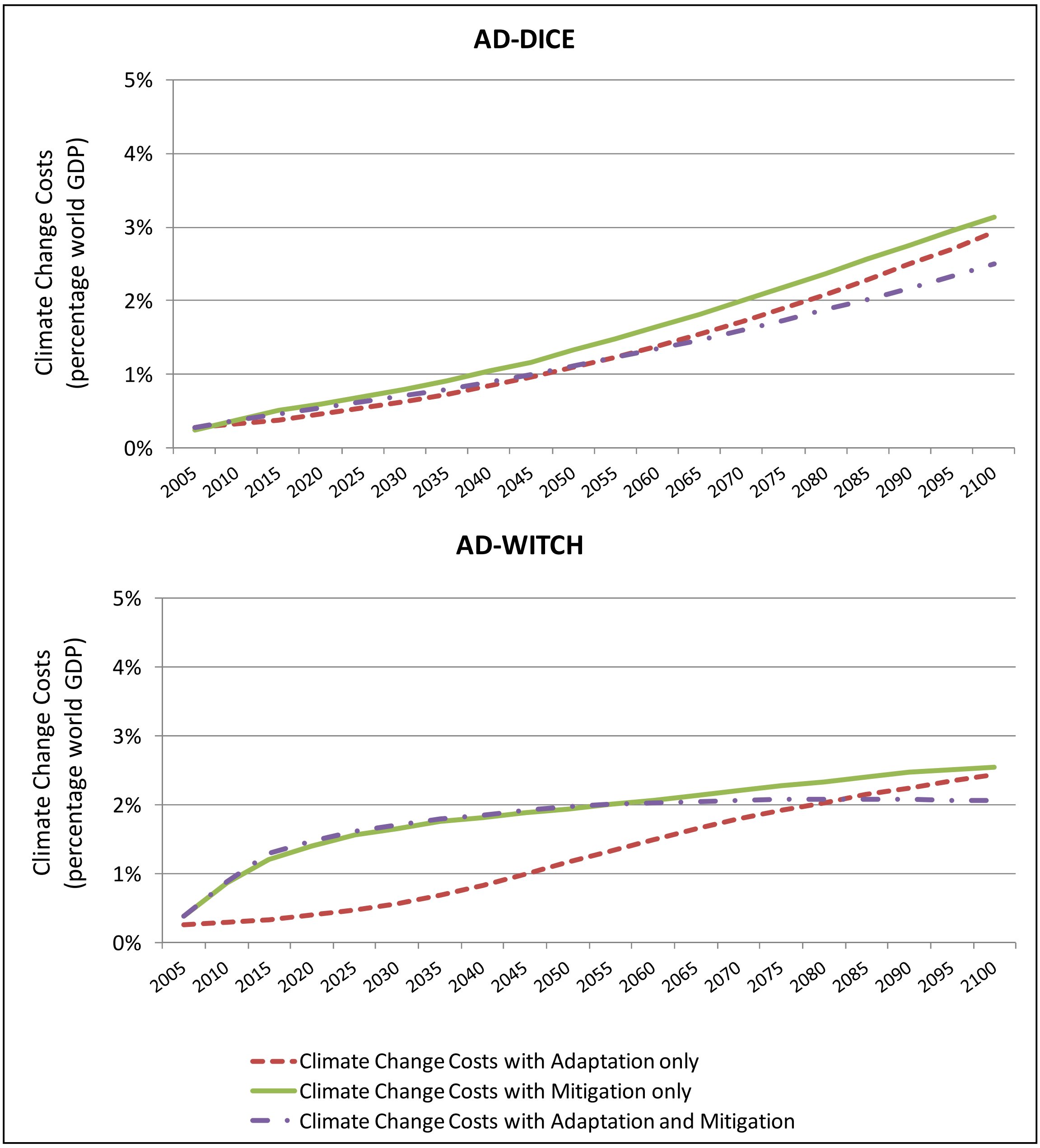
[10] Note that in the baseline scenario gross damage coincides with residual damage.

Figure 13. Effect of mitigation and/or adaptation on reducing damages



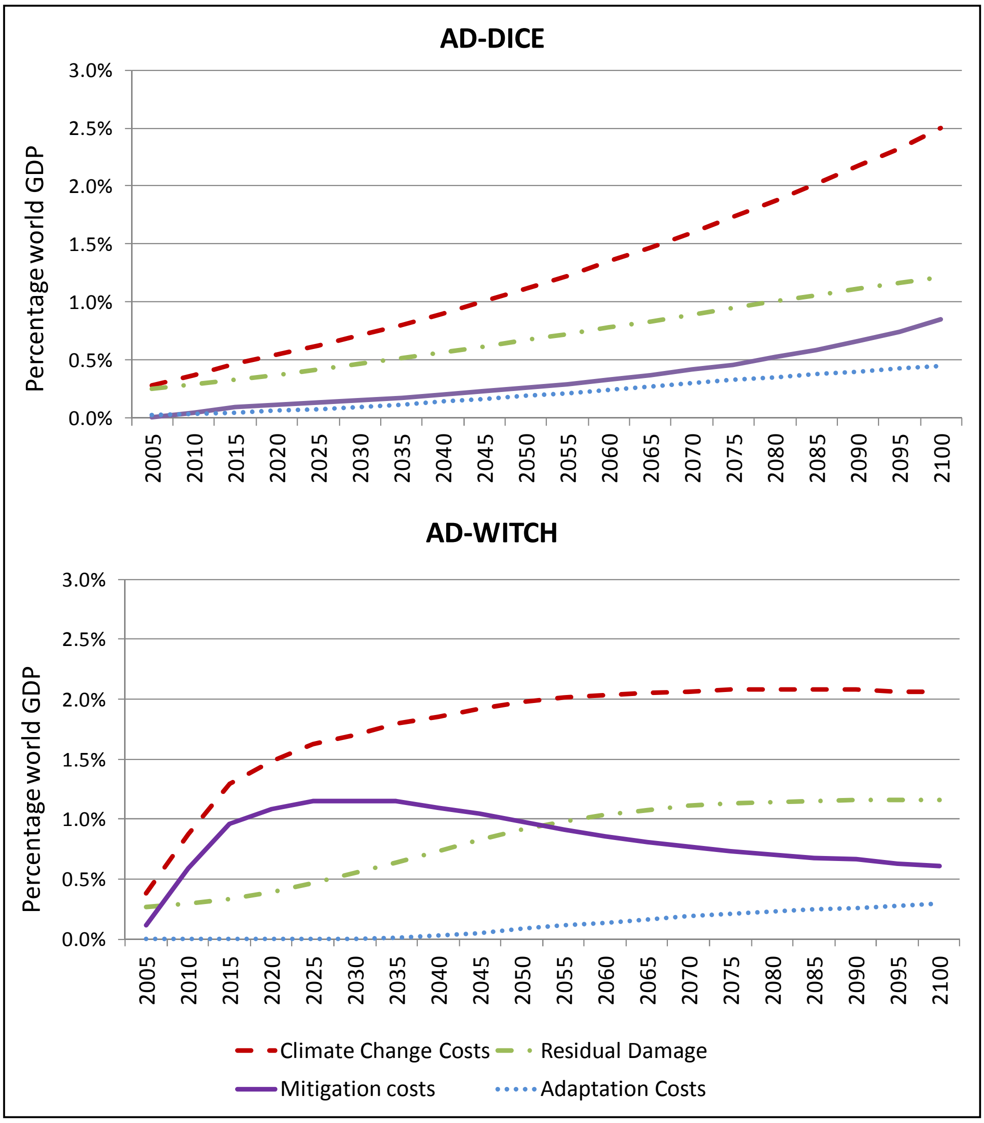
Although the results are similar in terms of how mitigation and adaptation reduce climate damages for the two models, the situation on the *costs* side is considerably different. Figure 14 shows the climate costs (i.e. adaptation and/or mitigation costs plus residual damages) side for the three policy scenarios (adaptation only, mitigation only and adaptation plus mitigation). While AD-DICE shows a monotonic build-up in costs under all scenarios, the results are markedly different for the two mitigation scenarios in AD-WITCH where costs build up very quickly early in the present century. This is because in order to achieve the stringent 550 ppm stabilisation target, it is necessary to invest in mitigation immediately due to the time lag in realising the benefits of such investments. This effect is present in both models but is much stronger in the AD-WITCH model because of the presence of a disaggregated energy sector and innovative technologies for which it is necessary to invest early.

Figure 14. The costs of climate change for the mitigation and/or adaptation scenarios



The dominating influence of the time profile of mitigation costs on the shape of the total cost curve is further illustrated in Figure 15 that unpacks the total costs for the Mitigation + Optimal Adaptation scenario into its three components: adaptation costs, mitigation costs and residual damages. The breakdown of costs, especially for the AD-WITCH model, allows a better understanding of the shape of the total climate change costs curve. Mitigation costs play a large role in determining the shape of the total climate cost curve. As is evident from this figure there is a substantial difference between AD-DICE and AD-WITCH in the time path of mitigation costs. They increase steadily over time in AD-DICE but are higher and skewed at the beginning for AD-WITCH, due to the manner in which the model treats mitigation investments.

Figure 15. Composition of climate costs in the presence of both adaptation and mitigation

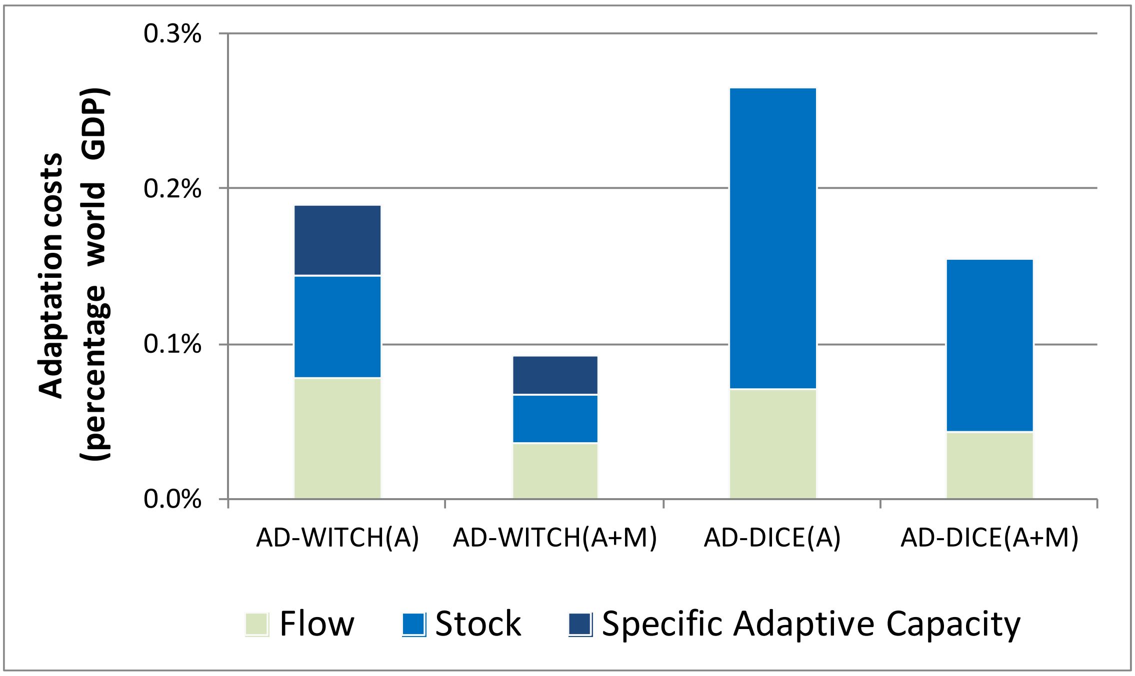


It is important to underline that the results should not be interpreted as suggesting that mitigation cost are higher in AD-WITCH. The difference is in the *timing* of the mitigation investments, which are also influenced by the overall time frame considered. The present analysis is limited to the year 2100. If, however, a longer time period were to be considered, then mitigation costs would continue to increase in AD-DICE and decrease in AD-WITCH.

Finally, this joint analysis of adaptation and mitigation can be used to offer insights on how the level and nature of investments in adaptation are affected by the presence of a (strong) mitigation policy. Figure 16 addresses this question by comparing (in Net Present Value terms) the level and mix of adaptation investments under the Adaptation + Mitigation (A+M), and the Adaptation (A) only scenarios for AD-DICE and AD-WITCH models.

As shown in Figure 16, the presence of a strong mitigation policy considerably lowers the optimal level of resources invested in adaptation. In this regard, mitigation and adaptation behave as partial substitutes. This is logical, in part because mitigation and adaptation may compete for resources but more importantly because stringent mitigation efforts would also reduce climate damages and therefore lower the need for adaptation investments over the long term. The fact that the optimal investment in adaptation declines in the presence of mitigation also illustrates that these two policy levers can be optimally combined to reduce climate damages. The presence of mitigation also alters the mix of adaptation investments. The share of investment in stock adaptation (and adaptive capacity) is reduced more than for flow adaptation in the presence of mitigation. This effect is particularly pronounced in the case of AD-DICE. Stock adaptation is indeed more similar to mitigation, with the need for upfront investments and lagged benefits.

Figure 16. Effect of mitigation on the level and mix of adaptation costs



9. Concluding Remarks

This report has sought to address critical questions with regard to the costs of adaptation and their distribution both over regions and over time. This is accomplished by developing a framework to incorporate adaptation as a policy choice variable within the context of three global Integrated Assessment Models (IAMs): DICE, RICE and WITCH. These modified models, AD-DICE, AD-RICE and AD-WITCH are calibrated and then used in a number of policy simulations to examine the composition of adaptation costs, as well as the interaction between adaptation and mitigation.

The framework to model adaptation developed in this report not only includes treatment of reactive adaptation actions, but also investments in adaptation stocks. This is significantly more comprehensive than the framework developed in the earlier report from this project that only considered adaptation as a "flow" variable, wherein all of its costs and benefits accrue just in one time period. Consequently, the dynamic aspects of adaptation, as well as the interactions between adaptation and mitigation are much better addressed in the current framework.

Besides stock and flow adaptation, the adaptation variant of the WITCH model is also used to distinguish between investments in building *adaptive capacity* and those used for adaptation actions that directly reduce the net climate damages. This is the first explicit treatment of adaptive capacity in economic modelling frameworks for assessing adaptation costs.

This report also presents the first inter-model comparison of results from the emerging category of adaptation-IAMs. The comparative nature of this assessment also facilitates testing of the robustness of some of the policy relevant results, as well as getting a better understanding of some of the uncertainties involved, for example in the case of regional adaptation cost curves. This in turn can be used to inform policy and also to guide further work on data collection and model development.

This analysis demonstrates that all types of adaptation options are important in offsetting some of the adverse impacts of climate change. These range from autonomous, reactive measures at one end to anticipatory investments in adaptation stock such as coastal protection infrastructure. They also include investments in adaptive capacity, in addition to measures that directly reduce climate damages. The costs and the policy mix of these investments, however, vary considerably across regions, over time, and depend upon the level of mitigation as well as assumptions about climate damages and discount rates. More important than the specific numbers, the inter-model comparison seeks to highlight the key drivers that underpin adaptation cost estimates.

The two regional adaptation-IAMs developed for this study, AD-RICE and AD-WITCH, show a number of consistent trends in regional cost curves. South Asia (India) and Sub-Saharan Africa generally show the highest adaptation costs (in % GDP terms), followed by low-income countries of East Asia and Western Europe. Meanwhile, Japan, USA and China fall at the lower end of spectrum in the case of both models in terms of costs as a % of GDP, although the adaptation costs in absolute terms are substantial in these regions. Regional adaptation costs are also examined as a function of time, as opposed to the level of protection. Cost "snapshots" for the years 2050 and 2100 are presented that show the highest adaptation costs in the Indian sub-continent and Sub-Saharan Africa. The range in cost estimates across the two models, however, is quite significant. For example, for the Indian-sub continent the adaptation costs range from about 0.15 to 0.50% of GDP for the year 2050, and from about 0.7% GDP to 1.4% GDP in the year 2100. For Sub-Saharan Africa the corresponding ranges are from 0.25% to 0.40 % of GDP in 2050 and from 0.5% to 1.4% of GDP in 2100.

These numerical estimates of adaptation costs however are preliminary and critically dependent upon the specification of the climate damages used in the two regional models examined here. There is an urgent need for a comprehensive effort to update information on regional damages that are used as inputs into these models to reflect more recent information from assessments like the IPCC Fourth Assessment Report as well as subsequent literature. More than the specific numbers, these numerical ranges obtained from the comparison of just two models highlight the considerable uncertainties that underlie any estimation of adaptation costs. Other models, alternate parameterisations of regional climate damages, as well as other frameworks for incorporating adaptation may well further expand this range of uncertainty.

The analysis presented in this report also shows that the timing and composition of adaptation interventions is also particularly critical. Investments in adaptation stocks become effective with a time delay, and should ideally be implemented early. As time goes by, however, the convexity of climate damages would imply that there would be limits to what can be accommodated with preventive investment on adaptation stock. Greater investment in reactive adaptation would therefore become increasingly necessary, although even these investments would reach their limits if climate damages continue to increase.

Besides the build-up in the stock of adaptation infrastructure, it is equally critical to build up adaptive capacity. Adaptive capacity (both generic and specific to climate change) is currently larger in OECD countries, and this provides the enabling environment to enhance the efficacy of adaptation actions. For non-OECD countries, on the other hand, greater investment in building adaptive capacity would be an essential prerequisite for more effective adaptation downstream. A fundamental challenge facing international policy is how much of this development deficit (such as lack of public health and other infrastructure) should be addressed as part of adaptation finance. Ultimately this is a matter of political choice, but adaptation-IAMs that distinguish between stock, flow and adaptive capacity of the type developed in this report can be used as tools to illuminate the implications of alternate choices.

This report also shows that both mitigation and adaptation are important in responding to climate change and should be part of a climate policy portfolio. The timing of the investments in adaptation and mitigation are also very important. In this respect, the results obtained with the AD-WITCH model, whose results on mitigation rely on a more detailed representation of the energy sector, diverge from the AD-DICE results on the timing of the strategies. According to WITCH, significant mitigation expenditure should take place in the near term, because of the inertia in the climate system, as well as the time-lags that are needed to put such investments and capacity in place. Therefore, according to the AD-WITCH results, investments should be made primarily in mitigation at the beginning of the century, while adaptation investments become progressively more important later. On the other hand, according to DICE and RICE, gradual build-up of mitigation action is optimal. For adaptation, this implies that there would be a greater emphasis on adaptation in earlier decades in response to the impacts of climatic changes that are already locked-in.

Finally, these models clearly illustrate that the different climate policy options are both complements and substitutes: they are complementary in the sense that any least-cost policy response to climate change will need to involve substantial amounts of mitigation efforts, investments in adaptation stock and reactive adaptation measures to limit the remaining damages. These options are substitutes in the sense that they compete for limited resources, and investing heavily in one option will reduce both the budget available for the other policy levers as well as the relative need for other policies. In particular, when optimal levels of action in one of these policies cannot be attained, there are possibilities to limit the excess costs by adjusting the other policies.

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ANNEX 1. OVERVIEW OF THE INTEGRATED ASSESSMENT MODELS

The DICE and RICE models

The RICE and DICE models are integrated economic and geophysical models of the economics of climate change. DICE is a dynamic integrated model of climate change in which a single world producer-consumer makes choices between current consumption, investing in productive capital, and reducing emissions to mitigate the effects of climate change (Nordhaus 1994, 2007). RICE is an extension of DICE and includes multiple regions and decision makers, to permit more disaggregated analyses (Nordhaus and Yang 1996; Nordhaus and Boyer 2000).

The Dynamic Integrated model for Climate and the Economy (DICE) was originally developed by Nordhaus in 1994 and updated most recently in 2007. It is a global model and includes economic growth functions as well as geophysical functions. In this model, utility, calculated as the discounted natural logarithm of consumption, is maximised. In each time period, consumption and savings/investment are endogenously chosen subject to available income reduced by the costs of climate change. The climate change damages are represented by a damage function that depends on the temperature increase compared to 1900 levels.

RICE is a regional version of DICE. It consists of 13: Japan, USA, Europe (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Greenland, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom), Other High Income countries (OHI: Australia, Canada, New Zealand, Singapore, Israel, and rich island states), Highly Industrialised Oil exporting regions (HIO: Bahrain, Brunei, Kuwait, Libya, Oman, Qatar, Saudi Arabia, and UAE), Middle Income countries (MI: Argentina, Brazil, Korea, and Malaysia), Russia, Low-Middle income countries (LMI: Mexico, South Africa, Thailand, most Latin American states, and many Caribbean states), Eastern Europe (EE), Low Income countries (LI: Egypt, Indonesia, Iraq, Pakistan and many Asian states), China, India and Africa (Sub-Saharan African countries, except Namibia and South Africa). RICE is a model of growth. Each region has its own production function which uses labour capital and energy inputs. The RICE model does not have an explicit mitigation variable but mitigation is incorporated implicitly in specification of the carbon energy input. The optimisation period is until 2200.

The damage function of RICE is of the same form as that of DICE; however, in RICE some regions can experience net benefits from climate change whereas in DICE the global average impact is always negative. For example in colder regions, the warming of the climate can make previously unutilized land arable (cf. IPCC, 2007).

The online RICE99 model is used for this report. The model is calibrated in such a way that it best replicates the results of the optimal control scenario of the original RICE model. Three regions (EE, OHI and Russia) were excluded from the calibration as they have very low, near zero, net benefits from climate change. Parameter values can be found for these regions but the information available is too weak to obtain reliable estimates.

The WITCH model

The WITCH – World Induced Technical Change Hybrid – model developed by the climate change research team at FEEM (Bosetti et al., 2006; Bosetti et al., 2007) is a hard-linked, energy-economy-climate model designed to deal with the main features of climate change.

The world economy is disaggregated into twelve macro regions: USA (United States), WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (Korea, South Africa, Australia), CAJAZ (Canada, Japan, New Zealand), TE (Transition Economies), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa), SASIA (South Asia), CHINA (China and Taiwan), EASIA (South East Asia), LACA (Latin America, Mexico and Caribbean). This grouping has been determined by economic, geographic, resource endowment and energy market similarities. The optimisation period covers the century until 2100.

WITCH considers explicitly the noncooperative nature of international relationships. Regions interact with each other through the presence of economic and environmental global externalities. Hence, forward-looking regional planners maximise their own intertemporal welfare taking into account the interactions with other regions (open-loop Nash solution). A cooperative solution can also be implemented in which a world central planner internalises all externalities by maximising the weighted sum of regional utilities.

The model has a bottom-up characterisation of the energy sector. Seven different energy-generating technologies are modelled: coal, oil, gas, wind & solar, nuclear, electricity, and biofuels. The model includes two breakthrough technologies whose penetration rate is driven by innovation. It distinguishes dedicated R&D investments for enhancing energy efficiency from investments aimed at facilitating the competitiveness of innovative low carbon technologies in both the electric and non-electric sectors (backstops). R&D processes are subject to stand on shoulders and neighbouring effects. International spillovers of knowledge are accounted to mimic the flow of ideas and knowledge across countries. Finally, experience processes through "learning-by-doing" are accounted for in the development of niche technologies such as renewable energy (Wind&Solar) and the backstops.

The climate modules of WITCH links greenhouse gas (GHG) emissions to GHG concentrations, and lastly to the global mean temperature. A damage function translates the temperature increase in regional GDP losses.

The production side of the economy is very aggregated. Each region produces one single commodity that can be used for consumption or investment. The final good is produced using capital, labour and energy services. Capital and labour are aggregated using a Cobb-Douglas production function. This nest is then aggregated with energy services with a Constant Elasticity of Substitution production function (CES). Gross damages are a non-linear function of difference between current and pre-industrial temperature. They drive a wedge between net and gross output.

The optimal path of consumption is obtained by optimising the intertemporal social welfare function, defined as the log utility of per capita consumption, weighted by regional population. The pure rate of time preference declines from 3% to 2% at the end of the century, and it has been chosen to reflect historical values of the interest rate. Through the optimisation process regions choose the optimal dynamic path of different investments, namely in physical capital, in R&D and energy technologies.

Recently, the WITCH model has been updated with more recent data. It has revised estimates for future projection of the main exogenous drivers. Socio-economic, energy and environmental variables have been re-calibrated to the year 2005 (Bosetti et al. 2009).

ANNEX 2. UNRAVELLING THE DAMAGE FUNCTION OF THE DICE AND RICE MODELS

Assessing the damages associated with climate change is a complicated and difficult issue due to the wide range of climate change impacts and the large uncertainties involved. However, to formulate optimal policies regarding adaptation and mitigation these damages need to be assessed and monetised. Although the many different forms of damages make aggregation difficult, there have been several attempts to create aggregated damage functions for major world regions. The most notable of these attempts are those of Nordhaus in the DICE/RICE model (e.g. Nordhaus and Boyer 2000), Tol in the FUND model (e.g. Tol 2002), Hope in the PAGE model (Hope 2006) and Mendelsohn (e.g. Mendelsohn et al., 2000).

To assess climate change damages in a comprehensive manner, damages are often divided into different categories. The estimation of damages carries with it great uncertainties and is often based on a mixture of extrapolating limited data, calibrating to existing information from the literature, applying the expert “guesstimates” of the authors and ignoring impacts that cannot be assessed or monetised. The damage functions of DICE, RICE and WITCH all have a common starting point in Nordhaus and Boyer (2000). The estimation and calibration of this damage function is clearly explained by the authors, whose approach is briefly summarised here. As the damage functions used in this analysis strongly rely on Nordhaus and Boyer (2000)’s work, the results presented in this paper crucially depend on these damage estimates.

The Nordhaus damage function has seven damage categories: Agriculture, Other Vulnerable Markets, Coastal, Health, Non Market Time Use, Catastrophic, and Settlements. Nordhaus’ regional damages/benefits estimates for these seven categories are provided in Table A2.1.

The ‘Agriculture’ category refers to the damages in the agricultural sector due to climate change. The damage estimates are based on studies done on crop yield variation under different temperatures and precipitation using the FARM model. Assuming that crop production will be adjusted to the new climate, the damages are assessed.

The ‘Other vulnerable markets’ category refers to the effect of climate change on other markets. Nordhaus and Boyer conclude that the only significantly affected markets are energy and water. More energy will be needed in some regions for air conditioning whereas colder regions will need less energy for heating. Water use is also expected to increase, for example, due to increased irrigation needs. Nordhaus and Boyer estimate these damages based on US data which are then extrapolated using the average temperature effects in the other regions.

The ‘Coastal’ category refers to the damages due to sea level rise. As the climate warms, the level of the sea rises. Adaptation options considered consist of either building sea walls to protect against sea level rise (incurring costs) or accepting the land loss (incurring residual damages). Nordhaus and Boyer use US estimates and extrapolate them based on a coastal vulnerability index (the coastal area to total land area ratio).

The ‘Health’ category refers to all damages incurred due to malaria, dengue, tropical diseases and pollution. Although heat- and cold-related deaths are also affected by climate change, they are not included here. In general, regions that are already vulnerable to such diseases have large damages, and thus developing regions tend to have the largest damages in this category.

‘Non market time use’ is a more abstract category and refers to the change in leisure activities. Due to a change in climate, people’s leisure hours will be affected. In colder regions, a warmer climate will lead to extra enjoyment of outdoor leisure activities. In warmer climates, however, leisure activities will be more restricted if the amount of extremely hot days increases. Most regions have benefits in this category, as illustrated in Table A2.1.

The ‘Catastrophic’ category refers to the Willingness to Pay (WTP) to avoid catastrophic events. Nordhaus and Boyer define a catastrophic event as an event that destroys 30% or more of a region’s GDP. They quantify the associated expected damages by estimating a risk premium, i.e. they do not actually quantify the damages of catastrophic events, but rather use the concept of insurance premium to value these effects.

The final category is ‘Settlements’. This again is a WTP analysis. They estimate the WTP to climate proof certain highly climate sensitive settlements. They estimate a WTP of 2% of GDP of the climate sensitive settlement.

Table A2.1. Nordhaus’ regional estimates of the damages/benefits for a 2.5ºC temperature rise

Region	TOTAL	Agriculture	Other vulnerable markets	Coastal	Health	Non market time use	Catastrophic	Settle-ments
USA	0.45	0.06	0	0.11	0.02	-0.28	0.44	0.1
China	0.22	-0.37	0.13	0.07	0.09	-0.26	0.52	0.05
Japan	0.5	-0.46	0	0.56	0.02	-0.31	0.45	0.25
EU	2.83	0.49	0	0.6	0.02	-0.43	1.91	0.25
Russia	-0.65	-0.69	-0.37	0.09	0.02	-0.75	0.99	0.05
India	4.93	1.08	0.4	0.09	0.69	0.3	2.27	0.1
Other High Income	-0.39	-0.95	-0.31	0.16	0.02	-0.35	0.94	0.1
High income OPEC	1.95	0	0.91	0.06	0.23	0.24	0.46	0.05
Eastern Europe	0.71	0.46	0	0.01	0.02	-0.36	0.47	0.1
Middle Income	2.44	1.13	0.41	0.04	0.32	-0.04	0.47	0.1
Lower middle Income	1.81	0.04	0.29	0.09	0.32	-0.04	1.01	0.1
Africa	3.91	0.05	0.09	0.02	3	0.25	0.39	0.1
Low Income	2.64	0.04	0.46	0.09	0.66	0.2	1.09	0.1
Global (Output weighted)	1.5	0.13	0.05	0.32	0.1	-0.29	0.17	1.02
Global (Population weighted)	2.19	0.17	0.23	0.12	0.56	-0.03	0.1	1.05

These different regional estimates are weighted on the basis of GDP to create the DICE damage function.

Finally, note that Nordhaus has updated the global estimate of damages, using the same categories as above, in the calibration of the DICE2007 model. His revised estimate is some 60 percent higher than those reported in Nordhaus and Boyer (2000). Unfortunately, the updated regional estimates have not been published yet. Therefore, the numerical estimates at the regional levels may not reflect the latest scientific insights into the impacts of climate change on specific regions. However, until now there have been no alternative comprehensive regional damage estimates that can be used instead. Therefore, in the numerical simulations presented in this paper a sensitivity analysis has been added on the level of global damages to assess the robustness of the results with respect to these estimates.

ANNEX 3. INCORPORATING ADAPTATION AS A POLICY VARIABLE

In this annex the modelling frameworks used in this document are presented in more detail. The incorporation of adaptation in the DICE, RICE and WITCH models follows the approach started by de Bruin et al. (2009a, 2009b). In these, the climate change damage function of the DICE and RICE models was unravelled in adaptation costs and residual damages. However, this previous work only considered reactive forms of adaptation (flow adaptation), while the present approach also considers adaptation actions that need an anticipated investment (stock adaptation). Thus, the current adaptation-versions of the models (AD-DICE, AD-RICE and AD-WITCH) unravel the damage function in residual damages and adaptation costs, where expenditure can be made in both stock and flow adaptation actions.

In the AD-WITCH model a further distinction is made between adaptation actions (stock and flow adaptation) and adaptive capacity building, which is composed of generic and specific adaptive capacity. Generic adaptive capacity captures components not necessarily related to adaptation itself but to the economic development of a region. The level of development influences the possibilities to adapt, with richer regions having more possibilities and pre-existing human capital and knowledge to engage in adaptation activities. Specific adaptive capacity depends not only on forms of investment such as R&D and early warning systems, but also on institutional capacity.

In the models gross damages (*GD*), that are the damages in absence of adaptation, are exponentially linked to temperature changes:

$$GD_{j,t} = \alpha_{0,j} T_t + \alpha_{1,j} {T_t}^{\alpha_{2,j}} \qquad (1)$$

Where the subscript j represents the region and the subscript t the time period. In AD-DICE/AD-RICE gross damages are given as a fraction of GDP. This is one of the most common forms for damage costs of climate change in IAMs, and it shows the level of climate change damages when no adaptation takes place. In the presence of mitigation, with lower emissions and thus lower temperatures, the gross damages decrease.

When adaptation is undertaken, the level of damage is reduced, but not completely, so that there is a residual damage (*RD*) left. In this case however, there is also an adaptation cost to be paid (*AC*). The net damage (*ND*) is then the damage in the presence of adaptation, and it is given by the sum of adaptation costs and residual damage. Expenditure in adaptation can be made in flow adaptation actions (*FAD*), stock adaptation (*SAD*), and in the AD-WITCH model also in specific adaptive capacity (*SAC*).

Flow adaptation entails simultaneous costs and benefits. Stock adaptation instead is created with investments in adaptation (*IA*). The build up of stock adaptation (investment, depreciation) is given by:

$$SAD_{j,t+1} = (1-\delta)\, SAD_{j,t} + IA_{j,t} \qquad (2)$$

In this equation δ is the capital depreciation rate (5% in AD-DICE and AD-RICE, and 10% in AD-WITCH) and $IA_{j,t}$ are the investments in stock adaptation. The build up for specific adaptive capacity is also based on the accumulation investments in specific adaptive capacity (*IAC*), which depreciates at a 3% rate. Adaptation costs are thus given by:

$$AC = \begin{cases} FAD + IA & \text{in AD} - \text{DICE and AD} - \text{RICE} \\ FAD + IA + IAC & \text{in AD} - \text{WITCH} \end{cases} \tag{3}$$

All variables in AD-DICE and AD-RICE are given in percentage GDP, while they are in dollars in AD-WITCH. This is an important difference between the two models, as the level of GDP will influence the decision to adapt in different ways.

Residual damages are linked to gross damages and the achieved level of adaptation (*ADAPT*) according to the following function: [11]

$$RD_{j,t} = \frac{GD_{j,t}}{1+ADAPT_{j,t}} \tag{4}$$

This functional form is chosen because it limits the fraction by which the gross damages can be reduced to the interval of 0 to 1. When total adaptation reaches infinity, all gross damages are reduced (the residual damages are zero) and when no adaptation is undertaken no gross damages are reduced (residual damages equal gross damages). This functional form also ensures decreasing marginal damage reduction of adaptation, that is the more adaptation is used the less effective additional adaptation will be. Thus, efficient measures of adaptation will first be applied whereas less effective measures will be used later.

Flow adaptation and investment in stock adaptation are aggregated together to adaptation actions (*ACT*) using a Constant Elasticity of Substitution (CES) function:

$$ACT_{j,t} = \beta_{1,j} \left(\beta_{2,j} FAD_{j,t}^{\rho} + (1-\beta_{2,j}) SAD_{j,t}^{\rho}\right)^{\frac{\beta_3}{\rho}} \tag{5}$$

In AD-RICE/AD-DICE adaptation strategies coincide with overall adaptation (*ADAPT*). Thus, for AD-DICE/AD-RICE adaptation coincides with the actions, so that$ADAPT_{j,t} = ACT_{j,t}$. In AD-WITCH instead, adaptation actions are part of a bigger nest in which they are combined with adaptive capacity building. Adaptive capacity is also derived as a CES combination of specific (*SAD*) and generic (*GAD*) adaptive capacity:

$$AC_{j,t} = \left(\varphi_j SAC_{j,t}^{\gamma} + (1-\varphi_j) GAC_{j,t}^{\gamma}\right)^{\frac{1}{\gamma}} \tag{6}$$

Finally, adaptation actions and adaptive capacity building are combined to form total adaptation, also with a CES function:

$$ADAPT_{j,t} = \left(\mu_j ACT_{j,t}^{\gamma} + (1-\mu_j) AC_{j,t}^{\gamma}\right)^{\frac{1}{\rho}} \tag{7}$$

Therefore, in the AD-WITCH model adaptation expenditures can be represented in the aggregation tree in the figure below. In AD-DICE/AD-RICE total adaptation coincides with the adaptation actions brunch in the AD-WITCH aggregation tree.

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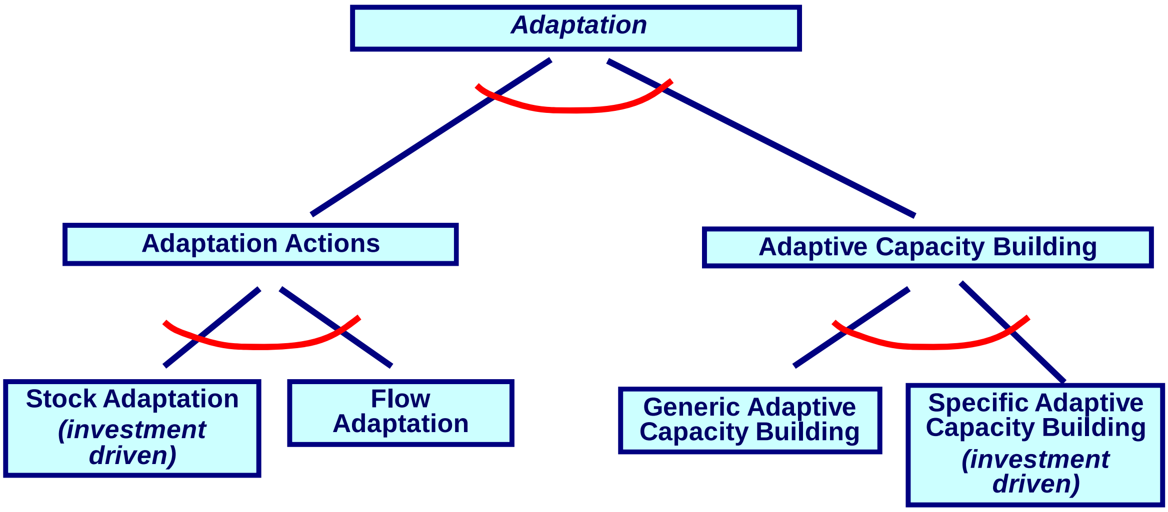
[11] De Bruin et al. (2009b) provide some insight into the implications of this functional form and contrast it with a specification of RD=(1-P)*GD and find that the differences are limited.

Figure A3.1. The adaptation tree



The chosen values for the elasticities of substitution are not the same between the models. AD-DICE and AD-RICE assume an elasticity of substitution between stock and flow adaptation equal to 2, so that the exponential parameter ρ in the CES function is .5. The elasticity of substitution in AD-WITCH is instead 1.2, with an exponential parameter ρ equal to 0.167. This is due to the fact that the stock and flow adaptation actions are part of a bigger nest in the AD-WITCH model. Specific and generic adaptive capacities are assumed to be gross complements with an elasticity of substitution equal to 0.2. Adaptive capacity building and adaptation actions are instead assumed to be gross substitutes and have an elasticity of substitution of 1.2.

ANNEX 4. CALIBRATION OF AD-DICE AND AD-RICE MODELS

This appendix describes the calibration procedure of AD-RICE and AD-DICE. This work does not aim at re-estimating or modifying the Nordhaus and Boyer estimates of damages, but to separate these damages into residual damages and stock adaptation costs and flow adaptation costs.

To calibrate the model each impact sector in the DICE/RICE models is described. First, each category that is used by Nordhaus and Boyer (2000) and the estimation of impacts for each category is describe. Then, relevant literature or expert judgment is used to estimate the levels of the relevant adaptation costs and benefits in each category. Finally, AD-RICE and AD-DICE are calibrated to replicate these estimates. As mentioned the net damages of Nordhaus and Boyer consist of residual damages, stock adaptation costs and flow adaptation costs. Besides estimating these variables it is also necessary to estimate the levels of gross damages. This is done by estimating the effectiveness of the different forms of adaptation. That is how much of the gross damages can be reduced through adaptation in this sector. This will allow understanding what the damage would be if adaptation did not take place and what the benefits of adaptation are.

Each impact sector is assessed by considering the main adaptation possibilities and what their costs and benefits are. Then, it is necessary to determine whether these options are of a stock nature or of a flow nature. In the DICE and RICE models a time period consists of 10 years, thus adaptation measures whose benefits and costs fall within this period are considered as a flow adaptation measure.

Very few empirical estimates have been made on the costs and benefits of adaptation and the ones that have been made are often about specific local adaptation options. This is because the costs and benefits of adaptation are often location specific. Agrawala and Fankhauser (2008) give an excellent overview of the current literature available on adaptation costs and benefits. This work draws strongly on this literature and gathers other literature where possible. The various variables are then assessed: gross damages, residual damages, flow adaptation costs, stock adaptation costs, optimal flow adaptation level and optimal stock adaptation level. The DICE/RICE damage function is calibrated at the point where temperature has increased by 2.5°C compared to the 1900 level. The damage function is calibrated to replicate the Nordhaus and Boyer damage function over the whole model horizons of DICE and RICE, in the optimal scenario. The levels of the various adaptation variables for the different sectors are assessed and these levels are assumed not change over time within each sector. Furthermore, the damage functions for the various sectors are reconstructed on the basis of Nordhaus and Boyer (2000) so that it is possible to see how the impacts in each sector evolve over time. It is then possible to understand how the adaptation variables change over time as the relevant importance of the sectors evolves.

Agriculture

Nordhaus and Boyer use sub-regional agricultural impact estimates, mostly referring to Darwin et al. (1995) but also to Dinar et al. (1998), and estimates of sub-regional temperature to produce a relationship between agricultural damage and temperature change.

The damages in agriculture as a fraction of GDP are given as a willingness to pay (WTP) function for each region *j*. These damage estimates reflect the adaptation incorporated in the Darwin et al. (1995) study. This includes farmers selecting the most profitable mix of inputs and outputs on existing cropland, adjustments in domestic markets and international trade, and increases in the amount of land under cultivation. Incorporating all of these adaptations leads to a slight increase (0.2-1.2%) in world cereals production under the climate change scenarios Darwin et al. (1995) consider. It should be noted that CO_2 fertilization is excluded in this study.

Adaptation can be very effective in combating the effects of climate change in this category. Measures such as irrigation, crop planting time changes, crop changes, utilizing previously non-arable land decrease the damages or increase the benefits in agriculture. Many studies include the effects of adaptation in reducing the agricultural damages (or enhancing the benefits) of climate change (e.g. Kane et al. 1992, Reilly et al. 1994, Rosenzweig and Parry 1994). More recent studies include Easterly (2007). For consistency only one study is used (as opposed to various regional studies) to estimate the effects of adaptation. The chosen study is Tan and Shibasaki (2003) as it is relatively recent and includes various world regions. The authors estimate the effects of climate change on the amount of crop yield for various regions for the year 2050. Table A4.1 shows the effect of adaptation for the various regions of Tan and Shibasaki (2003) and how they have been translated into the RICE regions. The form of adaptation that Tan and Shibasaki (2003) consider is the changing of crop planting dates.

Table A4.1. Adaptation estimates in the agricultural sector

RICE regions	**Tan & Shibasaki (2003) regions**	**Optimal Adaptation level**
USA	NORTH AMERICA	0.48
CHINA	ASIA	0.33
JAPAN	ASIA	0.33
EUROPE	EUROPE	0.43
RUSSIA	EUROPE	0.43
INDIA	ASIA	0.33
OHI	AUSTRALIA	0.27
HIO	(AVERAGE EUROPE-AFRICA)	0.33
EE	EUROPE	0.43
MI	SOUTH AMERICA	0.38
LMI	Average ASIA and south America	0.36
AFRICA	AFRICA	0.23
LI	(Average AFRICA and ASIA)	0.28

Source: Authors' calculations based on Tan & Shibasaki (2003), data for the year 2050 and protection is given as a fraction of yield loss avoided by adaptation

Tan and Shibasaki consider the amount of water available in regions without irrigation and assume that water is available for regions that do have irrigation facilities. They do not estimate the extra costs of water needed in these regions or the costs of changing the planting timing. The adaptation costs are thus likely to be very small, it is assumed that the percentage of adaptation costs in total net damages is 10% (and thus residual damages constitute 90%). Table A4.2 gives the different estimates of the adaptation variables. As Tan and Shibasaki only consider certain low cost adaptation options, estimates by Rosenzweig and Parry (1994) are also considered, are they include two forms of adaptation, one with small changes in agricultural systems and other more substantial changes. The first form of adaptation corresponds to that of Tan and Shibasaki. Thus, only the second form of adaptation is considered to include "more substantial change to agricultural systems, possibly requiring resources beyond the farmers' means, investment in regional and national agricultural infrastructure and policy changes. Such measures include large shifts in planting dates (> 1 month), increased fertilizer application, installation of irrigation systems and the development of new varieties".

Table A4.2 gives the breakdown of net damages in residual damages and adaptation costs for the various regions for the agricultural sector.

Table A4.2. RICE adaptation estimates in agriculture for a 2.5°C temperature increase

Regions	Net damages (original N&B) (% of output)	Optimal flow adaptation (fraction of gross damages reduced)	Optimal stock adaptation (fraction of gross damages reduced)	Flow adaptation costs (% of output)	Stock adaptation costs (% of output)	Residual damages (% of output)	Gross damages (% of output)
USA	0.06	0.48	0.10	0.01	0.01	0.05	0.11
CHINA	-0.37	0.33	0.30	0.06	0.06	-0.50	-0.30
JAPAN	-0.46	0.33	0.10	0.08	0.08	-0.62	-0.43
EUROPE	0.49	0.43	0.05	0.05	0.05	0.39	0.75
RUSSIA	-0.69	0.43	0.05	0.12	0.12	-0.92	-0.62
INDIA	1.08	0.33	0.30	0.11	0.11	0.86	2.34
OHI	-0.95	0.27	0.15	0.16	0.16	-1.27	-0.90
HIO	0.00	0.33	0.15	0.00	0.00	0.00	0.00
EE	0.46	0.43	0.05	0.05	0.05	0.37	0.71
MI	1.13	0.38	0.20	0.11	0.11	0.90	2.15
LMI	0.04	0.36	0.30	0.00	0.00	0.03	0.09
AFRICA	0.05	0.23	0.30	0.01	0.01	0.04	0.09
LI	0.04	0.28	0.30	0.00	0.00	0.03	0.08

Source: Authors' calculations based on Tan and Shibasaki (2003), Rosenzweig and Parry (1994) and Nordhaus and Boyer (2000)

Other vulnerable markets

This sector examines the effects of climate change on forestry, energy systems, water systems, construction, fisheries, and outdoor recreation. However, based on estimates by Cline (1992), Nordhaus (1991), and Mendelsohn and Neumann (1999), which estimate small losses, zero impacts, and small benefits in these sectors for the US, AD-RICE assumes that the impacts in this category are negligible for temperate climates. The only market that is substantially affected according to the authors is that of energy. They estimate a decline of 5% in energy expenditures in cold climates, and an increase of 8% in tropical and semi-tropical climates for a 2.5ºC warming. Note that more recent studies show different results (Fankhauser 1995, Mendelsohn 2000, Rosenthal et al. 1995, De Cian et al., 2007).

There are no quantitative estimates of the effects of adaptation in this sector. Though cooling and heating have a great potential to decrease damages and enhance benefits of climate change. Exposure to heat can cause discomfort, illness and even death, which cooling can prevent (Martens 1998; Gawith et al. 1999). This form of adaptation in relatively easy to apply as it is mostly an extension of regular behaviour (heating and cooling); therefore the protection potential is estimated to be high. It is assumed that that the optimal level of potential adaptation is 0.8. That is, by consuming more energy one can decrease 80% of the discomfort and sickness caused by the warmer climate. Adaptation will mostly be reactive as the infrastructure (energy supply) is often already in place. Investments in infrastructure may be needed, especially so in developing regions where energy demand is growing fast.

Because most gross damages can be reduced, it is assumed that most costs in this category are adaptation costs, i.e. adaptation costs compose 80% of total net damages. Note that some regions have benefits in this sector, i.e. the costs of increased air-conditioning are lower than the costs saved due to decreased heating. The corresponding estimates are given in Table A4.3.

Table A4.3. RICE adaptation estimates in other vulnerable markets for a 2.5°C temperature increase

Regions	Net damages (original N&B) (% of output)	Optimal flow adaptation (fraction of gross damages reduced)	Optimal stock adaptation (fraction of gross damages reduced)	Flow adaptation costs (% of output)	Stock adaptation costs (% of output)	Residual damages (% of output)	Gross damages (% of output)
USA	0.00	0.70	0.10	0.00	0.00	0.00	0.00
CHINA	0.13	0.60	0.20	0.08	0.03	0.03	0.07
JAPAN	0.00	0.70	0.10	0.00	0.00	0.00	0.00
EUROPE	0.00	0.70	0.10	0.00	0.00	0.00	0.00
RUSSIA	-0.37	0.60	0.20	0.18	0.00	-0.55	-0.34
INDIA	0.40	0.60	0.20	0.24	0.08	0.08	0.20
OHI	-0.31	0.70	0.10	0.15	0.00	-0.46	-0.27
HIO	0.93	0.60	0.20	0.60	0.14	0.19	0.46
EE	0.00	0.60	0.20	0.00	0.00	0.00	0.00
MI	0.41	0.60	0.20	0.27	0.06	0.08	0.21
LMI	0.29	0.60	0.20	0.17	0.06	0.06	0.15
AFRICA	0.09	0.60	0.20	0.06	0.02	0.02	0.05
LI	0.46	0.60	0.20	0.28	0.09	0.09	0.23

Source: Authors' calculations based on Nordhaus and Boyer (2000)

Coastal impacts

RICE estimates of coastal damages use the work of Yohe and Schlesinger (1998) on impacts from sea-level rise and a consideration of 1987-1995 storm damages from the Statistical Abstract (1997), based on which they estimate 0.1% of income as a reasonable WTP for preventing a 2.5ºC warming for the US. For other sub-regions, they scale this estimate based on the ratio of "coastal area" (within 10 km of the coast) to total land area, divided by the same ratio for the US.

Many studies have been done on coastal protection to sea level rise (e.g. Fankhauser 1998, Deke et al. 2001, Yohe et al. 1996, Nicholls and Klein, 2003, Hoozemans et al. 1993; Baarse 1995; Leatherman and Nicholls 1995; Nicholls et al. 1995, 1999; Nicholls 2002, 2004). The main means to adapt to coastal threats is to build sea walls, because of the high potential losses, such measures become very beneficial. In most regions with coastlines, most of the coast is protected. Other forms of adaptation are migration (resettlement).

To estimate the adaptation costs, adaptation level and residual damages, the FUND 2.9 model is used. The FUND model uses the framework proposed by Fankhauser (1994) to calculate the optimal level of coastal adaptation. The methodology used in FUND is described in detail in Tol (2007). This model estimates the costs of wetland loss, dryland loss, adaptation costs, migration costs and the adaptation level for more than 200 countries. Wetland losses are caused by both the rising sea level and the building of protection measures. Dryland losses and wetland losses due to sea level rise together constitute the residual damages. The adaptation costs and wetland losses due to protection and migration costs as given by FUND are totalled to get adaptation costs. The migration costs, however, are extremely low compared to sea wall construction costs. The FUND estimates of adaptation costs differ from those of the RICE model, as they are more recent. With the aim to replicate the original RICE damage function and divide it into residual damages and adaptation costs, the FUND data is used only to estimate the ratio of adaptation costs and residual damages and retain the total net damages of the RICE model.

Table A4.4 gives the results obtained concerning the adaptation variables. As can be seen from Table A4.4, the level of adaptation in the coastal sector is extremely high for most regions. This is because these are the optimal adaptation levels where the costs of protecting land are much lower than the costs of losing that land due to sea level rise. For Russia the level of adaptation is 0, as it has no vulnerable coastlines and thus no coastal damages to protect itself against. The levels of Europe and Other High Income countries are also relatively low. These regions have coastal areas where the costs of protecting are higher than the costs of losing land, creating a lower optimal adaptation level. There is a negligible amount of flow adaptation, as most coastal adaptation is of stock type, i.e. building of seawalls, strengthening coastlines etc.

Table A4.4. RICE adaptation estimates in the coastal sector for a 2.5°C temperature increase

Regions	Net damages (original N&B) (% of output)	Optimal flow adaptation (fraction of gross damages reduced)	Optimal stock adaptation (fraction of gross damages reduced)	Flow adaptation costs (% of output)	Stock adaptation costs (% of output)	Residual damages (% of output)	Gross damages (% of output)
USA	0.11	0.00	0.96	0.00	0.02	0.09	2.15
CHINA	0.07	0.00	0.95	0.00	0.07	0.00	0.06
JAPAN	0.56	0.00	0.95	0.00	0.31	0.25	4.93
EUROPE	0.60	0.00	0.56	0.00	0.31	0.27	0.61
RUSSIA	0.09	0.00	0.00	0.00	0.00	0.05	0.05
INDIA	0.09	0.00	0.95	0.00	0.09	0.00	0.00
OHI	0.16	0.00	0.14	0.00	0.10	0.05	0.06
HIO	0.06	0.00	0.98	0.00	0.03	0.03	1.71
EE	0.01	0.00	0.95	0.00	0.01	0.00	0.00
MI	0.04	0.00	0.89	0.00	0.02	0.02	0.17
LMI	0.09	0.00	0.95	0.00	0.06	0.03	0.65
AFRICA	0.02	0.00	0.99	0.00	0.02	0.00	0.06
LI	0.09	0.00	0.95	0.00	0.09	0.00	0.07

Source: Authors' calculations based on Nordhaus and Boyer (2000) and FUND 2.9

Health

In RICE, health is examined in the form of diseases (malaria, dengue and other tropical diseases) and pollution related inflictions. Heat and cold deaths are not considered. Due to increased climate change the spread of certain diseases will increase. Pollution will increase respiratory diseases, cardiovascular diseases and damage lungs. Their impact estimates are based on work by Murray and Lopez (1996). Murray and Lopez assume a certain amount of adaptation through their assumption of baseline improvements in health care, such as antimicrobials and vaccines, using time as a proxy, based on the rate of improvement over the 20th century. They estimate e.g. that damages will be reduced for Africa from 4.6% to 3.0% GDP loss for a 2.5ºC warming to account for expected additional improvements in public health in the region which reduce the incidence of climate-related diseases. Murray and Lopez estimate what they consider likely to happen in the line of adaptation and incorporate that in their damage estimates. This data is in the same order of magnitude as the adaptation levels to malaria estimated by the WHO (2008). The WHO report is used to estimate the level of adaptation in the case of diseases and estimate the adaptation to pollution in various regions.

The costs and benefits of adapting to climate change in the health sector remain hard to assess due to the fact that it is hard to disentangle the effects of climate change and other factors. It is assumed that the adaptation costs are so high that they are in the same order of magnitude as the residual damages for the pollution sector. Adaptation measures in the case of pollution include weather forecasts to predict air quality levels, the development of air quality advisory systems and public education.

The estimates regarding adaptation costs and benefits when assuming the same adaptation level as in Murray and Lopez (1996) are given in Table A4.5. In the case of diseases adaptation is relatively cheap as compared to the damages created by the diseases. For example the costs of losing a year of a life due to malaria is two times the GDP per capita of that person, whereas a mosquito net costs 4 dollars and will likely prevent malaria. General facilities such as hospitals and institutions will be needed to adapt effectively. In this case it is assumed that adaptation costs are 20% of net damages in the case of diseases and 0.3 in the case of pollution. Adapting to pollution will be more costly and less effective and it is assumed that adaptation costs will be some 30% of net damages.

Most adaptation actions in this category are of flow type. In developing regions, however, investments will be needed in the health sector as the health infrastructure is severely lacking.

Table A4.5. RICE adaptation estimates in health for a 2.5°C temperature increase

Regions	Net damages (original N&B) (% of output)	Optimal flow adaptation (fraction of gross damages reduced)	Optimal stock adaptation (fraction of gross damages reduced)	Flow adaptation costs (% of output)	Stock adaptation costs (% of output)	Residual damages (% of output)	Gross damages (% of output)
USA	0.02	0.60	0.00	0.01	0.00	0.01	0.04
CHINA	0.09	0.36	0.15	0.02	0.01	0.06	0.10
JAPAN	0.00	0.90	0.00	0.00	0.00	0.00	0.03
EUROPE	0.02	0.60	0.00	0.01	0.00	0.01	0.04
RUSSIA	0.02	0.30	0.10	0.01	0.00	0.01	0.02
INDIA	0.32	0.72	0.15	0.07	0.07	0.24	0.86
OHI	0.02	0.60	0.00	0.01	0.00	0.01	0.04
HIO	0.31	0.72	0.10	0.05	0.01	0.27	0.96
EE	0.02	0.50	0.10	0.01	0.00	0.01	0.03
MI	0.30	0.79	0.10	0.03	0.00	0.27	1.30
LMI	0.10	0.85	0.15	0.02	0.02	0.08	0.54
AFRICA	0.08	0.99	0.15	0.02	0.30	0.06	4.12
LI	0.20	0.83	0.15	0.05	0.07	0.16	0.91

Source: Authors’ calculations based on Nordhaus and Boyer (2000), WHO malaria report (2008) and Murray and Lopez (1996)

Non-market time use

The non-market time use impact sector focuses on outdoor recreation. Due to a change in climate, people can enjoy more outdoor activities in cold regions and less in warm regions. Nordhaus and Boyer (2000) cite a study by Nordhaus (1998) on the value of climate-related time use in the US, the authors estimate a benefit of 0.3% GDP for a 2.5ºC warming and a quadratic relationship between subregional mean temperature and time use impacts. These estimates are based on increased outdoor activities, thus assuming adaptation in the form of people engaging in more or fewer outdoor activities. This estimate is extended to other countries adjusting for differences in per capita GDP and average hourly earnings. Note that in many regions this category creates benefits of climate change.

Adaptation in this category involves simply adjusting one's activities. If it is nice weather people will go outdoors more, when it is too hot people will stay inside more. The protection level is quite high here as adaptation is needed to enjoy most benefits of better weather and avoid most costs of severe heat. A level of adaptation potential of 0.9 in developed regions and 0.6 in developing regions is chosen, as developing regions have less flexibility and luxury to adjust their leisure activities. Furthermore, it is assumed that it is harder to adapt to severe heat (when there are damages) then to nicer weather (when there are benefits). When there is sever heat, the adaptation level is assumed to be 0.3. It remains, however, hard to estimate how much of the gross damages are avoided by adapting one's activities in this case.

It is assumed that adaptation here is virtually cost free. It does not cost much to adapt ones activities. Therefore, very low adaptation costs are assumed, i.e. 10% of total net damages. The estimates are given in Table A4.6. As this form of adaptation consists of the changing of one's leisure habits and does need a beforehand investment it is considered as flow.

Table A4.6. RICE adaptation estimates in non market time use for a 2.5°C temperature increase

Regions	Net damages (original N&B) (% of output)	Optimal flow adaptation (fraction of gross damages reduced)	Optimal stock adaptation (fraction of gross damages reduced)	Flow adaptation costs (% of output)	Stock adaptation costs (% of output)	Residual damages (% of output)	Gross damages (% of output)
USA	-0.28	-0.28	0.90	0.00	0.03	0.00	-0.31
CHINA	-0.26	-0.26	0.70	0.00	0.03	0.00	-0.29
JAPAN	-0.31	-0.31	0.90	0.00	0.04	0.00	-0.35
EUROPE	-0.43	-0.43	0.90	0.00	0.05	0.00	-0.48
RUSSIA	-0.75	-0.75	0.80	0.00	0.09	0.00	-0.84
INDIA	0.30	0.30	0.30	0.00	0.03	0.00	0.27
OHI	-0.35	-0.35	0.90	0.00	0.04	0.00	-0.39
HIO	0.30	0.24	0.30	0.00	0.03	0.00	0.27
EE	-0.36	-0.36	0.80	0.00	0.04	0.00	-0.40
MI	-0.04	-0.04	0.70	0.00	0.00	0.00	-0.04
LMI	-0.04	-0.04	0.70	0.00	0.00	0.00	-0.04
AFRICA	0.25	0.25	0.30	0.00	0.03	0.00	0.23
LI	0.20	0.20	0.30	0.00	0.02	0.00	0.18

Source: Authors' calculations based on Nordhaus and Boyer (2000)

Catastrophic risks

This sector estimates the impacts of abrupt climate change creating catastrophic damages. Examples are rapid sea-level rise from an ice sheet collapse, shifting monsoons, and changing ocean currents. Here events with damages of 30% of GDP or higher are considered. It is assumed that there is a linear damage function up to 3ºC, and an unspecified power function for temperatures above 3ºC. Nordhaus bases his estimates of catastrophic damages by using the probability of catastrophic change on the expert survey by Nordhaus (1994), which reported results for scenarios of 3ºC warming by 2090 and 6ºC warming by 2175. Citing growing concerns over abrupt changes such as shutdown of the thermohaline circulation since the survey was completed, they estimate the probability of catastrophic change for 2.5ºC as double the original probability estimate for 3ºC warming (0.012), and the probability for 6ºC as double the original estimate for 6ºC (0.068). RICE also assumes that some sub-regions such as India and OECD Europe have a higher vulnerability than others. To calculate WTP, RICE assumes a rate of relative risk aversion of 4, and a loss of 30% of global GDP for a catastrophic event, distributed between sub-regions based on their relative vulnerability. Given these assumptions and the probabilities of occurrence, the authors calculate WTP for each subregion to avoid both temperature levels.

The difficulty of adapting to such impacts is a central criterion for inclusion in this sector. It is assumed that some the damages of a catastrophic event can be prevented through knowledge of the forthcoming disaster (early warning systems, scientific research etc.). Though early warning systems have been found to be very effective for extreme events (e.g. Adams et al., 2002), they will not likely be very effective for such catastrophes as considered here. Following a conservative assumption, some 10% of damages can be reduced that way (i.e. through stock adaptation), and that good adaptation strategies after a disaster (i.e. reactive) can further decrease damages by 10%. Most damages will be in the category of residual damages, so it is assumed that they comprise 90% of total net damages. Table A4.7 gives AD-RICE's estimates regarding adaptation costs and benefits and damages for this sector.

Table A4.7. RICE adaptation estimates in catastrophic events for a 2.5°C temperature increase

Regions	Net damages (original N&B) (% of output)	Optimal flow adaptation (fraction of gross damages reduced)	Optimal stock adaptation (fraction of gross damages reduced)	Flow adaptation costs (% of output)	Stock adaptation costs (% of output)	Residual damages (% of output)	Gross damages (% of output)
USA	0.44	0.10	0.10	0.02	0.02	0.40	0.50
CHINA	0.52	0.10	0.10	0.03	0.03	0.47	0.59
JAPAN	0.45	0.10	0.10	0.02	0.02	0.41	0.51
EUROPE	1.91	0.10	0.10	0.10	0.10	1.72	2.15
RUSSIA	0.99	0.10	0.10	0.05	0.05	0.89	1.11
INDIA	2.27	0.10	0.10	0.11	0.11	2.04	2.55
OHI	0.94	0.10	0.10	0.05	0.05	0.85	1.06
HIO	0.46	0.10	0.10	0.02	0.02	0.41	0.52
EE	0.47	0.10	0.10	0.02	0.02	0.42	0.53
MI	0.47	0.10	0.10	0.02	0.02	0.42	0.53
LMI	1.01	0.10	0.10	0.05	0.05	0.91	1.14
AFRICA	0.39	0.10	0.10	0.02	0.02	0.35	0.44
LI	1.09	0.10	0.10	0.05	0.05	0.98	1.23

Source: Authors' calculations based on Nordhaus and Boyer (2000)

Settlements

RICE considers two general settlement categories: natural settlements (ecosystems) and human settlements (cities, states). RICE uses an impact index function similar to that for coastal impacts, based on global temperature changes to estimate the damages to settlements. The authors cite unpublished estimates of the capital value of climate-sensitive human settlements and natural ecosystems in each sub-region, and estimate that each sub-region has an annual WTP of 1% of the capital value of the vulnerable system, for a 2.5ºC increase.

RICE acknowledges the difficulty of adaptation for coastal cities, islands, and natural ecosystems. Ecosystems cannot easily adapt to the changing climate and will often disappear, thus the adaptation potential is rather low (0.2), as are the associated adaptation costs (10% of net damages). Ecosystems form a smaller part of the total than do human settlements. Human settlements, such as the example given by Nordhaus and Boyer (2000), namely Venice, can adapt at high costs. Here the adaptation costs will be high, thus the assumptions of 90% of net damages. The adaptation level will also be high, namely 0.8, but will be lower in developing regions, namely, 0.4. Adaptation here is of the stock form as vulnerable settlements are protected before climate change impacts occur. The corresponding estimates are given in Table A4.8.

Table A4.8. RICE adaptation estimates in settlements for a 2.5°C temperature increase

Regions	**Net damages (original N&B) (% of output)**	**Optimal flow adaptation (fraction of gross damages reduced)**	**Optimal stock adaptation (fraction of gross damages reduced)**	**Flow adaptation costs (% of output)**	**Stock adaptation costs (% of output)**	**Residual damages (% of output)**	**Gross damages (% of output)**
USA	0.10	0.05	0.70	0.00	0.07	0.03	0.12
CHINA	0.05	0.05	0.70	0.00	0.04	0.02	0.06
JAPAN	0.25	0.05	0.70	0.00	0.18	0.08	0.30
EUROPE	0.25	0.05	0.70	0.00	0.18	0.08	0.30
RUSSIA	0.05	0.05	0.70	0.00	0.04	0.02	0.06
INDIA	0.10	0.05	0.70	0.00	0.07	0.03	0.12
OHI	0.10	0.05	0.70	0.00	0.07	0.03	0.12
HIO	0.05	0.05	0.70	0.00	0.04	0.02	0.06
EE	0.10	0.05	0.70	0.00	0.07	0.03	0.12
MI	0.10	0.05	0.70	0.00	0.07	0.03	0.12
LMI	0.10	0.05	0.70	0.00	0.07	0.03	0.12
AFRICA	0.10	0.05	0.70	0.00	0.07	0.03	0.12
LI	0.10	0.05	0.70	0.00	0.07	0.03	0.12

Source: Authors' calculations based on Nordhaus and Boyer (2000)

Total Impacts

Table A4.9 presents the overview of impacts per category for the different regions, summarizing the information above. It is important to note that the importance of the various categories differs widely across regions: not only is the level of impacts different across regions, also the type of major impact varies. This also implies differences in adaptation options and costs for the regions. The damage weighted totals of the adaptation variables per region are presented in A4.10, which also includes the global estimate. This is based on weighted average of the regional damages (in USD terms). These estimates are then used to calibrate the parameters of AD-DICE the global equivalent of AD-RICE. The calibrated values of the parameter of equations (1) and (4) are given in Table A4.11. The calibration fit is given in Table A4.12, where the AD-RICE and AD-DICE values are compared with the adaptation estimates and the original model. The table illustrates comparisons of the ratio of residual damages to protection costs, the level of adaptation with the estimated values based on the literature review. The net damages are compared with those of the original RICE and DICE net damages.

Table A4.9. Damage categories and estimates as % GDP for a 2.5°C temperature

Regions	Total damages	Agri-culture	Other vulnerable markets	Coastal	Health	Non market time use	Cata-strophic events	Settle-ments
USA	0.45	0.06	0	0.11	0.02	-0.28	0.44	0.1
CHINA	0.22	-0.37	0.13	0.07	0.09	-0.26	0.52	0.05
JAPAN	0.5	-0.46	0	0.56	0.02	-0.31	0.45	0.25
EUROPE	2.83	0.49	0	0.6	0.02	-0.43	1.91	0.25
RUSSIA	-0.65	-0.69	-0.37	0.09	0.02	-0.75	0.99	0.05
INDIA	4.93	1.08	0.4	0.09	0.69	0.3	2.27	0.1
OHI	-0.39	-0.95	-0.31	0.16	0.02	-0.35	0.94	0.1
HIO	1.95	0	0.91	0.06	0.23	0.24	0.46	0.05
EE	0.71	0.46	0	0.01	0.02	-0.36	0.47	0.1
MI	2.44	1.13	0.41	0.04	0.32	-0.04	0.47	0.1
LMI	1.81	0.04	0.29	0.09	0.32	-0.04	1.01	0.1
AFRICA	3.91	0.05	0.09	0.02	3	0.25	0.39	0.1
LI	2.64	0.04	0.46	0.09	0.66	0.2	1.09	0.1
Global	1.5	0.13	0.05	0.32	0.1	-0.29	0.17	1.02

Source: Nordhaus and Boyer (2000)

Table A4.10. RICE stock and flow adaptation estimates for a 2.5°C temperature increase

Regions	**Net damages (original N&B) (% of output)**	**Optimal flow adaptation (fraction of gross damages reduced)**	**Optimal stock adaptation (fraction of gross damages reduced)**	**Flow adaptation costs (% of output)**	**Stock adaptation costs (% of output)**	**Residual damages (% of output)**	**Gross damages (% of output)**
USA	0.45	0.34	0.22	0.07	0.12	0.88	2.01
CHINA	0.22	0.31	0.21	0.15	0.15	0.91	1.88
JAPAN	0.5	0.24	0.40	0.07	0.28	0.83	2.35
EUROPE	2.83	0.22	0.20	0.06	0.17	0.80	1.37
INDIA	4.93	0.22	0.18	0.11	0.11	0.78	1.29
MI	2.44	0.39	0.20	0.18	0.11	0.71	1.72
LMI	1.81	0.23	0.20	0.14	0.14	0.73	1.28
AFRICA	3.91	0.20	0.16	0.03	0.11	0.86	1.34
LI	2.64	0.24	0.18	0.15	0.14	0.71	1.21
Global	1.5	0.27	0.19	0.17	0.21	1.21	2.25

Source: Authors' calculations based on Nordhaus and Boyer (2000)

Table A4.11. Calibrated parameter values

	α_0	α_1	α_2	β_1	β_2	β_3
USA	0	0.00102	4.77	270	0.43	0.62
CHINA	0	0.00001	2.80	4500	0.55	0.61
JAPAN	0	0.00001	2.44	310	0.31	0.67
EUROPE	0	0.0038	1.65	450	0.34	1.08
INDIA	0	0.0139	1.55	100	0.54	0.87
MI	0	0.0074	1.88	850	0.55	1.07
LMI	0	0.0052	1.21	532	0.51	0.99
AFRICA	0	0.0787	1.21	40	0.39	0.87
LI	0	0.0096	1.51	525	0.52	1.1
GLOBAL	0.003	0.0007	3.62	90	0.49	0.8

Table A4.12. Calibration fit: data estimates compared with calibrated values at calibration point

	Adaptation cost ratio (PC/RD)		Adaptation level (P)		Net damages (RD+PC)	
	estimated	calibrated	estimated	calibrated	RICE	calibrated
USA	0.21	0.21	0.56	0.55	0.43%	0.38%
CHINA	0.33	0.33	0.51	0.61	0.26%	0.10%
JAPAN	0.42	0.38	0.65	0.66	0.47%	0.68%
EUROPE	0.28	0.28	0.42	0.38	2.88%	2.59%
INDIA	0.29	0.29	0.39	0.38	5.04%	4.43%
MI	0.41	0.41	0.57	0.54	1.81%	1.98%
LMI	0.38	0.38	0.40	0.48	2.24%	1.88%
AFRICA	0.16	0.16	0.32	0.35	4.58%	5.48%
LI	0.41	0.41	0.40	0.46	3.22%	2.78%
Global	0.32	0.32	0.49	0.48	2.15%	2.19%

ANNEX 5. CALIBRATION OF THE AD-WITCH MODEL

The main sources of information used are Nordhaus and Boyer (2000), an OECD report (Agrawala and Fankhauser, 2008) and UNFCCC (2007). They provide the most recent and complete assessment on costs and benefits of adaptation strategies. The aforementioned studies have been integrated with area-specific modelling or assessment studies in order to combine the best available quantitative knowledge. This section provides a full account of the sources used for the calibration of the AD-WITCH model.

The AD-WITCH model distinguishes between adaptation actions (stock and flow adaptation), and adaptive capacity building (specific and generic). The following table summarises the different adaptation activities for which data were available, and illustrates their allocation to the different types of adaptation.

Table A5.1. Different adaptation strategies

Proactive Adaptation Activities → Modelled as “stock” variable
Coastal Protection Activities Settlements, Other Infrastructures (Excluding Water) and Ecosystem Protection Activities Water Supply (Agriculture and Other) Protection Activities
Reactive adaptation activities → Modelled as “flow” variable
Agricultural Adaptation Practices Treatment of Climate-Related Diseases Space Heating and Cooling Expenditure
Generic adaptive capacity → Modelled as an exogenous trend
In the present specification generic adaptive capacity building is represented by an exogenous trend increasing at the rate of total factor productivity
Investment in specific adaptive capacity → Modelled as a “stock” variable
Investments in specific capacity have been set to be the 1% of world expenditure on education and total R&D in the calibration year (in absolute terms this amounts to USD 164 Billion in 2060). Then this global amount has been distributed across different regions proportionally to the normalised share of education expenditure over GDP. Information is available on three activities that can be considered investment in specific adaptive capacity: expenditure on early warning systems; research activities in the health sector, research activities for the development of climate-resilient crops.

SECTORAL ANALYSIS

Coastal Protection

Costs and benefits of coastal protection against climate change-induced sea level rise are the topics more deeply investigated by the adaptation literature. In 1991 the IPCC proposed methodologies and estimates concerning the cost of sea level rise and of the benefit of coastal protection (IPCC CZMS, 1991). This issue was subsequently investigated by a very large body of literature. Studies in this vein include investigation at the world level with macro regional and country detail.

The calibration is not based on region or country specific studies, but using the DIVA model to assess costs and effectiveness of coastal protection. DIVA is an interactive tool that makes it possible to perform an integrated assessment of coastal zones. It is specifically designed to explore the vulnerability of coastal areas to sea level rise for different climatic and socio-economic scenarios. DIVA includes four components. The first component outlines a detailed global database with biophysical and socio-economic coastal data. The second component of DIVA observes global and regionalised climate and socio-economic scenarios until the year 2500. The third component provides an integrated model enabling the interaction between modules that assess biophysical and socio-economic impacts and the potential effects and costs of adaptation. The final component exhibits a graphical user interface for selecting data and scenarios.

The DIVA model can be run under an optimal protection mode. It determines, for major IPCC scenarios, the optimal level of coastal protection and its cost for each (coastal) country of the world stemming from a cost and benefit analysis based on parameterised values of land at risk and cost of different adaptation measures. The value computed for the 12 WITCH macro-regions, referring to a medium level of sea level rise related to a temperature increase of 2.5°C are reported in Table A5.2. Coastal protection costs include all adaptation costs (dike building, beach nourishment and wetland nourishment). Average protection level is measured with years of protection, where maximum protection (100%) corresponds to 10000 years.

Table A5.2. Effectiveness and cost of coastal protection for a 2.5°C temperature increase

	Coastal Protection Level (100 = total)	Coastal Protection Costs (Billion USD)
USA	75	3.6
WEURO	54	5.0
EEURO	63	0.3
KOSAU	62	1.8
CAJAZ	37	2.9
TE	37	1.7
MENA	55	1.2
SSA	30	2.7
SASIA	47	1.3
CHINA	76	1.3
EASIA	25	4.3
LACA	46	7.7
Total		33.6

Settlement and ecosystem protection

Nordhaus and Boyer (2000) report the total cost of climate change for settlements and natural ecosystems. To separate the two components four items have to be identified: protection cost and residual damage both for settlements and ecosystems.

Practically any assumption about ecosystems is highly conjectural and the available literature is of scarce support. Ecosystems cannot easily adapt to the changing climate and will often disappear, thus the adaptation potential is rather low as are adaptation costs.

The AD-WITCH model assumes that adaptation costs are a large share of total damage because human settlements can adapt at high costs. More precisely, adaptation costs are separated from residual damage using the proportions for coastal protections that were obtained with the DIVA model. The share of protection costs ranges from 30% in LACA to 99% in some developed regions (KOSAU).

As far as the effectiveness of this investment is concerned, it is close to 90%, in protecting settlements, but very low (0 in fact) in protecting ecosystem. Weighting slightly more the ecosystem damage component it is arbitrarily assumed that that the overall protection level over settlements and ecosystems is 40%. The estimates are reported in Table A5.3.

Table A5.3. Investment in climate proof settlements for a 2.5°C temperature increase

	USD Billion
USA	22
WEURO	56
EEURO	3
KOSAU	5
CAJAZ	10
TE	3
MENA	4
SSA	4
SASIA	20
CHINA	17
EASIA	4
LACA	6
Total	154

Water protection

The reference for the assessment of the costs to adapting water infrastructures to climate change is UNFCCC (2007) based on Kirshen (2007). This last study proposes an estimate of the investment needed to meet projected water demand in 2030 consistent with the IPCC B1 and A1b scenarios in eight world regions. A drawback of this assessment is that adaptation in Kirshen (2007) is a response to both climatic and social-economic changes.

A way to disentangling the climatic from the social-economic component is suggested by UNFCCC (2007). UNFCCC assumed that 25% of additional investments are due to climate change. The remaining is used to confront social-economic changes (Table A5.4). Globally, adapting water infrastructure to climate change would require roughly USD 180 Billion investment in 2030, 94% of which concentrated in developing countries. However, the assumption of a 25% share has no empirical basis, as observed by the recently released report (Parry et al. 2009). This item drives up adaptation expenditure especially in MENA and SSA. Assuming a lower share of 15% gives a more smooth distribution across regions. Comparing the resulting expenditures with other data, a 15% share seems more reasonable. For example, Fisher et al.

(2007) estimated the costs to meet irrigation demand (infrastructure plus operating costs) between USD 24 and 27 Billion per year by 2080. According to Briscoe (1999), current spending on water infrastructure in developing countries amounts to USD 65 Billion. For this reason a 15% share was chosen instead of 25% as suggested by UNFCCC.

Table A5.4. Expenditure in water infrastructures to meet water demand in 2030

	Total (Climatic + Social Economic Pressures) USD Billion	Due to Climatic Pressures Only in 2030 – 25% assumption USD Billion	Due to Climatic Pressures Only in 2030 – 15% assumption USD Billion	Due to Climatic Pressures Only in 2060*– 25% assumption USD Billion	Due to Climatic Pressures Only in 2060*– 15% assumption USD Billion
Africa	223	56	33	100	60
Developing Asia	230	58	35	103	62
Latin America	23	6	3	10	6
Middle East	148	37	22	66	40
OECD Europe	25	6	4	11	7
OECD North America	16	4	2	7	4
OECD Pacific	1	0	0	0	0
Transition economies	54	14	8	24	14
Total	720	180	108	321	193

Source: UNFCCC, 2007 (IPCC B1 SRES)
* AD-WITCH calculations

Based on this data, first the potential total costs in 2060 are estimated shifting the 2030 data proportionally to the temperature gap between 2030 B1 temperature and the AD-WITCH reference 2.5°C. For the regions USA, EU, CAJANZ, TE and LACA the regional numbers reported in Table A5.4 (4th and 5th column) are used, scaled up to 2060. Africa (60) is divided between SSA, MENA and KOSAU on the basis of a vulnerability index based on Nordhaus and Boyer (2000) estimates in “Other Vulnerable Markets”. A similar procedure was used to split the data for ASIA (62) between SASIA, CHINA and EASIA. Finally, following Stern (2007) only 30% of this expenditure is attributed to the sector “other vulnerable markets” whereas the remaining 70% has been assigned to agriculture. It refers to irrigation and water conservation-production practices in the agricultural sector.

The results under both assumption of 15% and 25% are reported in Table A5.5. Developed countries show low adaptation costs as found in Nordhaus and Boyer (2000). Their water infrastructures are already able to contend with future climate change. The highest expenditure is expected in the Middle-East and North-Africa (MENA), followed by the South Asia (SASIA), Sub-Saharan Africa (SSA) and Transition Economies (TE).

Table A5.5. Water infrastructures costs in other vulnerable markets for a 2.5°C temperature increase.

	Other Vulnerable Markets (Billion USD -15%)	Other Vulnerable Markets (Billion USD- 25%)
USA	1.3	2.1
WEURO	2	3.3
EEURO	3.2	5.3
KOSAU	2.5	4.2
CAJAZ	0.7	1.1
TE	4.3	7.2
MENA	21.7	36
SSA	5.7	9.6
SASIA	7.3	12.1
CHINA	1.3	2.1
EASIA	0.5	0.9
LACA	1.8	3.1
Total	52.3	87

For what regards the effectiveness, several studies have been conducted on the effectiveness of adaptation in the water sector. The estimates are based on two particular studies. Kirshen et al. (2006) found that the effectiveness of adaptation can range from very low to very high values up to 100%. Effectiveness depends on the type of measure adopted. On the contrary, Callaway et al. (2006) analysed management adaptation costs for the Berg River in South Africa. This study demonstrates the importance of a water management system, which can increase the benefits of improved water storage capacity by 40%.

The AD-WITCH models assumes that it is more difficult in developing countries to implement efficient adaptation measures and water management practices, while in developed countries it would be relatively easier to accomplish. As a consequence the effectiveness of adaptation in developed countries is assumed to be quite high, 80% (see also the study of the Rhine River by EEA, 2007) while in developing countries it is assumed to be quite low, 40%.

Agriculture

The quantification of the costs of adaptation in agriculture (EEA, 2007; Agrawala and Fankhauser, 2008) is lacking in the literature on adaptation. This is mostly because a large part of agricultural adaptation practices are implemented at the farm level. The farmers decide “autonomously” without the direct intervention of public agencies. This suggests long-term planning and investment activities. Typical examples of these practices are seasonal adjustments in the crop mix or timing which in the literature are assumed to entail very low if not zero costs.

The most significant cost component of climate change adaptation in agriculture is presumably related to the improvement of irrigation, or water conservation systems. These are forms of adaptation that can be classified as proactive. As already mentioned, 70% of adaptation costs on water infrastructure extrapolated from UNFCCC (see Table A5.4) are assigned to the agricultural sector. The results of both assumption of 15% and 25% are reported in Table A5.6.

Table A5.6. Cost of water infrastructures in agriculture for a 2.5°C temperature increase.

	Agriculture (irrigation) (Billion USD) (15%)	Agriculture (irrigation) (Billion USD) (25%)
USA	3	5
WEURO	4.7	7.8
EEURO	7.4	12.3
KOSAU	5.9	9.8
CAJAZ	1.6	2.7
TE	10.1	16.9
MENA	50.7	84.1
SSA	13.4	22.3
SASIA	17	28.3
CHINA	3	4.9
EASIA	1.3	2.1
LACA	4.3	7.2
Total	122.4	203.4

Higher costs are estimated for some developing countries, namely Middle East and North Africa, South Asia and Sub-Saharan Africa. Among developed regions, only in Eastern Europe (EEURO) costs are significant, essentially because of the relevance of the agricultural sector. It is also highly vulnerable to climate change. Transition economies (TE) are another region in which agriculture plays a major role and features relatively high costs.

The literature on the effectiveness of climate change adaptation practices in agriculture respect both their impact on land productivity or on farmers' income is broad and dates back to the early 90's (Kane et al. 1992; Fisher et al. 1993; Reilly et al. 1994; Rosenzweigh and Parry 1994). Subsequently, the Working Group II of the IPCC contributed with specific chapters on impacts and adaptation in agriculture both in Third (IPCC 2001) and in the Fourth (IPCC 2007) Assessment Reports. Surveying this literature (for a non exhaustive list see Rosenzweigh and Hillel 1998; Antle et al. 2001; Tan and Shibasaky 2003, Easterling et al. 2007), a rough estimate of the effectiveness of adaptation in agriculture ranges between 40% and 98% of total climatic damage for a doubling of CO2 concentration. Such a wide range is determined by the country or site-specific characteristic of the study, the crop investigated the modelling approach, and the assumptions on adaptation practices available.

This makes it quite difficult to summarise in just one consistent value adaptation effectiveness encompassing all possible agricultural practices, especially referred to wide regional aggregates like those of the WITCH model. For this damage category the main source is Tan and Shibasaky (2003). They provide estimates of changes in crop yields for six world macro-regions (Asia, North America, South America, Europe, Australia, Africa) with and without adaptation in 2050. These differences in yields can be considered representative of the effectiveness of farmers' adaptation practices. When a WITCH region falls inside a Tan and Shibasaky aggregate, the same value reported by their study is assigned to the region. When a WITCH region falls over two Tan and Shibasaky aggregates, an average of the values reported by their study is assigned to the region. Table A5.7 reports the resulting protection levels for the WITCH regions.

Table A5.7. Effectiveness of adaptation practices in agriculture for a 2.5°C temperature increase.

	Reduced damage (1=100%)
USA	0.48
WEURO	0.43
EEURO	0.43
KOSAU	0.27
CAJAZ	0.38
TE	0.38
MENA	0.33
SSA	0.23
SASIA	0.33
CHINA	0.33
EASIA	0.33
LACA	0.38

Source: Tan & Shibasaki (2003) and authors' calculations for the extension to the WITCH regions

FLOW ADAPTATION

Health

Many studies describe the possible adaptation strategies that can be implemented by health sectors in developed and developing countries (WHO 2005; WHO 2006). Nevertheless, very few researches try a quantitative cost assessment of these measures. The problem here is double: first there is a general lack of information concerning the potential costs of some interventions. Second, it is very difficult conceptually and practically to separate the costs of adaptation to changes in health status induced by climate change from those related to change in health status per se.

Agrawala and Fankhauser (2008) report just one study, Ebi (2007), which estimates the treatment costs of additional number of cases of diarrhoeal diseases, malnutrition and malaria related to climate change. The additional cost for the world as a whole is between USD 4 and 12.6 Billion by 2030.

The assessment refers instead to Tol et al. (2001), who assess the treatment cost associated to malaria, dengue, schistosomiasis, diarrhoeal, cardiovascular and respiratory diseases, for different scenarios of temperature increases, for all countries of the world. Tol's information is rescaled to AD-WITCH temperature scenario of 2.5°C and the data is aggregated according to WITCH regional aggregation. Results are reported in Table A5.8.

Table A5.8. Additional treatment costs for climate related diseases for a 2.5°C temperature increase.

	Disease Treatment Costs (Billion USD)
USA	1.1
WEURO	-0.7
EEURO	-0.1
KOSAU	1.9
CAJAZ	3.0
TE	0.1
MENA	2.1
SSA	0.5
SASIA	1.1
CHINA	0.3
EASIA	4.7
LACA	5.7
Total	20.6

Developing regions are more adversely affected by climate change impacts on health than developed ones; accordingly they have to spend more in diseases' treatment. This is due to the effect of vector born diseases, above all malaria, which are almost unknown in developed regions. In European regions, the decreased morbidity due to cold-related diseases more than compensates the increased morbidity of hot related diseases. This explains the negative treatment costs in those regions.

The total treatment cost, roughly USD 20 Billion, is higher than that reported by EBI (2007) because Tol et al. (2001) includes additional diseases and considers a more climate scenario. Effectiveness of adaptation measures in the health care sector is even more controversial. For vector borne diseases the references is the World Malaria Report (WHO 2008). The study proposes a protection level quite low for developing countries that are affected primarily by vector borne diseases. Protection levels range from 20% in Africa to 40% in other non OECD countries. Despite the lack of data on developed regions, it is assumed that their protection levels, also considering financial resources, is much higher, ranging from the 60% to the 90%. Table A5.9 summarises the results.

Table A5.9. Effectiveness of adaptation practices in health for a 2.5°C temperature increase.

	Reduced damage (1=100%)
USA	0.90
WEURO	0.90
EEURO	0.60
KOSAU	0.81
CAJAZ	0.69
TE	0.70
MENA	0.60
SSA	0.20
SASIA	0.35
CHINA	0.40
EASIA	0.40
LACA	0.90

Space Heating and Cooling

In the present research the change in the heating and cooling expenditure has been considered as a proxy of adaptation costs in the energy sector. Only the demand side is taken into account here. There are several country level studies which identify the relationship between temperature and energy demand, but there are only three studies that estimated the effects of climate change on the demand for energy at the global level, namely Tol (2002; 2002a), Bigano et al. (2006), De Cian et al. (2007).

Tol (2002; 2002a) based his extrapolations on a UK-specific model that relates the energy used for heating or cooling to degree days, per capita income, and energy efficiency. Climatic change is likely to affect the consumption of energy via decreases in the demand for space heating and increases in demand for cooling. He hypothesised that both relationships are linear. Economic impacts were derived from energy price scenarios and extrapolated to the rest of the world. Energy efficiency is assumed to increase, lessening costs. According to these studies, benefits (reduced heating) are about 0.75% of GDP in 2100 and damages (increased cooling) are approximately 0.45%. The global savings from reduced demand for heating remain below 1% of GDP through 2200. However, by the 22nd century, they begin to level off because of increased energy efficiency. For cooling, the additional amount spent rises to just above 0.6% of GDP by 2200. Thus throughout the next two centuries, net energy demand decreases.

These findings are confirmed by Bigano et al. (2006). They conducted a dynamic panel data econometric estimation of the demand for coal, gas, electricity, oil and oil products by residential, commercial and industrial users in OECD and (a few) non-OECD countries. They derive long-run elasticities for temperature. The main findings highlighted that residential demand responds negatively to temperature increases, pointing at a prevalence of heating needs in determining residential demand. By contrast, industrial demand is insensitive to temperature increases. In the case of the service sector, only electricity demand displays a mildly significant negative elasticity to temperature changes. The estimated elasticities range from the –0.6 of electricity to the -3 for oil product. This study however neither considers seasonality effects nor differentiates among countries in different climatic areas.

These features are introduced by De Cian et al. (2007) which estimate the elasticity of energy demand to temperature for different energy vectors (oil, gas, electricity) differentiating among hot, mild, and cold regions. The study covers all developed countries, but few developing (the most prominent is India). It also refers only to households' energy consumption patterns, as the industry energy consumption did not appear to be significantly affected by climate change. Due to its geographical detail and the more satisfactory econometric specification we decided to use De Cian et al. (2007) elasticities in the present assessment.

Whenever possible, they have been used to compute the energy demand changes corresponding to a 2.5°C increase for the corresponding WITCH regions. The subsequent economic cost has been calculated pricing the change in quantity of energy consumed with prices reported by International Energy Agency. For the WITCH regions not covered by De Cian et al. (2007), we used reasonable averages of the available data. Changes in expenditure are reported in Table A5.10.

Table A5.10. Change in expenditure for space heating and cooling for a 2.5°C temperature increase.

	USD Billion
USA	3.9
WEURO	-8.8
EEURO	-0.8
KOSAU	7.7
CAJAZ	-7.8
TE	0.6
MENA	18.6
SSA	10.4
SASIA	50.7
CHINA	45.5
EASIA	25.9
LACA	2.0
Total	148.0

According to De Cian et al. (2007) household energy expenditures are projected to increase at the world level. This outcome results from the composition of two different effects. Energy use increases typically in hot and (richer regions, above all in Middle East and North Africa, while it decreases in the EU15 and in the Canada – Japan - Australia and New Zealand aggregates. In the first case, the increased households summer energy expenditure for conditioning more than compensate the decreased need for winter heating. The opposite happens in large colder regions such as North European ones or Canada. Here the decreased heating needs during colder seasons more than compensate the increased cooling demand during the summer.

Space cooling has a great potential to decrease indoor thermal discomfort and is of relatively easy implementation; therefore we assume its protection potential to be high, 80% in developed countries. We assumed it to be lower, even half, in developing countries essentially because of lower availability of cooling and heating facilities.

GENERAL AND SPECIFIC ADAPTIVE CAPACITY

Generic capacity captures all components not necessarily related to adaptation itself but to the economic development of a region. The underlined assumption is that the richer a region the more adaptable it is. Generic capacity is assumed to evolve exogenously with the growth rate of total factor productivity. The initial value is an indicator of local capacity based on human capital and knowledge stock. It is computed using data on education and R&D expenditure by World Development Indicators (2008). As a consequence, initial general capacity is larger in developed regions, but growth rates are higher in developing ones. Table A5.11 shows the initial level of generic capacity.

Table A5.11. Initial level of generic capacity (2005)

	USD Trillion
USA	9.03
WEURO	10.74
EEURO	0.30
KOSAU	0.83
CAJAZ	4.32
TE	0.40
MENA	0.69
SSA	0.05
SASIA	0.25
CHINA	0.32
EASIA	0.20
LACA	1.24
Total	28.36

Specific capacity includes all forms of expenditure, investments, and institutions that could increase the adaptive capacity of a system and thus make adaptation activities more effective in reducing climate change damages. Examples of investments that could fall within this category are meteorological services, climate modelling and impact assessment, agricultural extension, innovation for adaptation purposes, and early warning systems, etc.

There are serious data constraint problems in the calibration of this variable. The only activities we have data on are innovation in the agricultural sector and implementation of early warning systems. Agriculture and health are probably the sectors in which innovation is likely to play a particularly important role in the development of new and more effective adaptation responses. However, studies on the application of new inventions to adaptation purposes are still at a very early stage. Only UNFCCC (2007) provides global estimates for the additional expenditure on innovation in agriculture, for developing and developed regions, for a total of 2000 USD 5.420 Million.

Early warning systems can be considered as stock adaptation measure as they contribute to reducing potential downstream impacts of climate change. Their cost can also be considered a particular investment that builds an adaptation stock whose benefits will last more than 1 period.

Adams et al. (2000) founds that the benefits of an ENSO early warning system for Mexico is approximately USD 10 million annually. Benefits are measured as the saved costs for the agricultural sector that can plan in advance crop timing and mix. The cost assessed by Adams et al. (2000) amount to USD 5 Million. If only these two forms of specific capacity were considered, specific capacity would probably be heavily underestimated because many other items would be excluded. For this reason, we decided to calibrate investments in specific capacity as a share of total world expenditure on education and total R&D[12].We set the share to an arbitrarily low value, about 1%, which corresponds to USD 164 Billion in 2060. This global amount has then been distributed to the different regions according to the normalized share of education expenditure over GDP.

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[12] Data on R&D and education expenditure are from World Development Indicators, 2008.

Table A5.12. Investments in specific adaptive capacity for a 2.5°C temperature increase.

	AD-WITCH (USD Billion)
USA	11
WEURO	31
EEURO	1
KOSAU	2
CAJAZ	2
TE	2
MENA	21
SSA	6
SASIA	34
CHINA	17
EASIA	18
LACA	19
Total	164

CALIBRATION RESULTS

The calibration process results in region-specific estimates for the parameters described in Annex 2. The following tables summarize the calibration outcome, where both the extrapolated values from the literature and the calibrated ones for the AD-WITCH model are presented. Table A5.16 also compares the final calibration of the net damages for the AD-WITCH model with the original Nordhaus and Boyer (2000) and the original WITCH model's estimates.

Table A5.13. Adaptation costs for a doubling of CO_2 concentration.

	Water in Agriculture (irrigation) (Billion USD)	Water in Other Vulnerable Markets (Billion USD)	Early Warning Systems (Million USD)	Coastal Protection (Billion USD)	Settlements (Billion USD)	Cooling Expenditure (Billion USD)	Disease Treatment Costs (Billion USD)	Adapt. R&D (Billion USD)	TOTAL (Billion USD)	TOTAL (% of GDP)	AD-WITCH (% of GDP)
USA	3.0	1.3	5	3.57	22.1	3.9	1.13	2.92	37.9	0.09	0.10
WEURO	4.7	2.0	5	5.03	56.2	-8.8	-0.68	2.44	60.9	0.18	0.27
EEURO	7.4	3.2	5	0.26	3.2	-0.8	-0.06	0.03	13.2	0.37	0.18
KOSAU	5.9	2.5	5	1.77	5.2	7.7	1.86	0.29	25.3	0.48	0.19
CAJAZ	1.6	0.7	5	2.87	9.8	-7.8	3.02	1.66	11.8	0.09	0.06
TE	10.1	4.3	5	1.66	3.2	0.6	0.13	0.06	20.1	0.28	0.15
MENA	50.7	21.7	5	1.24	3.9	18.6	2.12	0.14	98.5	1.06	0.81
SSA	13.4	5.7	5	2.68	3.9	10.4	0.51	0.01	36.6	0.70	0.62
SASIA	17.0	7.3	5	1.28	19.7	50.7	1.10	0.04	97.1	0.49	0.68
CHINA	3.0	1.3	5	1.26	17.2	45.5	0.29	0.16	68.6	0.20	0.11
EASIA	1.3	0.5	5	4.26	3.9	25.9	4.74	0.04	40.7	0.40	0.45
LACA	4.3	1.8	5	7.75	5.9	2.0	5.72	0.07	27.7	0.13	0.24

Table A5.14. Effectiveness of adaptation for a doubling of CO_2 concentration.

	Agriculture	Other vulnerable markets	Cat. Events	Coastal systems	Settlements	Non market time use	Health	Weighted total (*)	AD-WITCH
USA	0.48	0.80	0.00	0.75	0.40	0.90	0.90	0.18	0.22
WEURO	0.43	0.80	0.00	0.54	0.40	0.80	0.90	0.13	0.13
EEURO	0.43	0.80	0.00	0.63	0.40	0.80	0.60	0.30	0.27
KOSAU	0.27	0.80	0.00	0.62	0.40	0.80	0.81	0.16	0.18
CAJAZ	0.38	0.80	0.00	0.37	0.40	0.90	0.69	0.20	0.11
TE	0.38	0.80	0.00	0.37	0.40	0.80	0.70	0.12	0.12
MENA	0.33	0.40	0.00	0.55	0.40	0.63	0.60	0.34	0.46
SSA	0.23	0.40	0.00	0.30	0.40	0.30	0.20	0.21	0.19
SASIA	0.33	0.40	0.00	0.47	0.40	0.50	0.35	0.19	0.23
CHINA	0.33	0.40	0.00	0.76	0.40	0.70	0.40	0.15	0.21
EASIA	0.33	0.40	0.00	0.25	0.40	0.43	0.40	0.18	0.21
LACA	0.38	0.40	0.00	0.46	0.40	0.70	0.90	0.38	0.25

(*) Reduction in each category of damage is weighted by the % contribution of that damage type to total damage. Then weighted damages are summed.

Table A5.15. Net Damages for a doubling of CO_2 concentration.

	Nordhaus and Boyer (2000) %GDP	WITCH model %GDP	AD-WITCH survey of the literature %GDP	AD-WITCH model (calibrated) %GDP
USA	0.45	0.41	0.4	0.5
WEURO	2.84	2.79	2.2	1.9
EEURO	0.70	-0.34	0.8	0.9
KOSAU	-0.39	0.12	0.2	1.0
CAJAZ	0.51	0.12	0.01	0.2
TE	-0.66	-0.34	-0.01	0.7
MENA	1.95	1.78	2.5	2.8
SSA	3.90	4.17	4.2	4.2
SASIA	4.93	4.17	4.8	4.4
CHINA	0.23	0.22	0.2	0. 6
EASIA	1.81	2.16	1.8	2.2
LACA	2.43	2.16	2.1	1.2

Table A5.16. Parameters of adaptation and damage functions (calibrated values)

	USA	WEURO	EEURO	KOSAU	CAJAZ	TE	MENA	SSA	SASIA	CHINA	EASIA	LACA
α_0	-0.0021	-0.0005	-0.0016	-0.0086	-0.008	-0.0077	0.0001	0.0003	0.0004	-0.0041	0.0003	0.001
α_1	0.0014	0.003	0.002	0.0042	0.003	0.0037	0.0089	0.0148	0.0095	0.002	0.0037	0.003
α_2	2	2	1.8	2	2	2	1.6	1.6	1.8	2	2	1.1
μ_2	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7
φ_2	0.1	0.1	0.3	0.4	0.1	0.1	0.1	0.1	0.01	0.01	0.1	0.01
β_1	6	0.9	70	30	40	8	13	8	1	10	7	5
β_2	0.5	0.5	0.5	0.5	0.1	0.1	0.5	0.6	0.6	0.85	0.6	0.6
β_3	1	1	1	1	1	1	1	1	1	1	1	1