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Economic Aspects of Adaptation to Climate Change: Integrated Assessment Modelling of Adaptation Costs and Benefits

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JEL Classification: Q25, Q28

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ECONOMIC ASPECTS OF ADAPTATION TO CLIMATE CHANGE: INTEGRATED ASSESSMENT MODELLING OF ADAPTATION COSTS AND BENEFITS

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ABSTRACT

The present report seeks to inform critical questions with regard to policy mixes of investments in adaptation and mitigation, and how they might vary over time. This is facilitated here by examining adaptation within global Integrated Assessment Modelling frameworks.

None of the existing Integrated Assessment Models (IAMs) captures adaptation satisfactorily. Many models do not specify the damages from climate change, and those that do mostly assume implicitly that adaptation is set at an "optimal" level that minimizes the sum total of the costs of adaptation and the residual climate damages that might occur.

This report develops and applies a framework for the explicit incorporation of adaptation in Integrated Assessment Models (IAMs). It provides a consistent framework to investigate "optimal" balances between investments in mitigating climate change, investments in adapting to climate change and accepting (future) climate change damages. By including adaptation into IAMs these already powerful tools for policy analysis are further improved and the interactions between mitigation and adaptation can be analysed in more detail.

To demonstrate the approach a framework for incorporating adaptation as a policy variable was developed 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 – are calibrated and then used in a number of policy simulations to examine the distribution of adaptation costs and the interactions between adaptation and mitigation.

Using the limited information available in current models, and calibrating to a specific damage level, so-called adaptation cost curves are estimated for the world. Adaptation cost curves are also estimated for different regions, although given the limited information available to calibrate the regional curves these should be considered as rough approximations of the actual adaptation potential in the different regions. These adaptation cost curves reflect how different adaptation levels will provide a wedge between gross damages (i.e. damages that would occur in the absence of adaptation) and residual damages.

The analysis presented suggests that a good adaptation policy matters especially when suboptimal mitigation policies are implemented. Similarly, a good mitigation strategy is more important when optimal adaptation levels are unattainable. The rationale for this result is that both policy control options can compensate to some extent for deviations from the efficient outcome caused by non-optimality of the other control option. It should be noted, however, that in many cases there are limits to adaptation with regard to the magnitude and rate of climate change.

The higher the current value of damages, the more important mitigation is as a policy option in comparison to adaptation. The comparison between adaptation and mitigation therefore depends crucially on the assumptions in the model, and especially on the discount rate and the level of future damages.

The policy simulations also suggest that to combat climate change in an efficient way, short term optimal policies would consist of a mixture of substantial investments in adaptation measures, coupled with investments in mitigation, even though the latter will only decrease damages in the longer term. The costs of inaction are high, and thus it is more important to start acting on mitigation and adaptation even when there is limited information on which to base the policies, than to ignore the problems climate change already poses. Ongoing increases in expected damages over time imply that adaptation is not an option that should be considered only for the coming decades, but it will be necessary to keep investing in adaptation options, as both the challenges and benefits of adaptation increase. The results of these policy simulations confirm the findings of the Intergovernmental Panel on Climate Change (IPCC) on the relationship between adaptation and mitigation as described in the Synthesis Report of the Fourth Assessment Report.

The framework developed in this report opens the door for further simulations that examine adaptation cost issues within other, more complex IAMs. The model additions investigated in this report can also shed light on how the next generation of IAMs will look. These tools can also be further strengthened by the incorporation of more detailed regional knowledge on the impacts of climate change and of adaptation options.

JEL Classification: Q25, Q28
Keywords: Integrated Assessment Modelling, Adaptation, Climate Change

RÉSUMÉ

Le présent rapport entend apporter un éclairage sur certaines problématiques essentielles concernant les politiques qui associent investissements dans l'adaptation et investissements dans l'atténuation et leur évolution possible dans le temps. Un tel objectif suppose d'analyser l'adaptation dans le cadre de modèles d'évaluation intégrée. Aucun modèle d'évaluation intégrée ne rend compte de manière satisfaisante de l'adaptation. Bon nombre d'entre eux ne tiennent pas compte des dommages causés par le changement climatique et ceux qui le font partent implicitement de l'hypothèse que l'adaptation est fixée à un niveau « optimal » qui réduit au minimum le montant total représenté par les coûts d'adaptation et les dommages climatiques résiduels risquant d'apparaître.

Dans ce rapport, un cadre permettant d'inclure explicitement l'adaptation dans les modèles d'évaluation intégrée a été créé et appliqué. On dispose ainsi d'un cadre cohérent pour examiner les compromis « optimaux » entre l'atténuation du changement climatique, l'adaptation au changement climatique et l'acceptation des (futurs) dommages induits par ce changement. Inclure l'adaptation dans les modèles d'évaluation intégrée permet d'améliorer ces instruments, déjà performants, d'analyse des politiques et d'examiner de manière plus précise les interactions entre adaptation et atténuation.

Plus précisément, pour les besoins de ce rapport, un cadre a été mis au point pour inclure l'adaptation parmi les variables de politique publique dans deux modèles d'évaluation intégrée – le *Dynamic Integrated model for Climate and the Economy* (DICE), qui est un modèle mondial, et son équivalent régional, le *Regional Integrated model of Climate and the Economy* (RICE). Les modèles modifiés – AD-DICE et AD-RICE – ont été calibrés et utilisés dans plusieurs simulations de politiques pour examiner la composition des coûts de l'adaptation au changement climatique et les interactions entre adaptation et atténuation.

Les courbes des coûts d'adaptation ont été estimées à l'échelle mondiale à partir des quelques informations disponibles dans les modèles actuels et après calibrage en fonction d'un niveau de dommages donné. Les mêmes courbes ont été estimées pour différentes régions mais doivent être considérées comme des évaluations approximatives du potentiel réel d'adaptation dans ces régions, compte tenu de la rareté des informations disponibles pour effectuer le calibrage. Ces courbes montrent l'écart que différents niveaux d'adaptation induisent entre les dommages bruts (ceux qui seraient subis en l'absence de mesures d'adaptation) et les dommages résiduels.

L'analyse présentée démontre qu'il importe de mettre en place une bonne politique d'adaptation, en particulier lorsque les stratégies d'atténuation sont d'une efficacité insuffisante. De même, la mise en place d'une bonne stratégie d'atténuation est d'autant plus importante que les niveaux d'adaptation optimaux sont impossibles à atteindre. Ce résultat s'explique par le fait que l'une et l'autre de ces options peuvent, dans une certaine mesure, compenser les écarts par rapport au résultat efficient liés à l'insuffisance de l'autre option.

Plus la valeur actuelle des dommages est élevée, moins l'adaptation occupe une place importante par rapport à l'atténuation. L'intérêt relatif des deux stratégies dépend beaucoup des hypothèses retenues dans le modèle, en particulier en ce qui concerne le taux d'actualisation et le niveau des futurs dommages. Les simulations de politiques montrent également que pour, lutter de manière efficiente contre le changement climatique, les politiques de court terme devraient associer des investissements substantiels dans des mesures d'adaptation et des investissements dans des mesures d'atténuation, même si la réduction des dommages induite par les mesures d'atténuation ne concerne que des périodes ultérieures. Le coût de l'inaction étant élevé, il vaut mieux agir même lorsque l'on dispose de peu d'informations à l'appui de l'élaboration des politiques qu'ignorer les problèmes qu'entraîne déjà le changement climatique. Les dommages attendus augmentant continûment au fil du temps, il convient de ne pas considérer que l'adaptation est une option à n'envisager que dans les décennies à venir et, au contraire, de continuer à investir dans les mesures d'adaptation puisque les bénéfices de ces mesures et les problèmes qu'elles posent augmentent. Les résultats de ces simulations de politique confirment les conclusions du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) sur la relation entre l'adaptation et l'atténuation décrite dans le Résumé du Quatrième Rapport d'évaluation.

Le cadre élaboré dans le présent rapport ouvre la voie à d'autres simulations, qui feront appel à des modèles d'évaluation intégrée plus complexes pour examiner les questions en lien avec les coûts de l'adaptation. Les modèles modifiés utilisés peuvent également fournir des informations sur ce que sera la prochaine génération de modèles d'évaluation intégrée. Ces outils peuvent aussi être renforcés en intégrant des connaissances régionales plus approfondies sur les effets du changement climatique et les options d'adaptation.

Classification JEL: modèle d'évaluation intégrée, adaptation, changement climatique.
Mots-clés : Q25, Q28

FOREWORD

This report on “Integrated Assessment Modelling of Adaptation Costs and Benefits” is the second output from the OECD project on Economic Aspects of Adaptation. The first report, published in early 2008, assessed empirical estimates of adaptation costs and benefits, as well as the role of policy instruments in incentivising adaptation. Preliminary results from this analysis were presented and discussed at the OECD Workshop on Economic Aspects of Adaptation on April 7-8, 2008. The present report incorporates the feedback received from experts and delegates at this workshop, and from delegates of the Working Party on Global and Structural Policies (WPGSP) that has overseen this work.

This report has been authored by Kelly de Bruin, Rob Dellink and Shardul Agrawala. In addition to WPGSP delegates, the authors are grateful to Jean-Marc Burniaux, Philip Bagnoli, Jan Corfee-Morlot, Florence Crick, Samuel Fankhauser, Helen Mountford, and Richard Tol for valuable input and feedback.

This document does not necessarily represent the views of either the OECD or its member countries. It is published under the responsibility of the Secretary General.

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1. Introduction

Effective and efficient climate policies will require a mix of both greenhouse gas mitigation and adaptation to the impacts of climate change. From a biophysical perspective this is because the near-term impacts of climate change are already "locked-in", irrespective of the stringency of mitigation efforts thus making adaptation inevitable. Meanwhile, without mitigation, the magnitude and rate of climate change will likely exceed the capacity of many systems and societies to adapt (IPCC 2007b, Chapter 18). From an economic perspective total social costs of climate change can be minimised by a combination of mitigation and adaptation. This is based on the assumption that while initial levels of both mitigation and adaptation can be achieved at low cost relative to the avoided climate damages, both sets of responses will face progressively rising marginal costs. Therefore, an optimal climate policy would require a mix of both mitigation and adaptation measures, as opposed to purely one or the other (McKibbin and Wilcoxen 2004; Ingham et al. 2005).

While there is extensive literature on both top-down and bottom up estimates of the costs of mitigation, the literature on adaptation costs and benefits is still at an early stage (Agrawala and Fankhauser 2008). In principle, assessment of adaptation costs and benefits is driven by three objectives. First, adaptation costs and benefits are relevant for sectoral decision-makers exposed to particular climate risks who need to make decisions about whether, how much, and when to invest in adaptation. Second, at the international level, cost estimates can be used to establish "price tags" for overall adaptation needs that inform policy makers and climate negotiators. Third, examination of adaptation costs and benefits can also be used to examine critical questions with regard to policy mixes of investments in adaptation and mitigation and how they might vary over time.

The first two of these objectives – sectoral and aggregate estimates of adaptation costs and benefits – have already been examined in the report "Economic Aspects of Adaptation to Climate Change: An Assessments of Costs, Benefits and Policy Instruments" (OECD 2008).

The present report seeks to address the third objective, i.e. questions with regard to policy mixes of investments in adaptation and mitigation. It moves beyond critical assessment of available empirical estimates of adaptation costs to actual modelling of adaptation as a policy variable. The objective of this report is to shed light on critical policy relevant questions, such as: How might the costs of adaptation vary over time? How can one assess optimal mixes of investments in mitigation and adaptation, and how might they vary over time? How might costs and level of adaptation affect optimal mitigation, and vice versa? And, to what extent can mitigation compensate for deviations from efficient outcomes that may be caused by the non-optimality of adaptation, and vice versa?

Questions such as these can only be addressed within the context of a global, integrated assessment modelling framework that has explicit treatment of climate damages, mitigation costs, as well as adaptation costs. Most existing Integrated Assessment Models (IAMs), however, either overlook adaptation or treat it only implicitly as part of climate damage estimates.

This report develops and tests a framework for explicit incorporation of adaptation as a policy variable within IAMs. By including adaptation into IAMs, these already powerful tools for policy advice are improved, and interactions between mitigation and adaptation strategies can be analysed in more detail. Furthermore, the inclusion of an explicit adaptation function allows the formulation of different scenarios that incorporate adaptation as a decision variable. Consequently, policymakers can use these improved models and analyses to better understand the interactions between adaptation and mitigation. The model additions investigated in this report can also shed light on how a next generation of IAMs might look.

The report is organised as follows. First the report reviews existing IAMs and identifies which models are suitable for adjustment to incorporate adaptation explicitly. Next, a subset of IAMs are identified which might be suitable for adjustment to explicitly incorporate adaptation as a policy variable. Next, two models – the global

Dynamic Integrated model for Climate and the Economy (DICE) and its regional sister-model Regional Integrated model for Climate Change and the Economy (RICE) – are modified to explicitly model adaptation as a policy variable. These modified models (AD-DICE and AD-RICE) are calibrated and cross-checked against results from the original models. These adaptation-IAMs are then used to examine the trade-offs between adaptation and mitigation at the global and regional level through a series of policy simulations. This is followed by a sensitivity analysis of model results with regard to assumptions about discount rates and climate damage functions. Finally some preliminary conclusions are provided, as well as plans for extending this approach to other IAMs.

A number of limitations of the analysis should be stressed from the start. The simulations in this analysis are set in a deterministic context. The uncertainties surrounding the costs and especially benefits of climate action are very large (cf. IPCC, 2007). While a good hedging strategy, i.e. an optimal portfolio of mitigation and adaptation policies taken under uncertainty may differ from policies that are based on deterministic scenarios, these issues require a study of their own. A second potential limitation is that the IAMs that are used in this report to explicitly incorporate adaptation: DICE and RICE are relatively simple relative to some other more complex IAMs. Therefore, the simulations on adaptation costs based on DICE and RICE should be viewed as a first step. Broader application of the approach developed in this report to more sophisticated IAMs will improve the numerical insights. Third, the formulation of adaptation in this report is based on a "flow approach", i.e. adaptation is essentially seen as reactive and its costs and benefits accrue within the same time period. A more elaborate stock-and-flow approach that follows the theoretical specification of Lecocq and Shalizi (2007) may be able to reflect the anticipatory nature of certain types of adaptation measures better. The current report provides the basis for such extended studies by providing a framework for inclusion of adaptation policy in a consistent manner.

2. Consideration of adaptation within Integrated Assessment Models (IAMs).

Climate change involves many interrelated processes each belonging to a different discipline. 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. Finally economic, ecological and socio-political processes link the changed climate to valued impacts as well as policies to both adapt to these impacts and to reduce the emissions of GHGs.

Integrated Assessment Models (IAMs) represent the above mentioned component processes within a formalised modelling framework. An important advantage of such models compared to the standard 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.

Virtually all existing IAMs focus on the trade-off between damages 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 and Tol 1998[1]). 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

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[1] The situation has not evolved much since this review.

socially optimal adaptation coincides with the adaptation provided by the market (see for example, Mendelsohn 2000a). 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, 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 as a policy variable for all sectors within an IAM[2]. Using the model for Policy Analysis for the Greenhouse Effect (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 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 unchanged (Hope, 2006).

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 less free resources for adaptation. Under this assumption it concludes that too high a level of abatement may actually have adverse effects as less adaptation can be undertaken, which leads to more net climate change damages. The also study concludes that 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.

While adaptation is currently not explicitly incorporated in other existing IAMs, at least some of these models can be potentially modified to treat adaptation as a decision variable. For the purposes of this project three criteria were used to screen potential IAMs for this purpose. First, only global IAMs (or models including several regions that together represent the globe) are considered. That is a full analysis of adaptation/mitigation interactions would require a global analysis, given that the effects of mitigation measures will influence global damages. Therefore, specific regional integrated models are not considered. Second, the model should include monetised damages from climate change. 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 damages, by specifying the costs and benefits of various abatement strategies. Third, the models should be contemporary, that is actively being used and reasonably up to date with respect to the literature.

Only a small subset of the 30 or so IAMs that were surveyed for this analysis fulfil the above mentioned three criteria: DICE, RICE, MERGE, FUND, FAIR, PAGE, and WITCH[3]. This analysis focuses on developing an explicit framework for adaptation within the global DICE model and the regionalised RICE model, which are both well-established models. Further, many of the other models have damage functions that are based on those of DICE and RICE. This analysis does not consider MERGE as its damage function is extracted from the RICE damage function and would not give further insights. Implementing adaptation into WITCH and FUND, however, may be a very fruitful exercise, which has been left for further research.

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[2] We do not consider here the larger literature on implementations of adaptation into partial models of (small) regions or of certain sectors, such as agriculture.

[3] For a recent overview of adaptation models, with special attention to adaptation, see Dickinson (2007).

3. Incorporating adaptation as a policy variable in 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 slow climate change (Nordhaus 1994, 2007). RICE is an extension of DICE and includes multiple regions and decision makers, to permit more disaggregated analysis (Nordhaus and Yang 1996; Nordhaus and Boyer 2000).

The DICE and RICE models have often been criticised because of their simplicity. For the purposes of this analysis, however, they have been selected primarily for the purpose of unpacking the climate damage function, in order to examine adaptation costs. For this purpose DICE and RICE are the best choice as most other IAMs are based upon the damage functions of DICE and RICE. Meanwhile, critiques with regard to specific assumptions within DICE and RICE - such as with regard to the discount rate and the form of the damage function – are examined in this report as part of the sensitivity analysis. A more detailed description of the DICE/RICE damage function is provided in Annex 1.

3.1 DICE and AD-DICE

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.

Adaptation to climate change would decrease the potential damages of climate change. This is the mechanism that is now explicitly added to the DICE model[4]. Gross damages are defined as the initial damages by climate change if no changes were to be made in ecological, social and economic systems. If these systems were to change to limit climate change damages (i.e. adapt) the 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 as adaptation costs. Thus, the net damages in DICE are now represented as the total of the residual damages and the adaptation costs.

In the DICE model the net damage function is a combination of the optimal mix of adaptation costs and residual damages. Thus the net damage function given in DICE can be unravelled into residual damages and adaptation costs (see Annex 2 for mathematical detail on the net, gross and residual damage functions and adaptation/protection costs).

It is assumed that the adaptation costs and the residual damages are separable, and can be represented as a fraction of income. Residual damages depend on both the gross damages and the level of adaptation. Effectively, this makes the decisions on the levels of adaptation and mitigation separable. Adaptation costs, meanwhile, are given as a function of the level of adaptation. It is assumed that this function is increasing at an increasing rate, as cheaper and more effective adaptation options will be applied first, and more expensive and less effective options will be used after these.

It is further assumed that the level of adaptation is chosen every time period (10 years). The adaptation in one time period does not affect damages in the next period, thus each decade the same problem is faced, and the same trade-off holds. This implies that both the costs and benefits of adaptation fall in the same time period (decade). The important implication of this assumption is that as long as adaptation is applied optimally, the

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[4] The mathematical framework of the original DICE model and its modification to explicitly account for adaptation are detailed in Annex 2 of this report. The AD-DICE framework was published as de Bruin et al. (2008), which this discussion draws heavily upon.

benefits of adaptation will always outweigh the costs (this follows directly from the maximisation) and hence the adaptation decision will never draw away funds from mitigation policy. This way of modelling adaptation benefits and costs is debatable. Many adaptation measures have this characteristic and fall under the category of *reactive adaptation*. Other adaptation measures, mostly in the category of *anticipatory adaptation*, however, have a time-lag in costs and benefits. Examples of such measures are building seawalls and early warning systems. The assumptions of adaptation costs and benefits accruing in the same time period, however, should not affect the general conclusions of this study. An analysis which adds an adaptation capital stock to represent anticipatory adaptation would, however, be interesting and is deferred to future work. In principle, such a future study can use the theoretical framework of Lecocq and Shalizi (2007) to formulate a stock-and-flow approach to adaptation that better reflects the anticipatory nature of some adaptation measures.

3.1.1 Calibration of AD-DICE

The DICE2007 model as available online is used to calibrate the AD-DICE model. The model is calibrated in such a way that it best replicates the results of the optimal control scenario of the original DICE model (see Annex 2 for an explanation of the calibration process).

Table 1 depicts the net damages estimated by AD-DICE and those estimated by DICE, for both the optimal control scenario and for the scenario without mitigation for the years 2055, 2105 and 2155. For both scenarios, the calibration fits well which shows that the parameter values are valid for both scenarios.

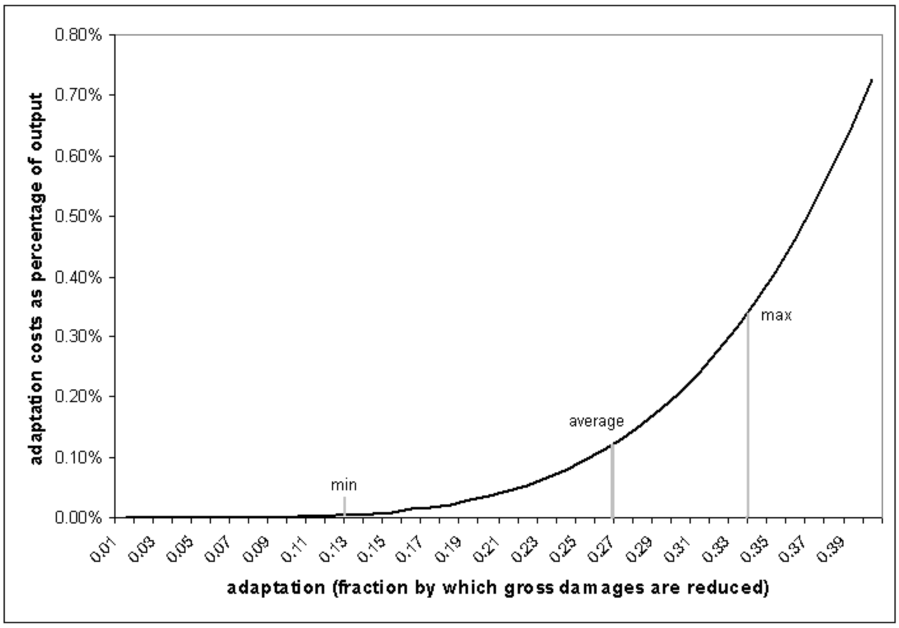
Table 1 also shows that the levels of mitigation are essentially the same in DICE and AD-DICE. This is because the decisions to mitigate and adapt are separable. In DICE, mitigation is set by the marginal damage cost. In AD-DICE, mitigation is set by the marginal residual damage plus adaptation cost. As the net damage profiles in DICE and AD-DICE are practically identical, so are the marginals. Thus this model will give the same results as the DICE model if adaptation is set at its optimal level.

Table 1. Net climate change costs and mitigation levels in percentages estimated by AD-DICE and DICE

	Climate change costs in optimal		Climate change costs when no mitigation		Mitigation	
Year	DICE	AD-DICE	DICE	AD-DICE	DICE	AD-DICE
2055	1.00	0.99	1.07	1.07	26.9	26.9
2105	2.32	2.31	2.88	2.88	44.3	44.1
2155	3.73	3.72	5.34	5.27	67.7	67.0

Using the parameter values for AD-DICE an adaptation cost curve can be drawn, as shown in Figure 1. The figure shows that the adaptation costs of the first 15% of gross damage reduction are extremely low after which they rise. In our calibrated model, the optimal level of adaptation varies from 0.13 to 0.34, with an average of 0.27, that is 27 percent of gross damages are reduced due to adaptation. It can easily be seen that the costs of adaptation rise to such a high level that it can never be optimal to fully adapt to climate change. In other words, solely adapting to climate change is not a solution and mitigation will be needed too.

Figure 1. The adaptation cost curve implicit in the DICE2007 model (range 0.15-0.4).



3.2 RICE and AD-RICE

RICE is a regional version of the Dynamic Integrated Climate and Economy model. It consists of 13 regions in the RICE99 online version. The regions are: Japan, USA, Europe[5], Other High Income countries (OHI)[6], Highly Industrialised Oil exporting regions (HIO)[7], Middle Income countries (MI)[8], Russia, Low-Middle income countries (LMI)[9], Eastern Europe (EE), Low Income countries (LI)[10], China, India and Africa[11]. The RICE model is a growth model. 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 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 was always negative. For example in colder regions, the warming of the climate can make previously unutilized land arable (cf. IPCC, 2007b). Further detail on the mathematical formulation for of the net, gross and residual damage functions and of the protection/adaptation costs is provided in Annex 3.

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[5] Austria, Belgium, Denmark, Finland, France, Germany, Greece, Greenland, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom

[6] Includes Australia, Canada, New Zealand, Singapore, Israel, and rich island states

[7] Includes Bahrain, Brunei, Kuwait, Libya, Oman, Qatar, Saudi Arabia, and UAE.

[8] Includes Argentina, Brazil, Korea, and Malaysia.

[9] Includes Mexico, South Africa, Thailand, most Latin American states, and many Caribbean states.

[10] Includes Egypt, Indonesia, Iraq, Pakistan and many Asian states.

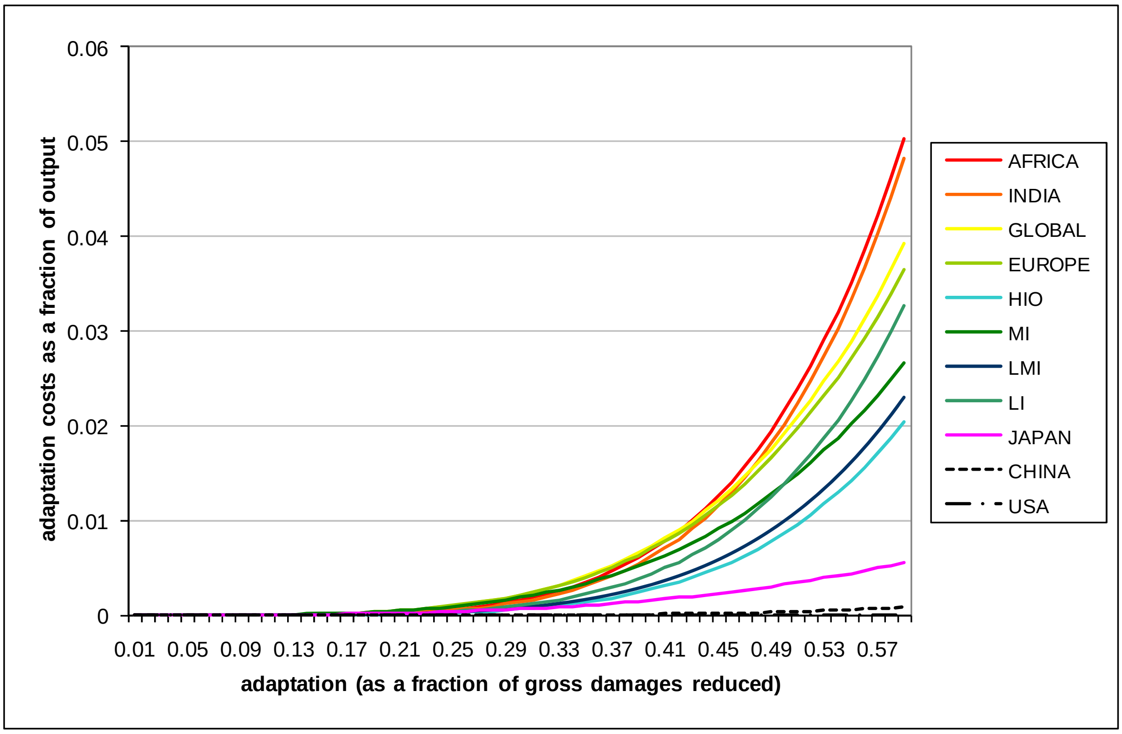
[11] Includes all sub Saharan African countries, except Namibia and South Africa

3.2.1 Calibration of AD-RICE

The online RICE99 model is used for this analysis. 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 result of the calibration is provided in Annex 3.

The adaptation cost curves for the remaining 10 regions are drawn in Figure 2. The line denominated as GLOBAL has been added and represents the AD-DICE 2007 global adaptation cost curve (from Figure 1). For the three regions not calibrated (EE, OHI and Russia), it was assumed that no adaptation will take place as the damages are so close to zero.

Figure 2. Adaptation costs curves implicit in the RICE model.



As can be seen, the adaptation costs in the different regions vary widely. Due to the limited information with which these curves are estimated, these curves are only tentative, and may not fully reflect the options available to individual regions. Clearly, such a top-down approach as the one presented here will miss many relevant aspects of adaptation at the local level. Nonetheless, it is relevant for examining the interaction between adaptation and mitigation at a macro level.

The relation between high estimated damages and high estimated adaptation costs for full adaptation is straightforward: the higher the damage level, the more effort it will take to avoid all these damages. As our variable for adaptation effort reflects an effort to avoid damages as a fraction, the interpretation in absolute terms is different: where a single adaptation measure (say a flood protection measure) may reduce 1 percent of all gross damages in one region, it may only reduce half a percent in another region that has higher damage levels. Consequently, one can observe that the extremely high adaptation costs for high adaptation levels are associated with regions that have high damage levels.

It should be stressed that the extremely high adaptation costs as projected by the curves for several regions when adaptation efforts approach one, i.e. when almost all damages are avoided by implementing adaptation measures, will never materialise. In this model the marginal adaptation costs will always be balanced with the marginal avoided damages. Thus, it is not likely that the end of the adaptation cost curve is reached: for the first adaptation measure the avoided damages are high and the associated adaptation costs are low, but as more adaptation measures are implemented this ratio shifts. At some stage, the additional cost of one more adaptation measure will not be outweighed by the avoided damages, and it is no longer optimal to increase the adaptation effort.

4. Policy simulations with AD-DICE and AD-RICE

This section first compares the baseline scenarios of AD-DICE and AD-RICE with the IPCC SRES scenarios. Next these models are used to run reference scenarios, to investigate the three cost components of climate change (adaptation costs, mitigation costs, and residual damages) as well as the interactions between adaptation and mitigation. Mitigation scenarios are then run to investigate the effects of different proposed mitigation policies and what effects adaptation has on these policies. Finally adaptation scenarios are run to understand the effects of under or over investment in adaptation.

4.1 Baseline Scenario Comparison

The baselines for AD-DICE and AD-RICE are compared with the common SRES 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 and AD-RICE as they are in the 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 3a-c.

Figure 3a. Emission estimates of the IPCC SRES and baseline scenarios of AD-DICE and AD-RICE

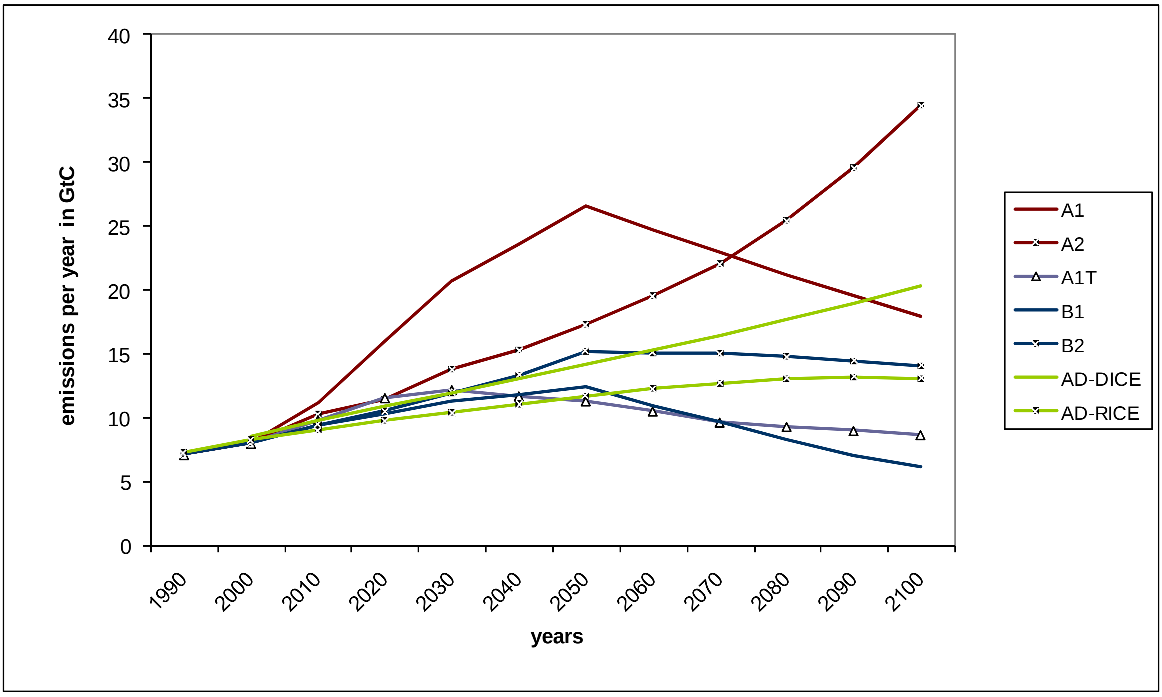


Figure 3b. Temperature estimates of the IPCC SRES and baseline scenarios of AD-DICE and AD-RICE.

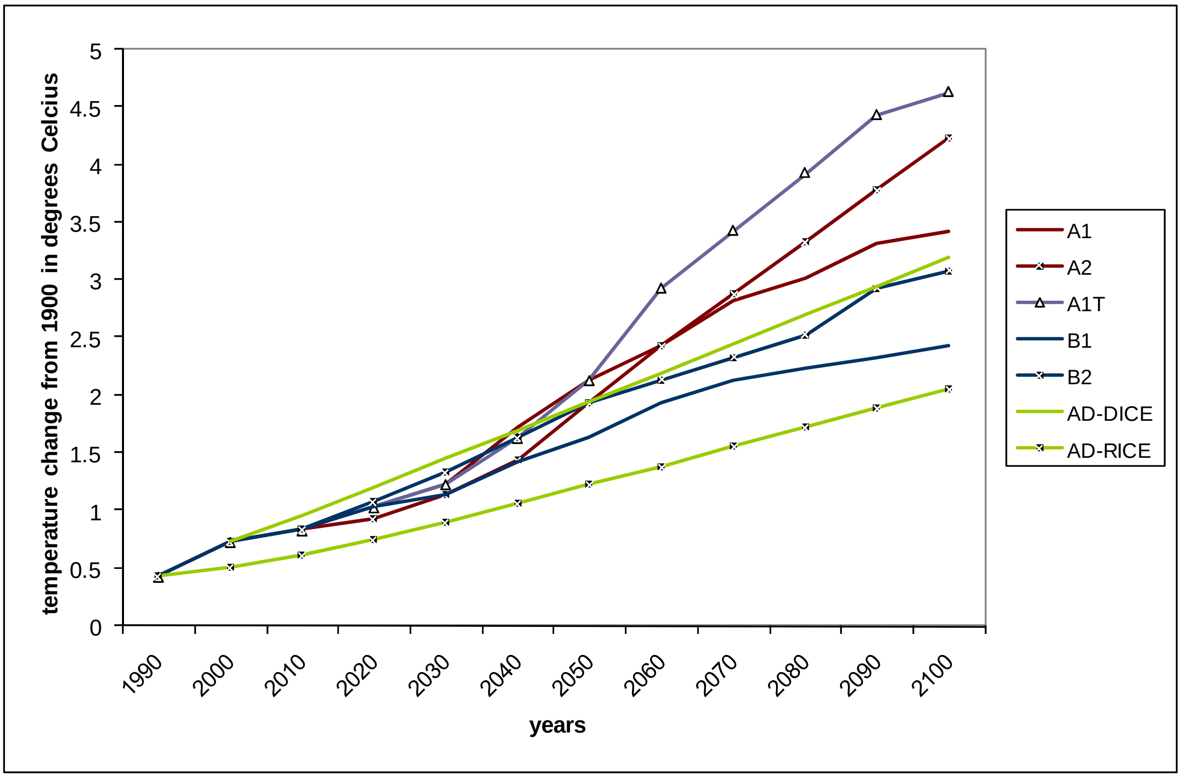
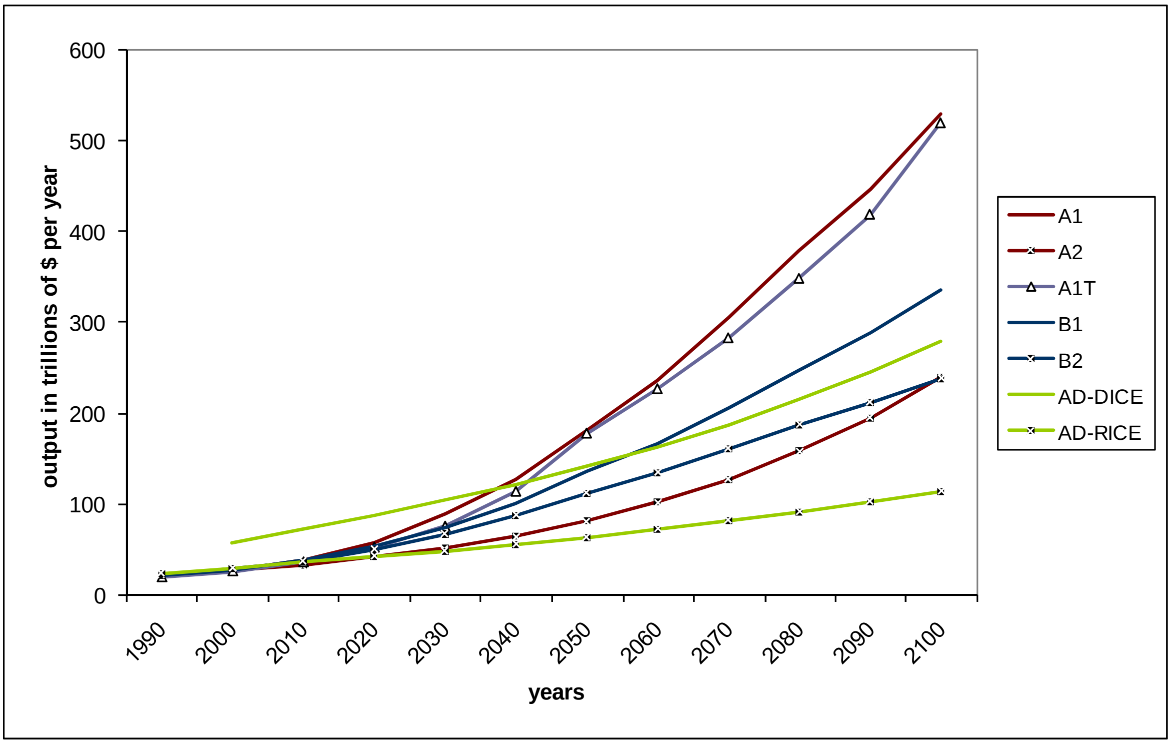


Figure 3c. Output estimates of the IPCC SRES and baseline scenarios of AD-DICE and AD-RICE



As shown in the above figures, the AD-DICE baseline generally falls within the SRES range and seems to most closely correspond to the B scenarios. The AD-RICE model, however, is somewhat on the low side for all indicators and falls beneath the SRES range. This is because the RICE model as used to construct AD-RICE, unlike DICE, has not been updated. Nordhaus (2007) compares the DICE99 model to the updated DICE2007 model and identifies large differences in global output and other variables. Furthermore damages were much lower in the older version.

Consequently, AD-DICE is the better model to investigate the interactions between adaptation and mitigation on a global scale, and AD-RICE should only be used for those comparisons where a regional differentiation is required. This principle (AD-DICE wherever possible, AD-RICE where regional specificity is needed) is therefore used in the analysis of the scenarios in the sections below.

4.2 Reference Scenarios

Four reference scenarios are used here for AD-DICE and AD-RICE: no control, optimal control, only adaptation and only mitigation; these are given in box 1. In the *no control* scenario, adaptation and mitigation levels are set at zero.[12] In "*optimal"*[13] *control*, both adaptation and mitigation levels are determined endogenously within the model to maximise discounted (present value) utility from consumption, i.e. for both variables optimal levels are chosen. In the *only adaptation scenario*, adaptation is at its optimal level while the mitigation level is zero. In the *only mitigation scenario*, the mitigation is at its optimal level while the adaptation level is zero.

Box 1. Reference scenarios

R1. No Control: Neither mitigation nor adaptation is employed, i.e. no climate policies are applied.

R2. "**Optimal"**: Mitigation, adaptation, consumption are set at a level to maximize the value of net economic consumption discounted over income per capita. Both the optimal mitigation and adaptation policies are applied.

R3. No mitigation, optimal adaptation: Only adaptation can be used to combat climate change. The optimal adaptation policy is applied.

R4. No Adaptation, optimal mitigation: Only mitigation can be used to combat climate change. The optimal mitigation policy is applied.

The utility of the different scenarios is shown in Figure 4. A utility index is used, where the level of utility in the optimal scenario is set at 100. The optimal control (R2) leads to the highest welfare level. This is followed by the only adaptation scenario (R3) and the only mitigation scenario (R4), which have similar levels of utility. Finally the scenario that creates the lowest utility is the no control scenario (R1). These results confirm the importance of adaptation.

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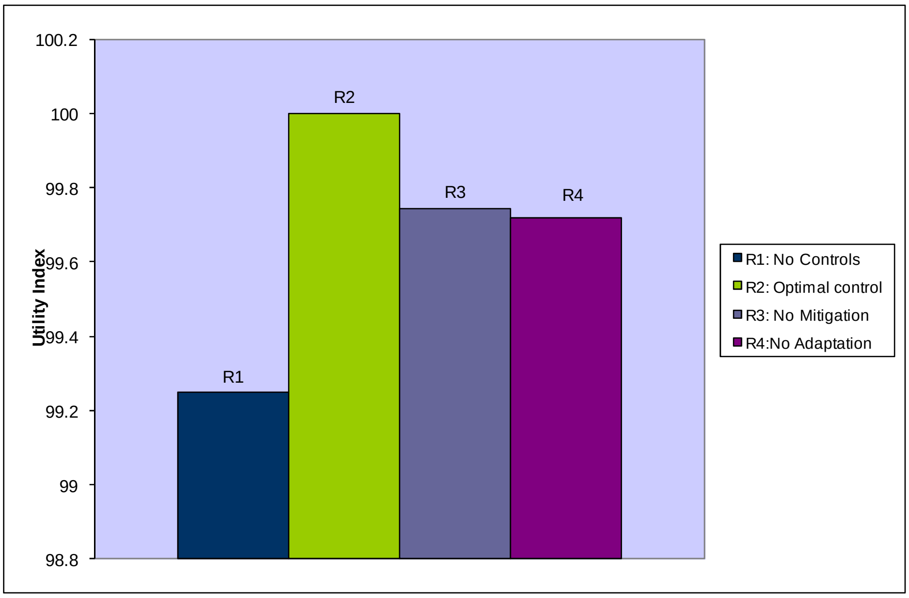
[12] It should be noted that in AD-DICE mitigation will not be exactly zero, as the model contains some mitigation efforts due to the exhaustion of fossil fuels (the Hotelling rents, which do not represent a policy option).

[13] The term "optimal" throughout this report refers to outcomes from the optimisation framework of the DICE and RICE models to maximise social welfare (utility) and are not intended to be policy prescriptive. Other models can result in different optimal outcomes. Further, alternate assumptions with regard to discount rates and damage functions within DICE and RICE can also change optimal outcomes. This is analysed in the sensitivity analysis in Section 5.

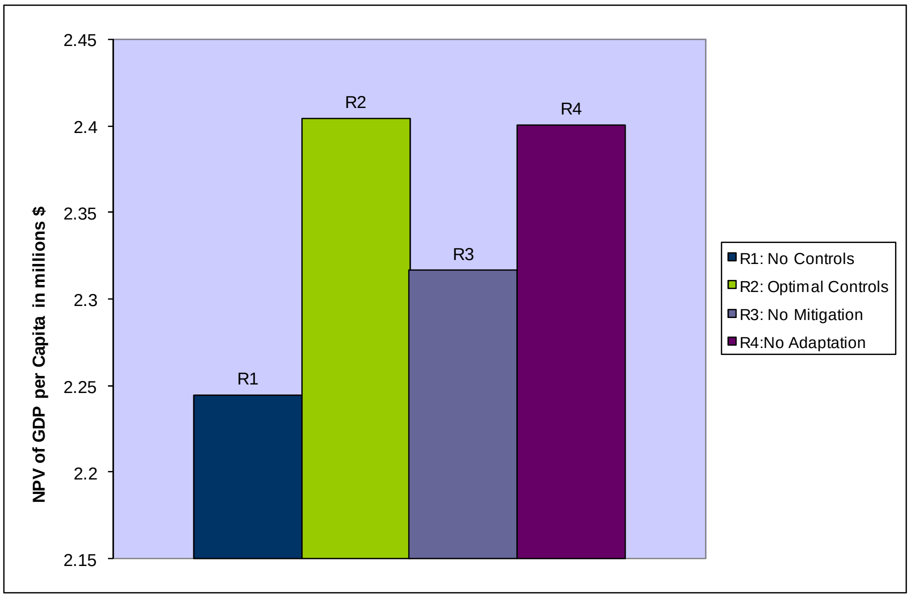
Figure 4. Utility index for the policy scenarios



While utility is the objective of the optimization procedure in DICE and RICE, it may be useful to look at other indicators of economic prosperity as well. Therefore, the net present value (NPV) of GDP per capita is given in Figure 5. As the level of GDP per capita is closely related to consumption levels per capita (which are the determinant of utility), utility and the NPV of GDP per capita mostly move in the same direction. Thus while the combination of both controls (the R2 optimal control scenario) is superior to having only one control variable, only adapting (no mitigation scenario R3) results in a lower GDP per capita than only mitigating (no adaptation scenario R4). In fact, when optimal mitigation is still available, GDP levels are hardly affected by the availability of adaptation, as shown by the negligible difference between R2 and R4.

However, when mitigation is unavailable, adaptation can prevent large GDP-losses, as shown by the significant difference between R3 and R1.

Figure 5. NPV of GDP per capita for the policy scenarios



There are clear differences between utility and the NPV of GDP per capita, especially for the influence of adaptation. The main rationale for this is that the marginal utility of consumption per capita decreases with increasing income (GDP) levels, and as GDP levels increase substantially over time, the large future mitigation benefits have a larger impact on GDP per capita than on utility. For adaptation, the benefits are more evenly spread over time.

4.2.1 The Composition of Climate Change Costs

The costs of climate change include residual damages, adaptation costs and abatement (or mitigation) costs. The composition of these costs is assessed over time at the global level using AD-DICE for the reference scenarios. This is followed by an exploration of the regional differences using AD-RICE.

Table 2 presents the components of climate costs in absolute terms (billion USD per year) for four specific decades. In the very short run (2025-2034) the damages from climate change and the costs of both adaptation and mitigation are relatively small. When no action is taken (R1), residual damages amount to 204 billion USD globally each year in the decade 2025-2034. However, the total costs are lowered only slightly (by 6 billion USD annually) by investing in both mitigation and adaptation (compare R2 and R1) in this time horizon. Looking a bit further in time (2045-2054) the total costs can now be reduced by 100 billion USD annually by investing in adaptation and mitigation (compare R2 and R1). The required investments in this case amount to 56 billion dollars for mitigation and 27 billion USD for adaptation annually, but decrease residual damages by 183 billion USD annually. In the scenario without adaptation (i.e. mitigation only) the climate costs are substantially higher than in the scenario without mitigation, even though residual damages do not differ much. Thus, in this case, adaptation only (R3) can reduce 132 billion USD of annual residual damages at a cost of 31 billion USD, whereas mitigation only can reduce 78 billion USD of residual damages at a cost of 85 billion USD. Thus, in the short run adaptation is more effective at reducing residual damages than mitigation. However, this short-term reasoning is flawed as it ignores the long-term benefits of mitigation.

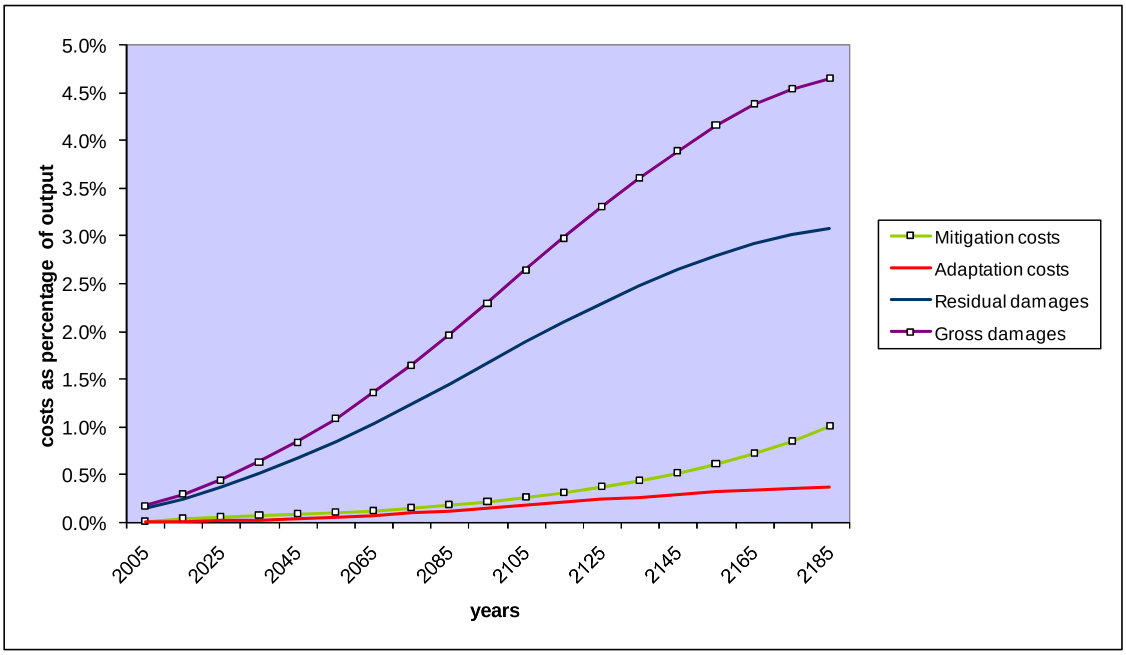
Table 2. Build-up of climate costs in the reference scenarios in billion USD per year

Annual costs (billion USD)	R1	R2	R3	R4
Period 2025-2034				
Adaptation costs	0	7	7	0
Mitigation costs	0	21	0	30
Residual damages	204	170	174	199
Total Costs	**204**	**198**	**181**	**229**
Period 2045-2054				
Adaptation costs	0	27	31	0
Mitigation costs	0	56	0	85
Residual damages	695	512	563	617
Total Costs	**695**	**595**	**594**	**703**
Period 2095-2105				
Adaptation costs	0	247	361	0
Mitigation costs	0	367	0	610
Residual damages	5430	3026	3920	3824
Total Costs	**5430**	**3639**	**4281**	**4435**
Period 2145-2155				
Adaptation costs	0	1013	1903	0
Mitigation costs	2	1672	2	2902
Residual damages	22083	9626	14437	12033
Total Costs	**22084**	**12311**	**16341**	**14936**

At the beginning of the 22nd century (2095-2105), the climate stakes are higher, as shown in Table 2. In the case of inaction, residual damages would have risen to 5.4 trillion USD annually in the decade, but nearly a half of those damages can be avoided by spending 247 and 367 billion USD (annually) on adaptation and mitigation respectively. As time goes on mitigation becomes a more important option (compare R3 and R4 over time), induced by the larger damages and longer lag time of mitigation benefits. Note furthermore that the benefits of mitigation (in the form of reduced damages) increase even more rapidly over time, as these reflect a combination of past and current mitigation efforts. Clearly the uncertainties surrounding these projections for such long time periods are very high and absolute numbers should be treated with caution. These projections, however, serve to highlight how adaptation and mitigation affect total climate costs over time. Given the inertia in the climate system, the benefits of mitigation policies become progressively more significant in later time periods. Therefore, a long-term perspective is required to fully examine the relationships between adaptation and mitigation.

The composition of climate change costs in the optimal scenario meanwhile can be examined over time by looking at Figure 6. As shown in this figure a large part of climate change costs under this optimal scenario for all time periods consist of residual damages. In the optimal control scenario, adaptation costs rise only slightly over time, while mitigation costs increase relatively steeply. As these results are expressed in percentage of GDP, the increasing GDP levels imply that absolute expenditures on adaptation are increasing substantially over time. It should be stressed that the optimal scenario identified in the AD-DICE model does not imply a strict limit on CO_2 concentrations: concentrations of CO_2 (excluding other greenhouse gases) peak around 680 ppm near the end of the 22nd century, and the associated temperature increase is almost 3.5°C. This is a much higher target of concentration and level of climate change identified as "acceptable" in a number of other studies. Several reasons account for the high DICE results, including a relatively high discount rate and low damage estimates compared to some other IAMs. The sensitivity of the analysis to these assumptions is examined in detail in Section 5. Furthermore, damages from extreme events and important irreversibilities are not included in the analysis.

Figure 6. Composition of climate change costs in the optimal scenario



While these graphs provide useful insights into the global components of climate costs, there are substantial regional differences. These are depicted using AD-RICE for the optimal control scenario in Table 3. In line with the existing insights from the literature (such as IPCC 2007b), the model simulations here suggest that climate change will particularly affect many developing countries and regions. Gross damages (in percentage of GDP) are projected to be especially high for India and Africa (cf. Figure 2), and it is thus not surprising that the largest adaptation efforts are made in these regions. Damages in Africa especially include health effects (75% of damages at 2.5 degrees of climate change). Damages in India are caused predominantly in agriculture, health, and as a result of catastrophic events. Residual damages are more evenly spread across regions, although clearly regions that have very small gross damages will also have the lowest residual damages.[14] At the other end of the spectrum, Nordhaus and Boyer (2001) project in their RICE model that Japan will have small but positive net benefits from climate change for the coming century, due to their benefits for agriculture and increased amenity values (see Annex 1 for detail on the RICE damage function). The AD-RICE model mimics these findings and projects a small negative number for gross damages in Japan, and thus adaptation costs remain relatively small. Note that the global numbers from these simulations with AD-RICE are not directly comparable to the global AD-DICE results, as the level of damages is much lower in RICE – and thus in AD-RICE – than in DICE – and thus AD-DICE.

Table 3. Regional components of damage and adaptation costs in the optimal control scenario, as projected by the AD-RICE model, expressed as a percentage of regional GDP.

	NPV Gross damages	NPV Residual damages	NPV Adaptation costs	NPV GDP	NPV Gross damages as a percentage of NPV GDP
JAPAN	-8	-91	25	183491	0.0%
USA	985	21	94	443078	0.2%
EUROPE	3852	2773	254	430159	0.9%
OHI	0	0	0	91864	0.0%
HIO	576	375	39	39442	1.5%
MI	2026	1497	133	183915	1.1%
RUSSIA	0	0	0	41081	0.0%
LMI	3440	2239	237	219515	1.6%
EE	0	0	0	55861	0.0%
LI	3237	2080	223	122537	2.6%
CHINA	277	33	39	166074	0.2%
INDIA	4661	2925	328	101871	4.6%
AFRICA	2051	1333	140	48598	4.2%
Global (AD-RICE)	**21097**	**13184**	**1515**	**2127485**	**1.0%**

4.2.2 Adaptation-mitigation interactions

This section focuses on the interactions between adaptation and mitigation over time. Furthermore the NPV of costs and benefits of each control in the various scenarios is examined.

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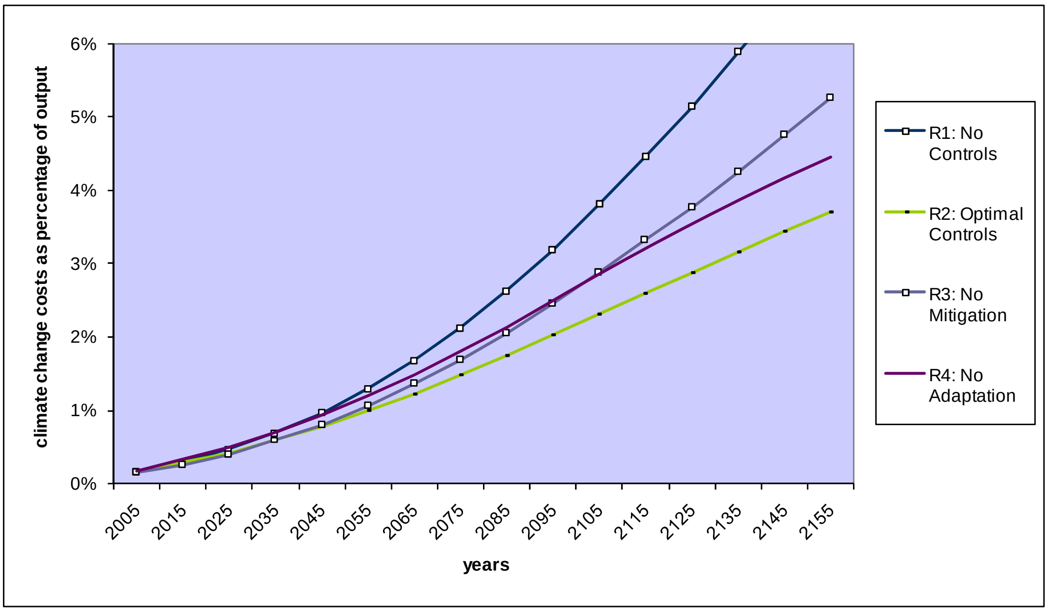
[14] As with most IAMs, the original RICE model, and consequently the AD-RICE model project fairly low damages estimates for China, even though may have severe flood problems in the highly developed coastal areas. This is again due to benefits in agricultural and increased amenity values, furthermore extreme weather events are not fully considered in this model underestimating damages in regions with high damage potential from such events.

Figure 7. Climate change costs (i.e. adaptation costs, mitigation costs and residual damages) over time for the different policy scenarios



The distribution of costs of climate change over time with the different policy scenarios is shown in Figure 7. As this figure shows, different scenarios distribute the costs of climate change quite differently over time. Thus changes in the discount rate will also change the ranking of the scenarios. The sensitivity of AD-DICE to assumptions about discount rates and damage functions is further examined in Section 5. Figure 7 furthermore shows that the optimal scenario has the least discounted climate change costs, while the no controls scenario has the highest discounted costs.

To examine the dynamics of adaptation and mitigation in more detail, the net benefits of adaptation and mitigation over time (both as a percentage of output) are examined in Figure 8. The net benefits of adaptation are calculated by comparing the residual damages in the scenarios with and without adaptation, i.e. by comparing scenarios R2 and R4 when assuming optimal mitigation and R3 and R1 when assuming zero mitigation. Similarly, the net benefits of mitigation are calculated by comparing scenarios R3 and R2 for optimal adaptation and R1 and R4 for no adaptation. The figure shows that adaptation has higher benefits initially, while mitigation becomes much more beneficial than adaptation over the long term. Thus even though it is optimal to start investing in mitigation immediately, few of these benefits will be felt in the initial decades – largely because of the considerable lags in the climate system.

Figure 8 also illuminates the interactions between adaptation and mitigation. The net benefits of mitigation are given for the case when only mitigation is an option and for the case where optimal adaptation is also possible. It can be seen (by comparing the benefits of mitigation with and without adaptation) that including adaptation as an option slightly increases the benefits of the optimal path of mitigation until 2035 (although the effects are so small that this is not clearly visible from the figure) but substantially decreases the benefits later. This is because adding adaptation as a control option will decrease the optimal level of mitigation. Because of this some costs of mitigation in the beginning periods will be avoided but this also entails that benefits of mitigation in later periods are lost. In other words, when the option of adaptation is available one does not need to over-invest in mitigation in earlier periods. Note that the analysis here does not consider direct interactions between adaptation and mitigation. The possibility of such direct effects was surveyed in the IPPC's 4th Assessment Report (IPCC 2007 Chapter 18) which concludes that the direct relationship between adaptation and mitigation is ambiguous and likely to be small.

There is a chance that policymakers do not look at the optimal control over time but only consider the near future. In other words, the world has a myopic view. In this case, because the benefits of adaptation are higher in earlier years, there may be an overinvestment in adaptation and an underinvestment in mitigation. This is a problem of intergenerational externalities: the burdens of mitigation are felt in earlier periods, while the benefits are reaped in later periods (or more accurately the benefits of a high level of consumption are reaped now, while the burdens are felt by later generations in the form of climate change damages).

Figure 8. Net benefits of adaptation and mitigation in different scenarios

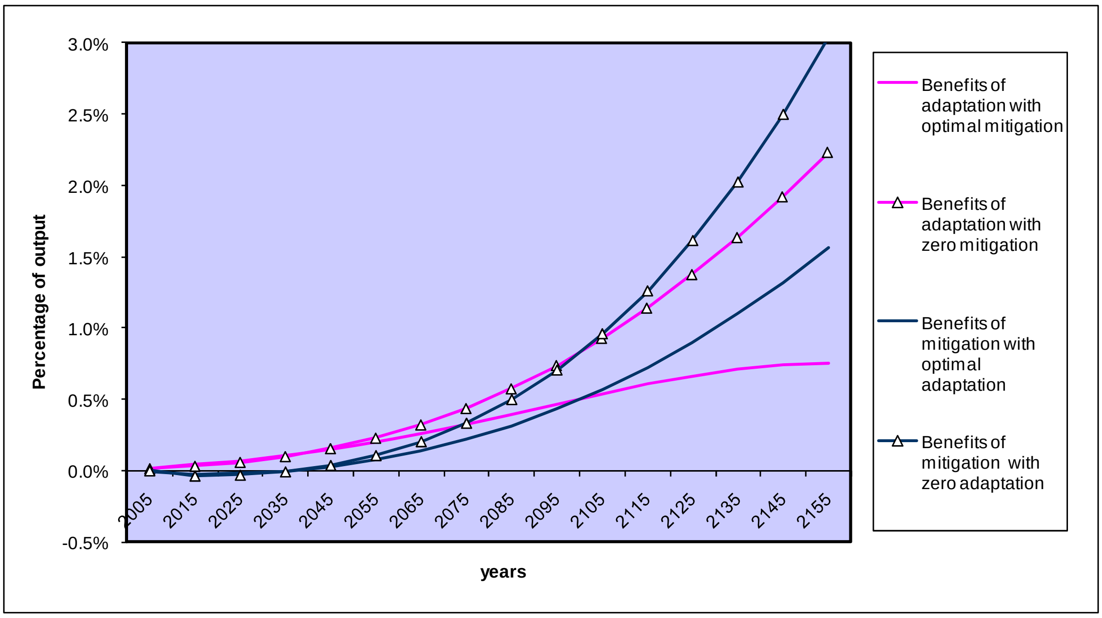


Figure 8 also shows that adaptation is less beneficial when mitigation is also an option. This is because mitigation reduces gross damages reducing the potential benefits of adaptation. The difference between benefits of adaptation with optimal mitigation and without mitigation increases over time, because the effect of mitigation becomes more pronounced over time. It is important to note that even though mitigation and adaptation decrease each other's effectiveness, i.e. there is a negative interaction effect, the simultaneous use of both options is still optimal. The marginal costs of both options increase more than proportionately with higher percentages of mitigation/adaptation, and this effect is stronger than the interaction effect, and the optimal policy involves a mixture of moderate amounts of both adaptation and mitigation.

The framework can also be used to examine costs of inaction, i.e. if neither mitigation nor adaptation is applied in the near future. For adaptation, the benefits occur immediately. Therefore the absence of adaptation will lead to a loss of GDP, even in the short term. However, the absence of mitigation may actually boost income levels initially. This reflects the delayed benefits of mitigation actions, while the costs are near term. However, the absence of either or both mitigation and adaptation will result in lower discounted utility relative to action on both mitigation and adaptation. Therefore climate policies cannot be based on short-term insights and short-term net benefits only, i.e. a myopic view could give the impression that postponing mitigation efforts is beneficial, but these short-term benefits are more than outweighed by the long-term additional losses of inaction.

4.3 Mitigation scenarios

This section examines the effect of different mitigation policies, specifically policies which put different caps on the level of temperature change or the amount of CO_2 concentrations in the atmosphere. Note that the DICE and RICE models only contain CO_2, and the impact of other greenhouse gases only enters the model through an exogenous additional radiative forcing parameter.

Box 2. Mitigation policy scenarios

M1 - Concentrations are limited to 450 ppm.

M2 - Concentrations are limited to 450 ppm after 2150. Overshooting is allowed.

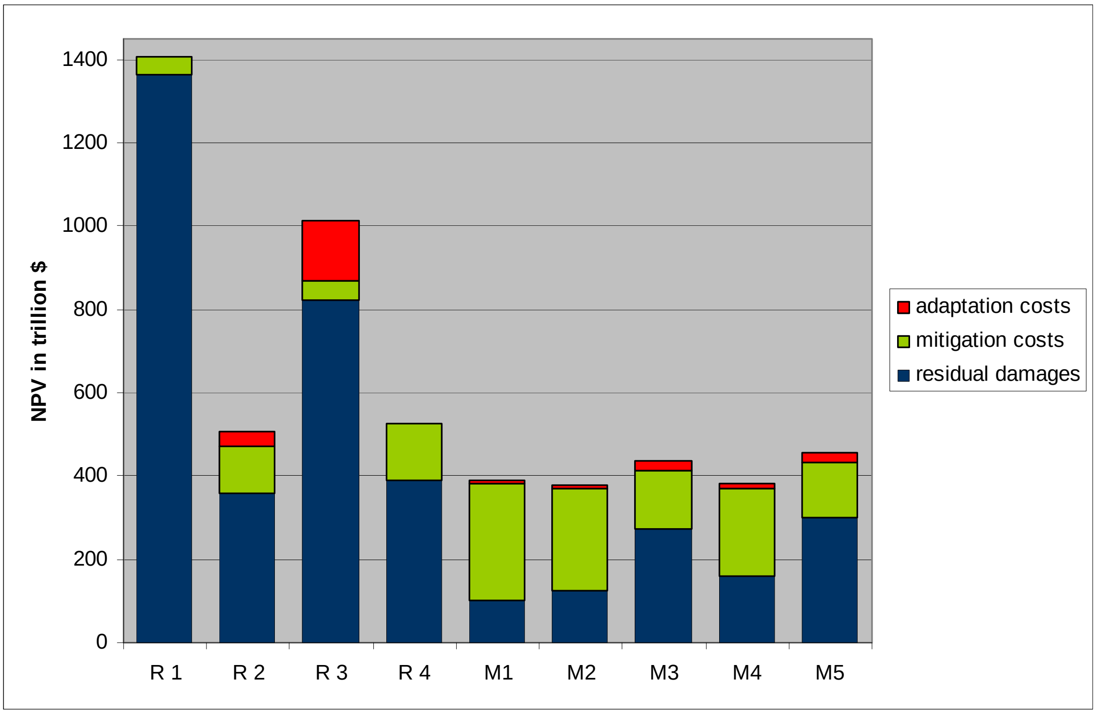
M3 - Concentrations are limited to 560 ppm (2x pre-industrial levels).

M4 - Temperature increase is limited to 2 C from 1900 levels.

M5 - Temperature increase is limited to 3 C from 1900 levels.

Figure 9 shows the composition and magnitude of the climate change costs for the mitigation as well as the reference scenarios. The figure shows firstly that residual damages can be decreased severely by mitigation and adaptation. This can be seen by comparing R1 with the other scenarios. Secondly, as mitigation policies become more stringent adaptation decreases, in M1 adaptation costs are virtually zero. Thirdly, the absence of adaptation boosts mitigation efforts, but only moderately (compare R2 and R4). Not surprisingly, the stringency of the climate policy target is more important for mitigation efforts than the availability of adaptation as a policy option. Fourthly, note that the climate change costs are lower in the mitigation scenarios M1-M5 than in the optimal (R2), whereas the utility is (by definition) the highest in the optimal. This is due to that fact that utility reflects a discounting of costs over time (to reflect social time preference) *and a* decreasing marginal utility of consumption as income (and thus consumption) levels rise over time. Compared to R2, scenarios M1-M5 require more investment in mitigation in earlier decades, which results in lower residual damages in the later decades. This decreases the total climate costs in present value terms, but also lowers the utility as the additional costs are borne by earlier (poorer) generations whereas the lower residual damages are experienced by later (richer) generations.

Figure 9. Composition of climate change costs



The mitigation scenarios (M1-M5, see Box 2) are examined in more detail in Table 4 where the benefits/costs of mitigation are computed with (optimal) adaptation, as well as without adaptation. The benefits of the mitigation policies generally decrease when adaptation is possible. What is more interesting is that the benefits/cost ratio does not increase evenly across scenarios when adaptation is not available. This shows that the effectiveness of different mitigation scenarios is somewhat dependent on the use of adaptation. The ranking of the scenarios does not change in this case. Thus it can be tentatively concluded that adaptation does not significantly change the results on the preference of a certain mitigation scenario compared to other mitigation scenarios. However, though the general conclusions based on optimal adaptation are valid, they may not properly describe all relevant variables involved, such as the magnitude of benefits from mitigation.

Table 4. The costs and benefits of mitigation in different scenarios

	NPV of benefits	NPV of costs	Benefit/ cost ratio	NPV of benefits	NPV of costs	Benefit/ cost ratio
	Mitigation with adaptation			Mitigation without adaptation		
M1	859.44	249.81	3.44	1240.59	237.31	5.23
M2	835.14	215.04	3.88	1210.42	202.00	5.99
M3	674.41	113.96	5.92	1023.13	105.84	9.67
M4	797.03	181.70	4.39	1164.54	169.26	6.88
M5	643.16	102.87	6.25	983.37	94.59	10.40

4.4 Adaptation scenarios

This section examines the effects of different restrictions on adaptation. There are many reasons why the optimal level of adaptation may not be attainable (see for example, IPCC2007b, Chapter 17). This section discusses some of the key constraints and limits to adaptation, and "adaptation scenarios" are then constructed to look at the effects hereof (Box 3).

An often mentioned limitation to adaptation is that of lack of knowledge. The exact effects of climate change may not be known or the adaptation measures to be taken may not be known to the people concerned (Fankhauser, 1997). These limitations are mimicked, albeit in a crude fashion, in scenarios A1 and A2, where the amount of adaptation is limited.

A second issue is the problem of not having enough funds to adapt. For example a farmer may not have enough money to invest in seeds for new crop types or a government may not have the funds to build a sea wall. This limitation is usually mentioned with reference to developing countries (scenario A3), but there is a qualification (c.f. MacMichaels, 1996, and Fankhauser, 1998) that it concerns the poorest individuals in each country (scenarios A4 and A5).

A third constraint on adaptation entails inertia (cf. Burton and Lim 2005): adaptation levels may not be able to change (quickly) over time (scenario A6). A different type of inertia refers to the problem of a delayed reaction (scenario A7). It might take considerable time to implement adaptation measures (Mendelsohn, 2000, and Berkhout et al., 2006). Finally it may be the case that because of imperfect knowledge there are over-investments in adaptation. This is simulated in A8 and A9.

Box 3. Adaptation policy scenarios

Limits on adaptation

A1 - Adaptation can only be 50% of optimal

A2 - Adaptation can only be 75% of optimal

Limits on adaptation costs

A4 - Adaptation costs can only be 50% of optimal

A5 - Adaptation costs can only be 75% of optimal

Rigidness of adaptation

A6 - The level of adaptation cannot vary over time

A7 - Adaptation cannot be implemented in the first 30 years

Overinvestment in adaptation

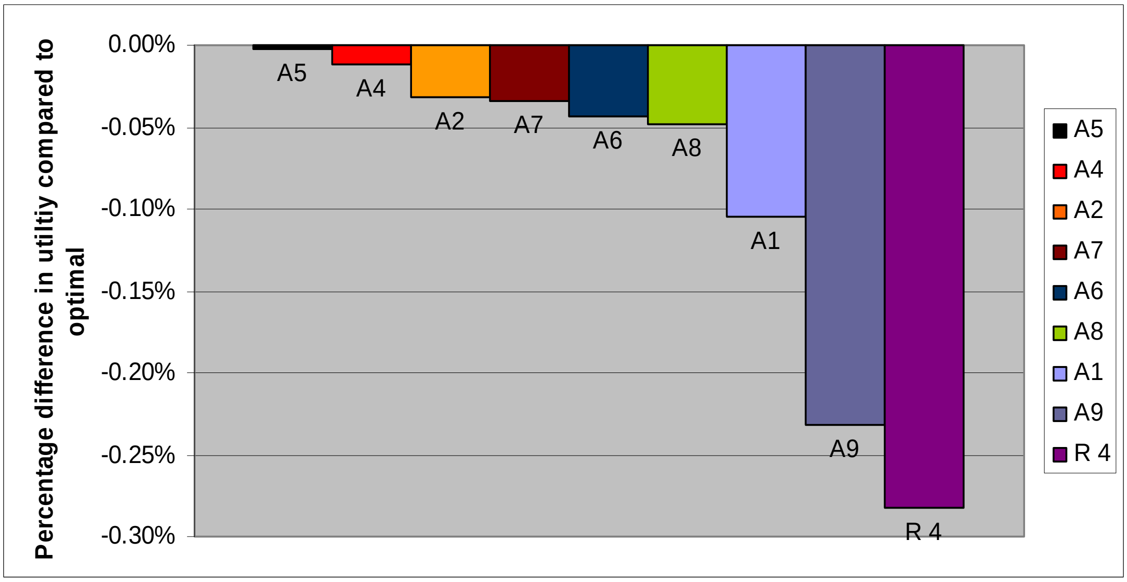
A8 - Adaptation is set at a level 125% of the optimal

A9 - Adaptation is set at a level 150% of the optimal

Note: Mitigation is set at optimal levels in all these scenarios.

Figure 10 shows how the different adaptation scenarios affect utility. To ease comparison utility differences compared to the optimal control scenario (R2) are used. For reference purposes the no-adaptation scenario (R4) is also shown. Not surprisingly, the more stringent restrictions on adaptation affect utility more than those scenarios that are closer to the optimum.

Figure 10. Utility difference compared to optimal of different adaptation scenarios in the AD-DICE model.



The results also show that limits on the funds available for adaptation are less harmful than limits on adaptation efforts themselves. But bearing in mind that the A1 and A9 scenarios are rather extreme, the overall conclusion can be that as long as mitigation options can be freely chosen, most limitations on adaptation will have only very minor influence on global welfare. This does not mean that some regions will not incur severe losses when adaptation is limited. Thus, uncertainty about the exact optimal amount of adaptation should not prevent investment in adaptation, but caution is warranted: choosing the adaptation level should be done with care and more adaptation is not always better. Still, it is preferable to over-invest or under-invest than to not invest at all (R4).

5. Sensitivity analysis

This section assesses the sensitivity of the models used here and the results presented. It first looks at the effects of applying different discount rates in DICE and then at how a higher damage function will affect the results.

5.1 Alternative Discounting

One of the major points of discussion within cost-benefit analysis of climate change is that of the discount rate. Often the DICE model formulation by Nordhaus is criticized for having a too high discount rate. To test the effect of the discount rate assumptions we run several key scenarios from our analysis using different discount rate specifications. We have chosen to use two discount rates, suggested respectively by the UK Treasury and that applied in the Stern Review.

The discount rates are determined based on the Ramsey equation. This equation states that the discount rate is equal to $\rho + \mu g$, where ρ is the rate of pure time preference, μ represents the absolute value of the elasticity of marginal utility, and g the per capita growth rate of consumption. The first term ρ in the Ramsey equation reflects the discount rate that would apply if future generations had the same wealth as the current generation. The second term μg is the wealth-based component and reflects the assumption that one extra dollar is worth more to a person with a low income than to a person with a high income. The different assumptions on these parameters for the different discounting methods are given in Table 5. Note that because DICE endogenously estimates economic growth, the assumptions about that are not changed within the model.

Table 5. The parameter values assumed in the different discounting methods

Method	μ = elasticity of marginal utility of consumption	ρ =pure rate of time preference
Nordhaus	2	1.5
UK Treasury	1	1.5
Stern	1	0.1

In Figure 11 the different discount rates are plotted over time. Due to the fact that we use endogenous economic growth the discount rates have similar forms but vary in magnitude. As can be seen, the DICE discount rate chosen by Nordhaus is the highest, the Stern Review the lowest and the UK Treasury lies in between.

Figure 11. Discount rates over time for the different discounting methods.

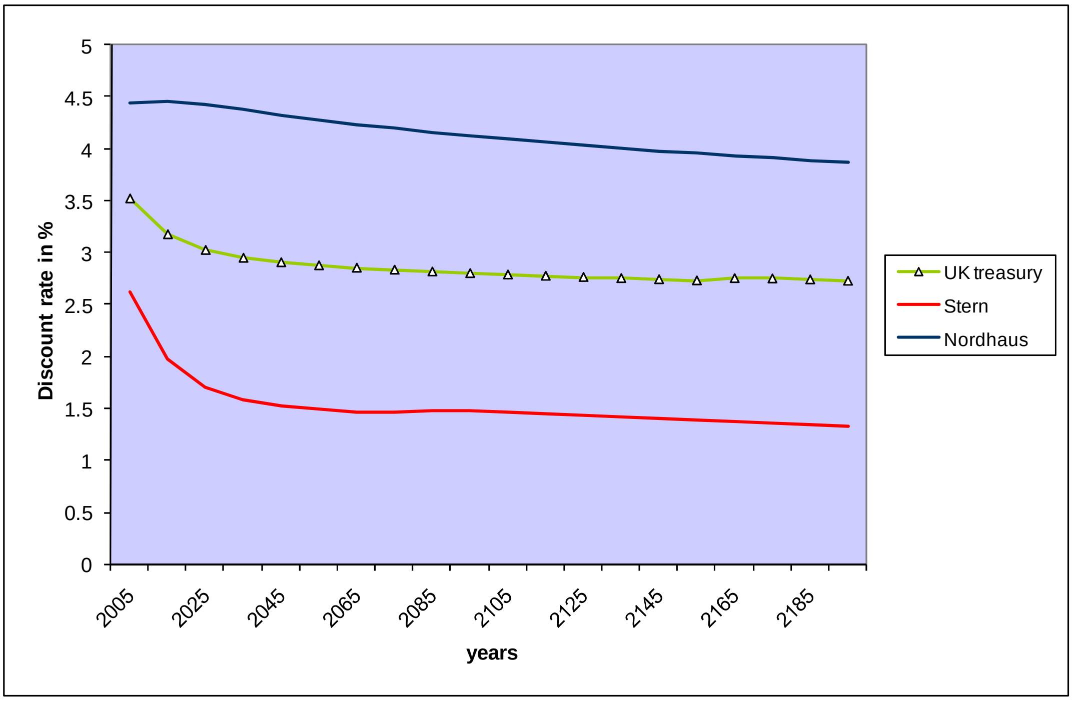
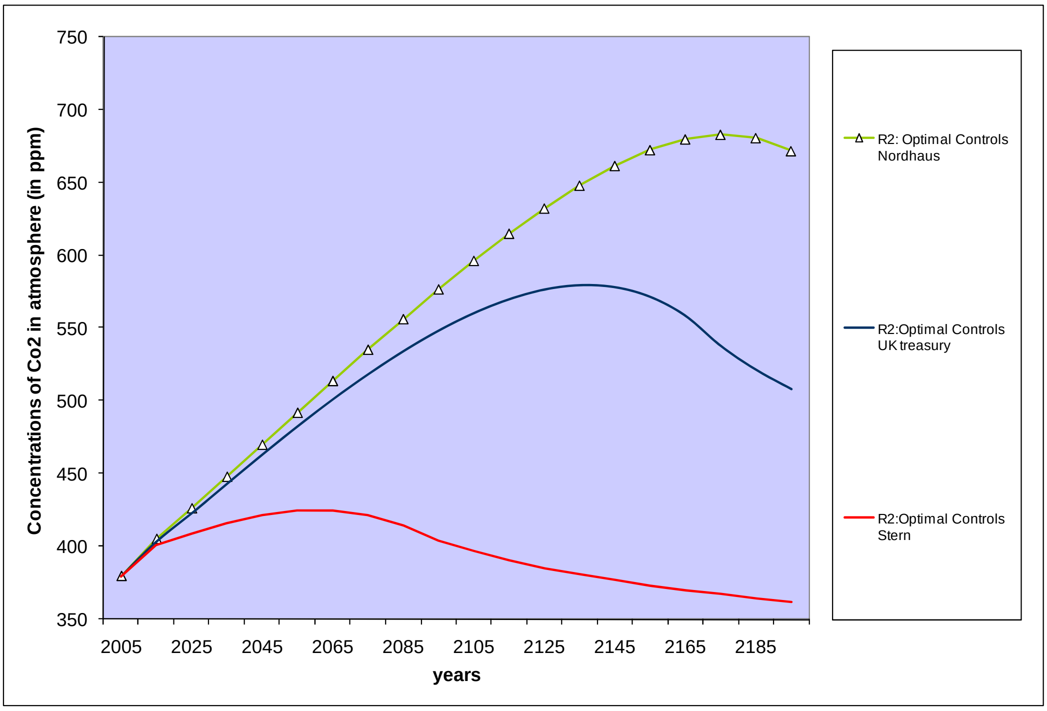


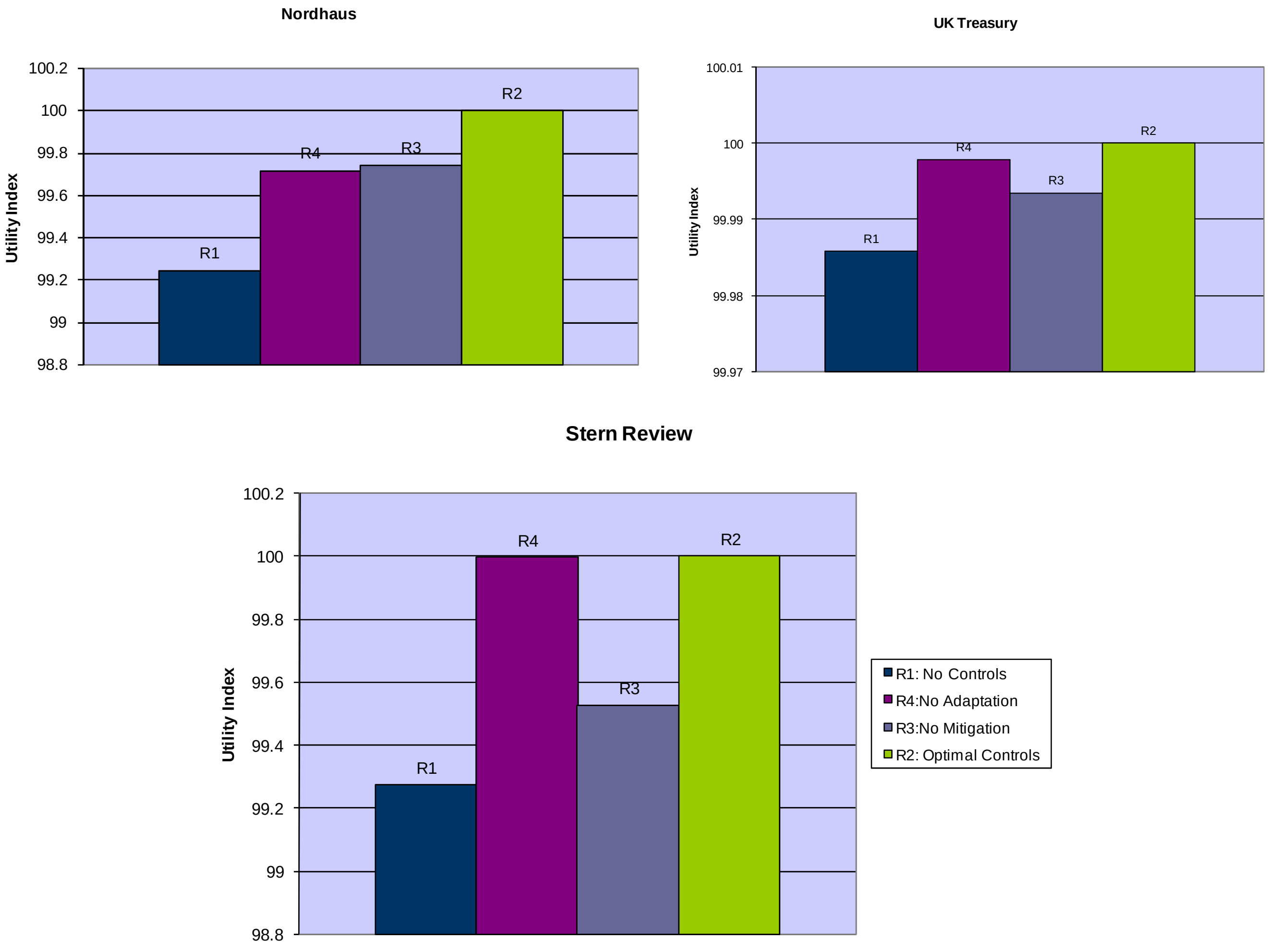
Figure 12. CO_2 concentration levels (in ppm) over time for the different discounting methods



The concentration levels of CO_2 in the optimal scenarios using the different discounting methods are given in Figure 12. There are large differences between the optimal levels of concentrations with the different discounting methods. According to the Stern Review, the optimal level of concentration peaks at a level slightly above 400 ppm whereas the Nordhaus optimal level of concentrations is above 650 ppm. The Treasury's discount rate suggests an optimal level peaking at 550 ppm. It can be seen that the high discount rate used by Nordhaus causes the optimal level of CO_2 to be significantly higher than when using alternative discounting methods.

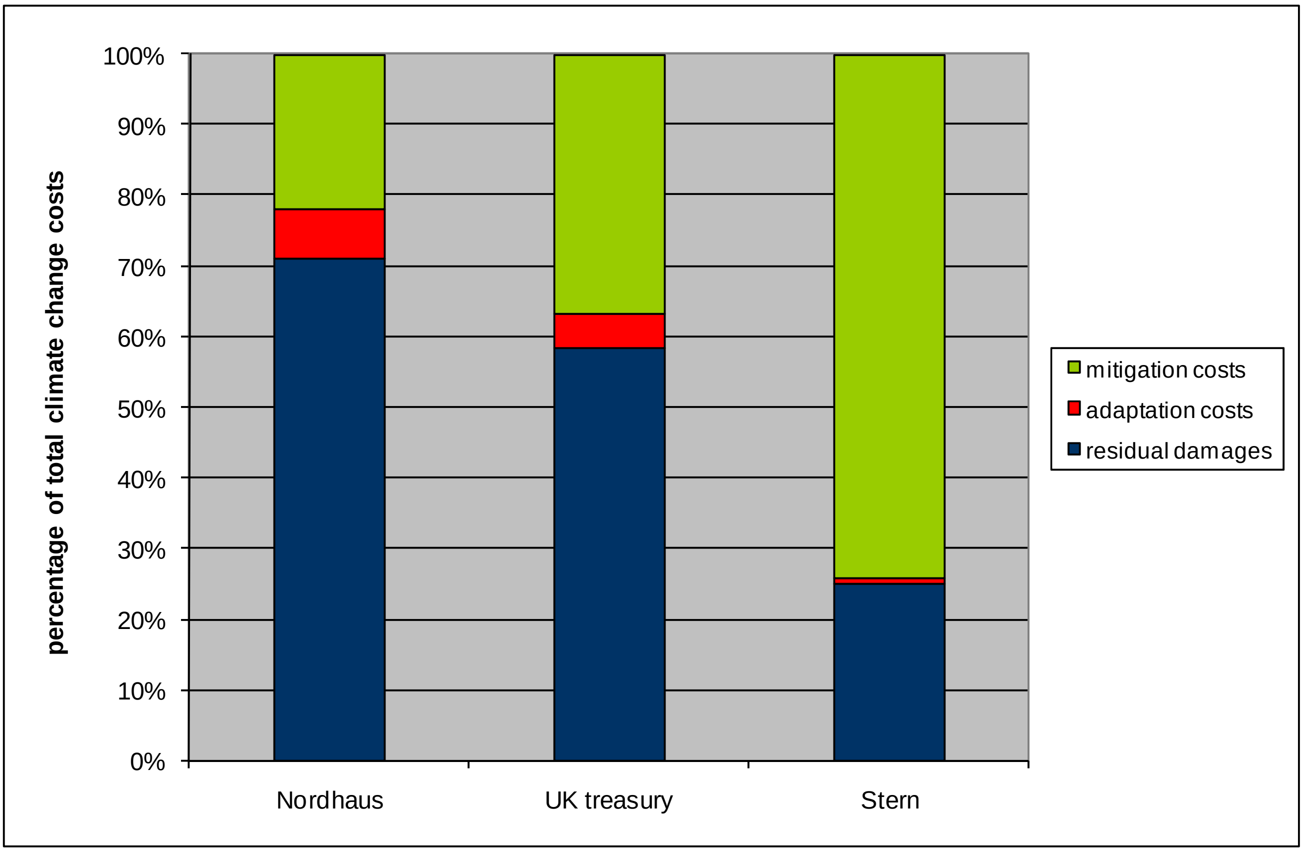
To investigate if the discounting method has effects on the different scenarios, the reference scenarios are re-run using the Stern Review and UK Treasury discounting methods (R1: no controls, R2: optimal, R3: no mitigation, R4: no adaptation). In Figure 13 the relative utilities of the scenarios are shown for each discounting method. Due to the higher discount rate applied, and therefore a more short-sighted view, adaptation plays a more important role as a policy option in the Nordhaus discounting scenarios (the R4 utility is lower than R3) than in the other two settings. The Stern Review discounting puts much more weight on future generations causing a higher level of mitigation to be optimal. This is turns makes adaptation less beneficial. As can be seen in the figure adding the option of adaptation makes very little difference to utility (compare R2 and R4). Using the UK Treasury discounting, adaptation remains an important option but less important as mitigation.

Figure 13. Utility index for the reference scenarios using different discount rates



This is also reflected in the differences in the composition of climate change costs with the different discounting methods. In Figure 14 the composition of climate change costs for each discounting method is given. The Nordhaus discounting method has the highest residual damages and the lowest mitigation costs. The Stern discounting leads to very low adaptation costs in this case.

Figure 14. Climate change costs compostion for different discount rates (percentage of total NPV of climate change costs)



To get a better understanding of the influence of the discounting method on the climate change cost we present the different undiscounted climate change costs in Table 6. It can be sees that the amount spent on adaptation is tenfold higher with the Nordhaus discounting than with the Stern Review discounting. Thus this sensitivity analysis suggests that, as expected, a lower discount rate increases the optimal level of mitigation and thus decreases the optimal level of climate change. As the DICE model on which our main analysis is based uses a relatively high default discount rate, we should be careful in interpreting the optimal policies that it suggests.

Table 6. Undiscounted climate change costs in AD-DICE between 2005 and 2105 in trillions of dollars.

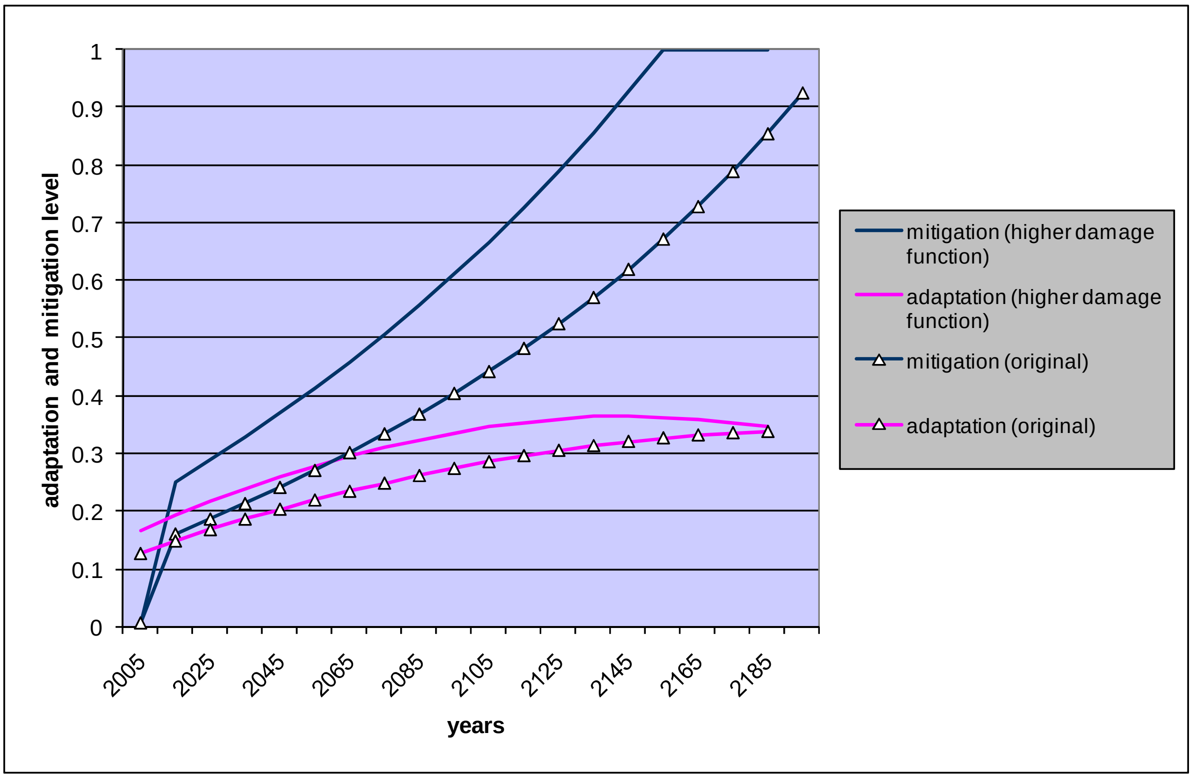
Discounting method	Adaptation Costs	Mitigation Costs	Residual Damages
DICE	10.5	16.5	139.3
UK Treasury	9.9	48.1	137.4
Stern Review	4.3	342.4	79.6

5.2 Alternative damage function

As mentioned earlier one critique of the DICE and RICE models is that the damage function is low (although it must be noted that many other IAMs also use the DICE/RICE damage functions). This section examines the effects of using a damage function that has higher damages. Recent estimates by Michael Hanemann (2008a, b) suggest that damages could be 2.5 times higher than the DICE 2007 model suggests. Some key scenarios discussed earlier are re-run with a damage function that is scaled up 2.5 times.

Figure 15 shows the optimal levels of mitigation and adaptation using the original and the scaled-up damage function in DICE. As can be seen both the adaptation and mitigation levels increase when the damage function is scaled up. Furthermore the level of mitigation increases much more than that of adaptation.

Figure 15. Optimal mitigation and adaptation levels (in percentages) with the original and scaled-up damage functions

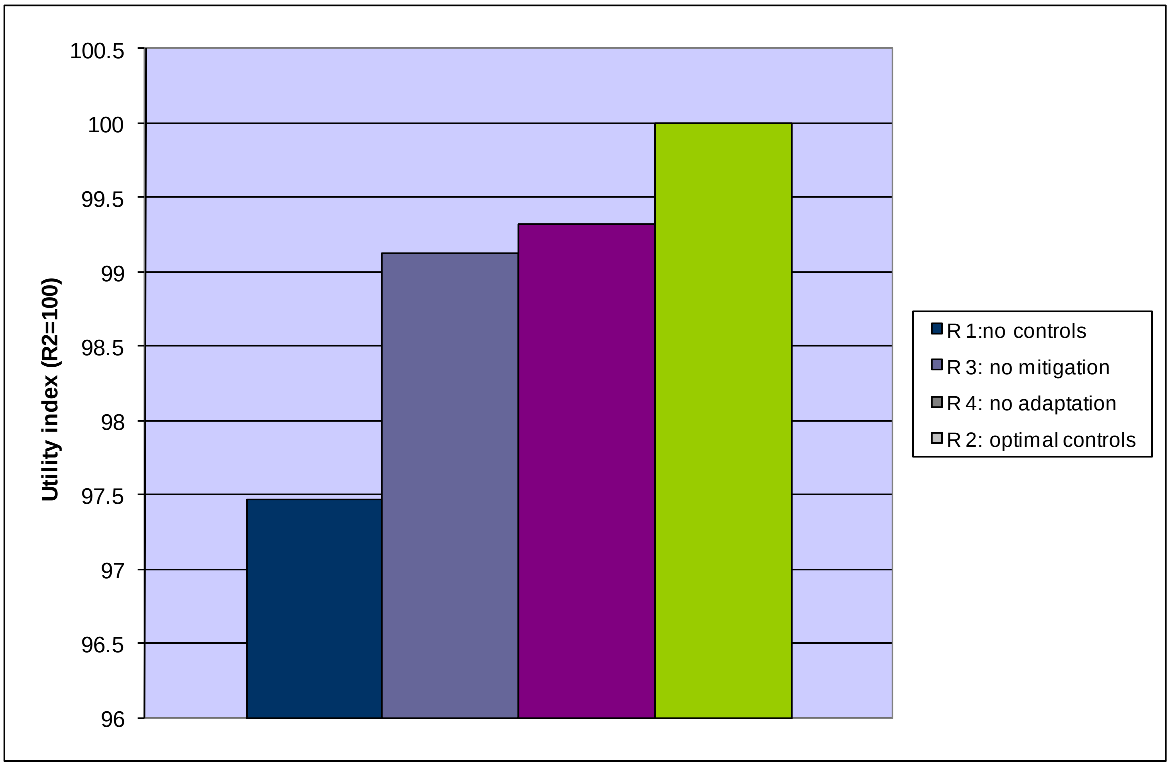


As shown in Table 7, optimal peak levels in CO_2 concentration are also much lower with the higher damage function, which is intuitive.

Table 7. CO_2 concentration (ppm) with different damage functions

Model	2055	2105	2155
AD-DICE (original)	492	596	672
AD-DICE (higher damages)	474	536	525

Figure 16. Utility of reference scenarios (AD-DICE) under a scaled up damage function



An interesting issue is to look at the effect of a higher damage function on adaptation and mitigation effectiveness. As can be seen in Figure 16, when damages are scaled up the scenario without adaptation is no longer worse than that of no mitigation as with the original damage function. Thus a higher damage function will increase the effectiveness of mitigation relative to adaptation. Once again it can be concluded that the results given by the DICE model are likely to overestimate the role of adaptation and the optimal level of climate change.

A scenario with higher damages has also been run using AD-RICE. As in the AD-DICE sensitivity analysis, we choose for a value that is 2.5 times higher than in the base AD-DICE specification; as the damage level in AD-RICE is about 40 percent lower than in AD-DICE, we multiply the base AD-RICE values fourfold to get comparable damage levels[15]. Table 8 shows that in net present value terms, gross damages only increase 2.6 times. Thus, the higher damage function invokes more substantial mitigation efforts to avoid these large damages. Implementation of adaptation measures further reduces these damages: residual damages are just 2.4 times as high as in the base specification. Note that these damage reductions do not come for free: the net present value of adaptation costs more than triples. Most regional results follow the global trend.

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[15] For some regions, parameter α_1 is negative, i.e. for small levels of temperature increase there are initial climate benefits. To avoid that these benefits also get larger, only parameter α_2 is rescaled such that gross damages are 4 times higher for a temperature increase of 2.5 degrees (more or less corresponding to a doubling of CO_2 concentrations).

Table 8. Regional components of damage and adaptation costs in the Optimal control scenario in trillion USD for the base model and increased damages (AD-RICE)

	NPV gross damages		NPV residual damages		NPV adaptation costs	
	Base model	Higher damages	Base model	Higher damages	Base model	Higher damages
JAPAN	-1	31	-9	16	3	5
USA	99	163	2	26	9	13
EUROPE	385	996	277	647	25	82
OHI	0	0	0	0	0	0
HIO	58	166	37	92	4	14
MI	203	600	150	380	13	55
RUSSIA	0	0	0	0	0	0
LMI	344	902	224	511	24	77
EE	0	0	0	0	0	0
LI	324	870	208	479	22	75
CHINA	28	45	3	16	4	5
INDIA	466	1143	293	619	33	99
AFRICA	205	581	133	317	14	51
Global	**2110**	**5495**	**1318**	**3103**	**151**	**478**

Note: The climate costs projections reported here are based on relatively old estimates of damages in the RICE99 model, as discussed in Annex 1, and may not reflect the latest scientific insights into the impacts of climate change on specific regions.

6. Concluding remarks

This report seeks to inform critical questions with regard to policy mixes of investments in adaptation and mitigation, and how they might vary over time. This is accomplished here by examining adaptation within global Integrated Assessment Modelling (IAM) frameworks that have explicit treatment of the costs of mitigation, the costs of adaptation, and the residual damages from climate change.

None of the existing IAMs captures adaptation satisfactorily. Many models do not specify the damages from climate change, and those that do mostly assume implicitly that adaptation is set at an "optimal" level that minimizes the sum total of the costs of adaptation and the residual climate damages that might occur.

This report develops and applies a framework to include adaptation explicitly as a policy variable in IAMs. By including adaptation into IAMs, these already powerful tools for policy analysis are further improved, and the interactions between mitigation and adaptation can be analysed in more detail. Specifically the approach is applied to 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 – are calibrated and then used in a number of policy simulations to examine the distribution of adaptation costs and the interactions between adaptation and mitigation.

Based on this methodology, and keeping in mind the limitations of the model simulations, a number of conclusions can be drawn. *First*, both mitigation and adaptation are important in responding to climate change. A good adaptation policy matters; especially when suboptimal mitigation policies are implemented. Similarly, a good mitigation strategy is more important when optimal adaptation levels are unattainable. The rationale for this result is that both policy control options can compensate to some extent for deviations from the efficient outcome caused by non-optimality of the other control option. The policy simulations presented in this report suggest that overinvestment in adaptation may be worse from a welfare perspective than underinvestment, although moderate overinvestment is still far preferable to no adaptation at all. Thus, uncertainty about the exact optimal amount of adaptation should not prevent investment in adaptation, but caution is warranted: choosing the adaptation level should be done with care and more adaptation need not always be better.

Second, the higher the current value of damages the less important adaptation is as a policy option in comparison to mitigation. The comparison between adaptation and mitigation therefore depends crucially on the assumptions in the model, and especially on the discount rate and the level of future damages. A lower discount rate changes the optimal mixture of policies away from adaptation towards more mitigation and may thus imply lower adaptation efforts; for higher damage levels, adaptation efforts increase, but the optimal level of mitigation will also increase, which dampens the higher need for adaptation. The models used in this report adopt assumptions that imply that the current value of damages is relatively low and in this case adaptation matters as much as mitigation. In all cases, however, a good policy decision on the level of adaptation is an essential part of an optimal strategy to combat climate change. The marginal costs of both adaptation and mitigation increase more than proportionately with higher levels of the policy, and the optimal policy involves a mixture of both adaptation and mitigation. As adaptation and mitigation both limit climate change damages, when one or the other is set too low the other may compensate to some extent by taking a higher level.

Third, optimal adaptation efforts start at a reasonably high level immediately, whereas optimal mitigation levels are slowly increasing over time. This is mainly related to the considerable lags in the climate system: the benefits of adaptation are felt immediately, whereas the emission reductions achieved through mitigation will lead to a stream of benefits in the future. Thus to combat climate change in an efficient way, the short term optimal policy consists of a mixture of adaptation measures and investments in mitigation, even though the latter will only decrease damages in later periods. The costs of inaction are high, and thus it is more important to start acting even when there is a lack of information on which to base the policies, than to ignore the problems climate change already poses. At the end of the 21st century, the climate stakes have become substantial: the policy simulations presented here suggest that in the case of prolonged inaction, damages may have risen to more than 5 trillion dollars annually, but a third of those damages can be avoided by spending some 250 and 370 billion dollars annually on adaptation and mitigation, respectively. The longer-term also consists of a mixture of adaptation and mitigation policies, and ongoing increases in expected damages over time imply that adaptation is not an option that should be considered only for the coming decades, but it is important to keep investing in adaptation options, as both the challenges and benefits of adaptation increase.

Finally, at the regional level there are substantial differences in the optimal adaptation efforts: especially in vulnerable regions, adaptation is an essential ingredient in the policy mix. Limitations to adaptation may not have a substantial impact at the global level, but may induce severe climate damages in vulnerable regions. Unfortunately, these are also the regions where funds and good information are scarce, and thus it is especially hard to formulate good policies for these regions. The results presented in this report suggest that in some less vulnerable regions adaptation may completely remove all damages, and in principle even transform (gross) climate damages into (residual) climate benefits. Such transformations are not available for free, however; the region will have to invest in adaptation to create such opportunities. Note finally that while optimal adaptation unambiguously increases welfare in the adapting region itself, it reduces the optimal level of mitigation for a given region, and therefore lowers the positive spillovers of mitigation to other regions.

The above results, however, are subject to a number of caveats in the analysis and should therefore be interpreted with sufficient care. Specifically, there are four major limitations. First, a main caveat is the absence of detailed regional knowledge on damages and adaptation options to reduce these damages. Thus, this analysis was confined to a top-down assessment, and the results could not be refined with more detailed bottom-up information. A second caveat is the exclusion of uncertainty and risk. In reality, policy decisions have to be made without full information, and the recent climate change literature on low-chance, high-damage possibilities and hedging strategies stresses the weakness of “point estimates” and deterministic analysis. A more systematic uncertainty analysis was beyond the scope of the present work but should be a high priority for further research in this area. Third, the formulation of adaptation in the model is a flow approach, i.e. adaptation is essentially seen as reactive. A more elaborate stock-and-flow approach may be able to reflect the anticipatory nature of certain types of adaptation measures better. Finally, it is important to stress that two specific existing models, DICE and RICE, form the basis for this quantitative analysis. Optimal mitigation scenarios in these two models do not imply stabilization of greenhouse gas concentrations at low levels; consequently, the results, especially with respect to the optimality of slowly increasing mitigation levels, may be different when other IAMs are used as the basis for analysis and it would be best if a canopy of models is used to investigate the interactions between adaptation and mitigation to be able to derive robust policies. In the sensitivity analysis presented in this report it is shown that running the models with a higher discount rate or including a higher damage function leads to much higher levels of optimal mitigation.

This report opens the door for such alternative simulations as the methodology used can be applied to other IAMs. Another extension of this work relates to the formulation of a combined “stock and flow” approach to modelling adaptation where both near-term and lagged benefits of adaptation actions are incorporated with IAMs.

REFERENCES

Agrawala, S. and S. Fankhauser (2008), “Putting climate change adaptation in an economic context” in Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments, OECD, Paris.

Berkhout, F., J. Hertin and D.M. Gann, 2006: Learning to adapt: organisational adaptation to climate change impacts. Climatic Change, 78, 135-156

De Bruin K, R. Dellink, and R. Tol (2008), AD-DICE: an implementation of adaptation in the DICE model. Climatic Change, forthcoming.

Burton, I. and Lim, B.: 2005, ‘Achieving adequate adaptation in agriculture’, Clim. Change 70, 191–200.

Fankhauser, S. (1994), Protection vs. Retreat – The Economic Costs of Sea Level Rise. Environment and Planning A, 27, 299-319.

Fankhauser, S. (1998), The costs of adapting to Climate Change. GEF Working Paper Series 16, Global Environmental Facility.

Hanemann, M. (2008a). “Observations on the Economics of Adaptation: Uncertainty and Timing”. Paper presented at the OECD Expert Workshop on the Economic Aspects of Adaptation to Climate Change, April 7-8, Paris.

Hanemann, M. (2008b). What is the Economic Cost of Climate Change ? CUDARE working paper 1071, University of California, Berkeley.

Hof AF, den Elzen MGJ, van Vuuren DP (2008). Analyzing the costs and benefits of climate policy: Value judgements and scientific uncertainties. Global Environmental Change 18(3), 412-424.

Hope, C.W., J. Anderson, and P. Wenman (1993), Policy analysis of the greenhouse effect-an application of the page model. Energy Policy, 15, 328-338.

Hope, C.W. (2006), The marginal impact of CO2 from PAGE2002: an integrated assessment model incorporating the ipcc’s five reasons for concern. The Integrated Assessment Journal, 6 (1), 19-56.

Ingham A., J. Ma and A.M. Ulph (2005). How do the costs of adaptation affect optimal mitigation when there is uncertainty, irreversibility and learning?. Tyndall Centre working paper 79.

IPCC, (2007), Fourth Assessment Report: http://www.ipcc.ch/activity/ar.htm#ar4.

Kelly, D.L. and C.D. Kolstad (1999), Integrated Assessment for climate control. In: H. Folmer and T. Tietenberg (eds), International Yearbook of Environmental and Resource Economics 1999/2000: A Survey of Current Issues, Edward Elgar, Cheltenham, UK.

Klein, R. et al. (2007) Adaptation to Climate Change in the Context of Sustainable Development and Equity, IPCC (2007b), op.cit..

Lecocq, F. and Shalizi, Z. 2007. "Balancing expenditures on mitigation of and adaptation to climate change : an exploration of Issues relevant to developing countries," Policy Research Working Paper Series 4299, The World Bank.

McKibbin, W.J. and P.J. Wilcoxen (2004). Climate Policy and Uncertainty: The Role of Adaptation versus Mitigation. Paper prepared for the Australian National Academies conference on "Living With Climate Change". http://www.msgpl.com.au/download/aas4.pdf

McMichael, A.J. (1997). Integrated Assessment of potential health impact of global environmental change: prospects and limitations, Environmental modelling and assessment 2, 129-137.

Mendelsohn, R, Morrison, W, Schlesinger, M. E., Andronova, N. G. (2000). Country Specific market Impacts of Climate Change. Climatic Change 45: 553–569, 2000.

Mendelsohn, R. (2000), Efficient adaptation to climate change. Climatic Change, 45, 583-600.

Nordhaus, W.D. (1994). Managing the Global Commons: The Economics of the Greenhouse Effect. MIT Press, Cambridge, MA.

Nordhaus, W.D. and Z. Yang (1996), A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies, American Economic Review, 86(4), 741-765.

Nordhaus, W.D., and Boyer, J (2000) Warming the World: Economic Models of Global Warming. MIT Press, Cambridge, ma.

Nordhaus, W.D. (2007), http://nordhaus.econ.yale.edu/dice_mss_091107_public.pdf.

OECD (2008) Economic Aspects of Adaptation to Climate Change, 133pp., OECD Paris

Parry, M., N. Arnell, M. Hulme, R. Nicholls, and M. Livermore, 1998: Adapting to the inevitable. Nature, 395, 741-742.

Reilly, J., N. Hohmann, and S. Kane, 1994: Climate change and agricultural trade: who benefits, who loses? Global Environmental Change, 4(1), 24-36.

Tol, R.S.J. and S. Fankhauser (1998), On the Representation of Impact in Integrated Assessment Models of Climate Change. Environmental Modelling and Assessment, 3, 63-74.

Tol, R.S. J., Fankhauser, S. and Smith, J.B. (1998), The Scope for adaptation to climate change: what can we learn from the impact literature? Global Environmental Change, 8(2), 109-123.

Tol, R.S.J., S. Fankhauser, R.G. Richels and J.B.Smith (2000), How Much Damage Will Climate Change Do? Recent Estimates, World Economics,1(4), 179-206.

Tol, R.S.J. (2002), Estimates of the Damage Costs of Climate Change. Environmental and Resource Economics, 21, 47-73.

Tol, R.S.J., (2005), Adaptation and Mitigation: Trade-Offs in Substance and Methods. Environmental Science and Policy, 8 (6), 572-578.

Tol, R.S.J., (2008) The Double Trade-Off between Adaptation and Mitigation for Sea Level Rise: An Application of fund. Mitigation and Adaptation Strategies for Global Change, forthcoming.

ANNEX 1. UNRAVELING 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 2001), Tol in the FUND model (e.g. Tol 2002), Hope in the PAGE model (Hope et al. 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 function of DICE/RICE and its estimation and calibration are explained in detail in Nordhaus and Boyer (2001). Their approach is briefly summarised here. As this is the damage function used in this analysis, the results presented in this paper rely crucially 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 9.

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 protection 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. Table 9 shows that most regions have benefits in this category.

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 9. Nordhaus’ regional estimates of the damages/benefits per damage category 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 (2001). 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 2. INCORPORATING ADAPTATION AS A POLICY VARIABLE IN THE DICE MODEL

The Dynamic Integrated model for Climate and the Economy (DICE) was originally developed by Nordhaus (1994). 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 (residual damages, mitigation costs and adaptation costs). The climate change damages are represented by a damage function that depends on the temperature increase compared to 1900 levels.

Adaptation to climate change would decrease the potential damages of climate change. This is the mechanism that is added to the DICE model[16]. Gross damages are defined as the initial damages by climate change if no changes were to be made in ecological, social and economic systems. If these systems were to change to limit climate change damages (i.e. adapt) the 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 as adaptation costs. Thus, the net damages in DICE are the total of the residual damages and the adaptation costs.

In the DICE model the net damage function is a combination of the optimal mix of adaptation costs and residual damages. Thus the net damage function given in DICE can be unravelled into residual damages and adaptation costs. The original damage function in DICE is given as

$$(1)\ \frac{D_t}{Y_t} = a_1 TE_t + a_2 TE_t^{\ 2},$$

where D_t represents the net damages, Y_t the output and TE_t the temperature change compared to the 1900 temperature. The net damages can be split into residual damages (RD_t) and adaptation costs (PC_t).

$$(2)\ \frac{D_t}{Y_t} = \frac{RD_t(GD_t, P_t)}{Y_t} + \frac{PC_t(P_t)}{Y_t}$$

It is assumed that the adaptation costs and the residual damages are separable, and can be represented as a fraction of income. They both depend on adaptation (P_t) but the costs are independent of each other. Residual damages depend on both the gross damages (GD_t) and the level of adaptation (P_t). Effectively, this makes the decisions on the levels of adaptation and mitigation separable. Although intuition suggests that adaptation and mitigation are linked, and the famous example that switching on air conditioning as an adaptation measure will lead to higher emissions of greenhouse gases and thus have implications for optimal mitigation strategies, the quantitative links between adaptation and mitigation are actually estimated to be rather weak (cf. Klein et al., 2007). While there are some feedback links between the two types of climate policy, the simplifying assumption that the two are unconnected may not lead to a huge bias in the model simulations.

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[16] The AD-DICE framework was co-developed by the authors of this report and Richard Tol and published as de Bruin et al. (2008), which this discussion draws heavily upon.

The following form is assumed for the gross damage function:

$$(3)\ \frac{GD_t}{Y_t} = \alpha_1 TE_t + \alpha_2 TE_t^{\alpha_3}, \text{ where } \alpha_2 > 0 \text{ and } \alpha_3 > 1.$$

This is the most commonly used form for damage costs of climate change in IAMs, where α_3 generally takes a value between 1 and 3 (Tol and Fankhauser 1998). This is also the same form as used in the DICE model, however, α_3 is assumed to be 2 in the DICE model, but is left to be determined through calibration in AD-DICE. α_1 can take values both positive and negative, as net benefits of climate change are possible at low levels of climate change.

The following function is used to express RD_t as a function of P_t and GD_t;[17]

$$(4)\ RD_t = GD_t \cdot (1 - P_t), \text{ where } 0 \le P_t \le 1.$$

The main advantage of using the form given in (4) is that *P* has an intuitive interpretation. Adaptation is then given on a scale from 0 to 1, where 0 represents no adaptation: none of the gross climate change damages are decreased through adaptation. A value of 1 would mean that all gross climate change damages are avoided through adaptation. Thus, *P* gives the fraction by which gross damages are reduced: $P_t = \frac{GD_t - RD_t}{GD_t}$.

Adaptation costs are given as a function of the level of adaptation. It is assumed that this function is increasing at an increasing rate, as cheaper and more effective adaptation options will be applied first, and more expensive and less effective options will be used after these, thus

$$\frac{\partial PC_t}{\partial P_t} > 0 \text{ and } \frac{\partial^2 PC_t}{\partial P_t^2} > 0 .$$

There are many types of functions that fit these criteria. It is assumed that this function takes the form of a power function:

$$(5)\ \frac{PC_t}{Y_t} = \gamma_1 P_t^{\gamma_2}, \text{ where } \gamma_1 > 0 \text{ and } \gamma_2 > 1.$$

It is further assumed that the level of adaptation is chosen every time period (10 years). The adaptation in one time period does not affect damages in the next period, thus each decade the same problem is faced, and the same trade-off holds. This implies that both the costs and benefits of adaptation are “instantaneous”, i.e. they fall in the same time period (decade). The important implication of this assumption is that as long as adaptation is applied optimally, the benefits of adaptation will always outweigh the costs (this follows directly from the maximisation) and hence the adaptation decision will never draw away funds from mitigation policy. This way of modelling adaptation benefits and costs is debatable. Many adaptation measures have this characteristic and fall under the category of *reactive adaptation*. Examples of such adaptation measures are applying sun block, switching on air-conditioning, changing holiday destinations and changing crop types. Other adaptation measures,

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mostly in the category of *anticipatory adaptation*, however, have a time-lag in costs and benefits. Examples of such measures are building seawalls and early warning systems.

The assumptions of instantaneous costs and benefits should not affect the general conclusions of this study. Furthermore, this assumption was made in the DICE model and thus to replicate it as best possible we need to assume the same. An analysis which adds an adaptation capital stock to represent anticipatory adaptation would, however, be interesting and is deferred to future work. In principle, such a future study can use the theoretical framework of Lecocq and Shalizi (2007) to formulate a stock-and-flow approach to adaptation that better reflects the anticipatory nature of some adaptation measures.

Equation (5) gives us an adaptation cost curve. Combined with Equation (4), it compares the reduced damages (as a fraction of gross damages) with the costs of the adaptation (as a fraction of output).

Calibration of AD-DICE

The DICE2007 model as available online is used to calibrate the AD-DICE model. The model is calibrated in such a way that it best replicates the results of the optimal control scenario of the original DICE model. To do this, another model is constructed that minimizes the discounted squared difference between net damages (D_t) in the original DICE and net damages ($RD_t + PC_t$) in AD-DICE, holding TE_t at the level obtained in the DICE optimal control scenario.

The following additional information was used for the calibration of the parameters α_1, α_2, α_3, γ_1 and γ_2. Firstly, the P_t chosen must be optimal. Thus for all P_t, $\frac{\partial D_t}{\partial P_t} = 0$ must hold, or $\frac{\partial RD}{\partial P} = \frac{\partial PC}{\partial P}$. Next, a point is identified on the adaptation cost curve to be able to calibrate the function.

The AD-DICE model is calibrated to the same point as used to calibrate the damages in the original DICE model: a doubling of CO_2 concentrations compared to pre-industrial levels. This is assumed to occur after 90 years (t=9), which corresponds in the DICE model to a temperature rise of 2.4 degrees compared to 1900. The second condition states that *PC* takes a value of 7-25% of total damages in the calibration point. This condition is taken from an estimate by Tol et al. (1998), which is based on an extensive review of impact assessment literature. Moreover, the parameter *P* is restricted based on literature (Parry 1994, Reilly1994, Fankhauser 1998 and Mendelsohn 2000) at a level between 0.3 and 0.8 at the calibration point. Furthermore, according to Tol et al. (1998), *PC* should lie between 0.1 and 0.5 % of GDP at the calibration point; this restriction was also implemented. It should be noted that these restriction are implemented primarily to filter out solutions where adaptation is simply set at 0. The restrictions themselves are not binding.

The AD-DICE2007 model, when calibrated with these restrictions, is able to reproduce the damages of the DICE2007 model well. To test the significance of this model, the DICE and AD-DICE damages are regressed and the hypothesis that they are equal is tested. The p-value, which may be interpreted as the chance that they are indeed equal, is given in Table 9, along with the parameter estimates, where α_1 .and α_2 are in fraction of output per degree of climate change. γ_1 and γ_2 are given in fraction of output per protection, i.e. for full protection. The high p-value indicates that DICE and AD-DICE are almost identical.

Table 10. Parameter values from AD-DICE2007 in the optimal scenario calibration.

Parameter	α_1	α_2	α_3	γ_1	γ_2	p-value
Value	0.0004	0.0027	2.243	0.388	4.341	0.99

ANNEX 3. INCORPORATING ADAPTATION AS A POLICY VARIABLE IN THE RICE MODEL

RICE is a regional version of the Dynamic Integrated Climate and Economy model. It consists of 13 regions in the RICE99 online version. The regions are: Japan, USA, Europe, Other High Income countries (OHI), Highly Industrialised Oil exporting regions (HIO), Middle Income countries (MI), Russia, Low-Middle income countries (LMI), Eastern Europe (EE), Low Income countries (LI), China, India and Africa. The RICE model is a growth model. Each region has its own production function which uses the inputs labour capital and energy inputs. Energy inputs can be traded across region, besides this there is no form of trade, which is naturally an unrealistic assumption. The RICE model does not have an explicit mitigation variable but mitigation is incorporated implicitly in specification of the carbon energy input.

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 was always negative. Obviously, equation (4) of AD-DICE does not suffice to model the possibility to maximise the benefits from climate change by investing in adaptation. For example in colder regions, the warming of the climate can make previously unutilized land arable. By applying adaptation efforts more profitable crops can be grown (cf. IPCC, 2001b). A well-known example in this context is the use of greenhouses in Dutch horticulture: by adapting to the new climate conditions, farmers can raise profits by cultivating more profitable crops.

In the following, regions are donated by the subscript j .To incorporate the mechanism of adapting to net benefits of climate change a variable $PR_{t,j}$ is introduced. In this formulation adaptation takes two forms: adaptation to climate change damages ($P_{t,j}$) and the adaptation to climate change benefits ($PR_{t,j}$). Adaptation costs and residual damages both depend on adaptation ($P_{t,j}$ and $PR_{t,j}$). Residual damages depend on both the gross damages ($GD_{t,j}$) and the level of adaptation ($P_{t,j}$ and $PR_{t,j}$). Thus the previous equation 2 is replaced by equation 6:

$$(6)\quad \frac{D_{t,j}}{Y_{t,j}} = RD_{t,j}(GD_{t,j}, P_{t,j}, PR_{t,j}) + PC_{t,j}(P_{t,j}, PR_{t,j})$$

The following function is used to express $RD_{t,j}$ as a function of $PR_{t,j}$, $P_{t,j}$ and $GD_{t,j}$;

$$(7)\quad RD_{t,j} = GD_{t,j} \cdot (1 - P_{t,j}) + PR_{t,j} \cdot GD_{t,j}\,,$$

where $0 \leq P_{t,j} \leq 1$ and either $P_{t,j}$ or $PR_{t,j}$ equals zero. This equation replaces equation 4. Finally equation 5 is replaced by equation 8:

$$(8)\, PC_{t,j} = \gamma_{1,j} P_{t,j}^{\gamma_{2,j}} + \gamma_{1,j} PR_{t,j}^{\gamma_{2,j}}\text{, where } \gamma_{1,j} > 0 \text{ and } \gamma_{2,j} > 1\,.$$

Calibration of AD-RICE

The online RICE99 model is used for this analysis. The model is calibrated in such a way that it best replicates the results of the optimal control scenario of the original RICE model. To do this another model is constructed that minimizes the discounted squared difference between net damages ($D_{t,j}$) in the original RICE and net damages ($RD_{t,j} + PC_{t,j}$) in AD-RICE, holding TE_t at the level obtained in the RICE optimal control scenario. It is also assumed that $PR_{t,j}$ is set at an optimal level and thus $\frac{\partial D_{t,j}}{\partial PR_{t,j}} = 0$ must hold for each point in time.

Table 11. Parameter values from AD-RICE in the optimal scenario calibration.

	ALPHA1	ALPHA2	ALPHA3	GAMMA1	GAMMA2
JAPAN	-0.0028	0.0012	2.65	0.031	3.26
USA	-0.0010	0.0004	4.06	0.016	10.21
EUROPE	-0.0002	0.0046	2.29	0.341	4.24
HIO	-	0.0070	1.53	0.315	5.19
MI	-	0.00587	1.49	0.216	3.97
LMI	-	0.00571	1.85	0.332	5.06
LI	-	0.01091	1.55	0.502	5.18
CHINA	-0.0022	0.00064	2.97	0.0225	6.29
INDIA	-	0.01512	1.70	0.783	5.28
AFRICA	-	0.02152	1.21	0.751	5.12

The calibrated parameter values of AD-RICE are given in Table 11. Three regions have been excluded as they have very low, near zero, net benefits from climate change; the absence of climate damages for the first two centuries, and thus the very small net present values, makes them hard to calibrate properly. Parameter values can be found for these regions but the information available is too weak to obtain significant estimates.