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AD-DICE: An Implementation of Adaptation in the DICE Mode

Kelly C. de Bruin, Rob B. Dellink
and Richard S.J. Tol

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Kelly C. de Bruin, *Environmental Economics and Natural Resources Group, Wageningen University*
Rob B. Dellink, *Environmental Economics and Natural Resources Group, Wageningen University and Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands*
Richard S.J. Tol , *Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands, Economic and Social Research Institute, Dublin, Ireland and Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA*

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AD-DICE: An Implementation of Adaptation In The DICE Model

Summary

Integrated Assessment Models (IAMS) have helped us over the past decade to understand the interactions between the environment and the economy in the context of climate change. Although it has also long been recognized that adaptation is a powerful and necessary tool to combat the adverse effects of climate change, most IAMs have not explicitly included the option of adaptation in combating climate change. This paper adds to the IAM and climate change literature by explicitly including adaptation in an IAM, thereby making the trade-offs between adaptation and mitigation visible. Specifically, a theoretical framework is created and used to implement adaptation as a decision variable into the DICE model. We use our new AD-DICE model to derive the adaptation cost functions implicit in the DICE model. In our set-up, adaptation and mitigation decisions are separable and AD-DICE can mimic DICE when adaptation is optimal. We find that our specification of the adaptation costs is robust with respect to the mitigation policy scenarios. Our numerical results show that adaptation is a powerful option to combat climate change, as it reduces most of the potential costs of climate change in earlier periods, while mitigation does so in later periods.

Keywords: Integrated Assessment Modelling, Adaptation, Climate Change

JEL Classification: Q25, Q28

Address for correspondence:

Kelly C. de Bruin
Environmental Economics and Natural Resources Group
Wageningen University
Hollandseweg 1
6706KN Wageningen
The Netherlands
Phone: +31 317 48 23 62
Fax: +31 317 48 49 33
E-mail: kelly.debruin@wur.nl

1 Introduction

Global warming poses one of the biggest global environmental threats for current and even more so for future generations. There is a scientific consensus that human activities, through which greenhouse gases are emitted into the atmosphere, are changing our climate (IPCC, 2001a). Greenhouse gases have accumulated in the atmosphere for centuries and the decay of most greenhouse gases takes more than fifty years. Therefore, the global warming problem will persist for at least the next century. Climate change is expected to do damages to the economy, with estimates of, on average, 2% of GDP (IPCC, 2001b) by 2100 and perhaps much higher damages after that.

Consequently, it is important to design efficient long-term climate policies. There are two main options that a nation has in addressing climate change. Firstly it can try to limit climate change by reducing its greenhouse gas emissions or exploiting carbon sinks. This is referred to as mitigation. The other option is adaptation. Adaptation refers to adjustments in ecological, social or economic systems in response to actual or expected climate stimuli and their effects or impacts. It refers to changes in processes, practices and structures to moderate potential damages or to benefit from opportunities associated with climate change (Klein *et al.* 2001). Examples of adaptation are the building of dykes, the changing of crop types, and vaccinations. Adaptation can be private or public, anticipatory or reactive.

To understand the issue of climate change, Integrated Assessment Models (IAMs) have been developed that integrate the main causes and effects of climate change. IAMs models combine disciplines as to evaluate the whole cause and effect chain of climate change. In such a manner the effects of the economy on climate change and the effects of climate change on the economy are linked. The advantage of IAMs models is that they can deal with important issues such as the efficient allocation of abatement burdens and accepted damages, by specifying the costs and benefits of various abatement strategies, using a detailed description of both economic and environmental developments. IAMs, therefore, can analyse what the optimal climate strategy should be. Up to now, however, IAMs focus on the trade-off between damages due to climate change and mitigation costs and ignore the option of adaptation or at best treat it implicitly as part of the damage estimate.[i] Tol and Fankhauser (1998) survey the IAM literature and conclude that in the majority of the models adaptation is not included; this situation has hardly improved since then. Furthermore, mostly when adaptation was included in a model, only induced adaptation and implicit adaptation were considered and not explicit adaptation. This means that adaptation is not modelled as a decision variable. The PAGE model (Hope et al., 1993; Plambeck et al., 1997, Hope, 2006) is an exception. However, adaptation is an exogenous decision variable that is, it is set by the modeller, and not on the basis of an optimisation.

Because of the private nature of most adaptation, it is sometimes argued that adaptation is not a decision variable for a region, as the adaptation decisions are not in the hands of the leaders of that region (Tol, 2005). However, besides the fact that many forms of adaptation are public, private adaptation is still a decision taken in a region, even if not by the leaders of that region. One may also argue that, under certain assumptions, the socially optimal adaptation (as calculated below) coincides with the adaptation provided by the market. This, however, is unlikely as the public lacks information on the effects of climate change and adaptation options, and adaptation often entails big scale projects that the market cannot provide. Studies have shown that the effects of adaptation can be enormous, decreasing gross damages by up to 80% (Mendelsohn, 2000). Therefore, to fully understand the effects of climate change and climate change policies adaptation also needs to be considered and modelled as a policy variable.

In this paper, we include adaptation as a policy variable in an IAM, namely the Dynamic Integrated model of Climate and the Economy (DICE), which was originally developed by Nordhaus (1994). The DICE model is a global model and includes economic growth functions as well as geophysical functions. The use of adaptation is assumed to be optimal and is already included in the damage function. We develop what we have named the Adaptation in DICE (AD-DICE) model that includes adaptation as a decision variable.

Estimates from empirical literature on the costs and benefits of adaptation are used to calibrate the model and derive the adaptation cost curve that is implicit in the DICE model. We then construct new policy scenarios with no adaptation to understand the effects of adaptation. We take a closer look at the effects of adaptation and mitigation on each other.

This paper is structured as follows; in the next section the literature on adaptation in IAMs is reviewed. The third section lays out the AD-DICE model and its theoretical framework. In the fourth section the details of the calibration are described and the parameter values of the AD-DICE model are given. The fifth section presents the results with an analysis of the different policy options and the interactions of mitigation and adaptation. In the sixth section a sensitivity analysis is done. Finally we conclude and make a few suggestions for further research.

2 Literature review

There have been many articles calling for more research on adaptation, especially in the modelling context. Tol and Fankhauser (1998) specifically call for the introduction of explicit adaptation in IAMs. They survey 20 IAMs and find that adaptation is distinguished only in very few of the models. Furthermore, they find only one model, the PAGE model (Hope et al., 1993; Plambeck et al., 1997), where adaptation is considered as a policy variable. Since Tol and Fankhauser (1998), nothing has changed with regard to the inclusion of adaptation in IAMs.

Hope et al. (1993) is still the only paper to date, to our knowledge, that models adaptation as a policy variable for all sectors. Using the model for Policy Analysis of the Greenhouse Effect (PAGE), the authors look at two adaptation policy choices, namely no adaptation and aggressive adaptation. Aggressive adaptation decreases initial climate change impacts by up to 90%. Hope et al. (1993) say that this reduction will cost 0.5 trillion Euro and decrease impacts by 17.5 trillion Euro. These estimates do not seem realistic and contradict existing empirical literature on the costs and effects of adaptation (Reilly et al., 1994, Parry et al., 1998a/b, Fankhauser, 1998, Mendelsohn, 2000). The benefits of adaptation estimated by Hope et al. (1993) are much higher than is found in this literature. Not surprisingly, Hope et al. (1993) find that an aggressive adaptation policy is beneficial and should be implemented. It should be noted that the authors of this article also call for incorporating improved information on adaptation in their model. Hope et al. (1993) model adaptation such that it decreases the "tolerable" rate of climate change, the "tolerable" absolute climate change and the impacts beyond these “tolerable” amounts. Although Hope et al. (1993) take a step in considering adaptation and how it may be implemented into IAMs, the values used are very unrealistic and teach us little about dynamics of adaptation or the trade-offs with mitigation. Furthermore, adaptation is not a continuous choice, but a discrete variable; and it is a scenario variable rather than a choice variable. Later versions of the PAGE model have been developed, however, the same specification of adaptation were used (Hope, 2006).

A more recent and detailed paper where adaptation is explicitly modelled is that of Tol (forthcoming). This model only considers sea-level rise and coastal protection. It models protection as a continuous decision variable, based on Fankhauser (1994), and gives insights into adaptation dynamics. Tol (forthcoming) shows that protection is a very important option to combat the impacts of sea level rise. Furthermore mitigation and adaptation need to be traded off as more mitigation will lead to less free resources for adaptation. This paper finds that investments increase over time. Tol (forthcoming) also points out that a too high level of abatement may actually have adverse effects as less adaptation can be undertaken, which leads to more net climate change damages. Tol and Dowlatabadi (2001) did a similar analysis looking at vector-borne diseases, focusing on malaria. They find that aggressive mitigation increases the adverse effects of climate change due to decreased adaptation.

Previous papers have taken the first steps to explicitly including adaptation in IAMs, but clearly do not exhaust the potential. Adaptation is an important policy option that needs to be included in IAM analyses for all climate change damages. This article adds to the IAM and climate change literature by doing that.

3 A framework with explicit adaptation decisions

In the DICE model, utility is maximized. Utility is calculated as the discounted natural logarithm of consumption. Consumption is the optimal share of income. Income is reduced by the costs of greenhouse gas mitigation and by the damage done by 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 initial damages of climate change. This is the mechanism we add to the DICE model. We define gross damages 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. We refer to these "left-over" damages as residual damages. Reducing gross damages, however, comes at a cost, i.e. we need to invest resources in adaptation. These costs are referred to as protection costs or adaptation costs. Thus, the net damages in DICE are the total of the residual damages and the protection costs.

In the DICE model the net damage function is a combination of the optimal mix of protection costs and residual damages.[ii] Thus the net damage function given in DICE can be unravelled into residual damages and protection costs. We do this as follows. 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. We split the net damages into residual damages (RD_t) and protection costs (PC_t).

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

Here we assume that the protection costs and the residual damages are separable, and can be represented as a fraction of income. They both depend on protection (P_t) but the costs are independent of each other. Residual damages depend on both the gross damages (GD_t) and the level of protection (P_t). Effectively, this makes the decisions on the levels of protection and mitigation separable.

We assume that the gross damage function takes the form given in:

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

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 not assumed to be 2 as in the DICE model, but is left to be determined through calibration.

We use the following function to express RD_t as a function of P_t and GD_t;[iii]

(4) $RD_t = GD_t * (1 - P_t)$, where $0 \leq P_t \leq 1$.

The main advantage of using the form given in (4) is that *P* has an intuitive interpretation. Protection is then given on a scale from 0 to 1, where 0 represents no protection: none of the gross climate change damages are decreased through protection. 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: $P_t = \dfrac{GD_t - RD_t}{GD_t}$.

Protection costs are given as a function of the level of protection. We assume 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

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

There are many types of functions that fit these criteria. We assume this function takes the form of a power function[iv]

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

We assume that the level of protection is chosen every time period (10 years). The protection 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. 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).

4 Calibration of the AD-DICE model

In our analysis we use the DICE99 model. We calibrate the AD-DICE model using the optimal control scenario of DICE. We calibrated the model in such a way that it best replicates the results of the original DICE model. To do this we constructed a model that minimized 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.

We use additional information for the calibration of the parameters: $\alpha_1, \alpha_2, \alpha_3, \gamma_1$ 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, we have to identify a point on the protection cost curve to be able to calibrate the function. We chose to calibrate on the same point as used to calibrate the damages in the original DICE model: a doubling of CO_2 concentrations. This is assumed to occur after 130 years (*t*=13), this corresponds in the DICE model to a temperature rise of 2.3 degrees (*TE*=2.3) 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. (1998b), which is based on an extensive review of impact assessment literature. We also restrict the parameter *P* based on literature (Parry 1994, Reilly1994, Fankhauser 1997 and Mendelsohn 2000) at a level between 0.3 and 0.8 at the calibration point. Furthermore, according to Tol et al. (1999), *PC* should lie between 0.1 and 0.5 % of GDP at the calibration point; this restriction was also implemented.

Our AD-DICE model, when calibrated with these restrictions, is well able to reproduce the damages of the DICE model. To test the significance of our models we regress the DICE damages on the AD-DICE and test the hypothesis that they are equal using an F-test. The p-value, which may be interpreted as the chance that they are indeed equal, is given in Table 1, along with the parameter estimates.

Insert Table 1 here

The very high p-value indicates that DICE and AD-DICE are almost identical. Figure 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 both scenarios, our calibration fits well with some small diversions in later periods (the present value of these differences are negligible due to the positive discount rate used). This shows that our parameter values are valid for both scenarios.

Insert Figure 1 here

As can be seen in Figure 2, the AD-DICE levels of mitigation, given as the percentage of total emissions reduced, are slightly lower in later periods. Mitigation is 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 our model will give the same results as the DICE model if we keep adaptation at its optimal level.

Insert Figure 2 here

Using the parameter values found in ad-dice we can draw an adaptation cost curve, given in figure 3. We see that the protection costs of the first 15% of gross damage reduction are extremely low after which they rise. The optimal level of adaptation varies from 0.09 to 0.45, with an average of 0.33, that is 33 percent of gross damages are reduced due to adaptation.

Insert Figure 3 here

5 Results

In this section we present our results. We first look at how climate change costs are composed. Then we compare different policy options. Finally we look at the dynamics of adaptation and mitigation and how they affect each other.

5.1 Costs of climate change

The costs of climate change include residual damages, protection costs and abatement costs. In Figure 4, we see that a large part of climate change costs consist of residual damages in the optimal control scenario. Mitigation costs increase relatively steeply over time.

Insert Figure 4 here

5.2 Climate policy options

Now we compare different policy options using the ad-dice model. We take two climate change policy scenarios created by Nordhaus (1994) as a starting point. We revise these scenarios by including non-optimal adaptation. We then compare the effects of the different scenarios on the basis of utility.

The two scenarios of Nordhaus(1996) are the no mitigation baseline scenario, which Nordhaus(1996) refers to as the “no control” scenario, and the optimal control scenario. In the no mitigation scenario, adaptation is chosen at its optimal level, thus in such a way as to maximise utility, but the level of mitigation is set at zero. In the optimal control scenario both adaptation and mitigation are chosen at their optimal levels. We use four scenarios in AD-DICE: optimal control, no control, only adaptation and only mitigation. Our optimal case is the same as that of Nordhaus (1996). In our no control scenario, adaptation and mitigation levels are set at zero. In the only adaptation scenario, the 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.

We first look at the utility of the different scenarios. We use no control as the base case and show the percentage difference of the utility compared to the base case. This is given in Figure 5. As mentioned earlier, the ad-dice results concerning scenarios with optimal adaptation are the same as those of dice.

Logically we see that the optimal control is the best scenario, followed by the only adaptation scenario. This is followed by the only mitigation scenario. Finally the scenario that creates the lowest utility is the no control scenario. Thus only adapting results in a higher utility than only mitigating and adaptation is a more cost effective control. These results confirm the importance of adaptation.

Insert Figure 5 here

In Figure 6, we compare the distribution of costs of climate change over time with the different policy scenarios. The different scenarios distribute the cost of climate change quite differently over time. Thus changes in the discount rate will also change the ranking of the scenarios.

We see that in the only-mitigation scenario damages in the last periods are much smaller than in the no control scenario. The only-adaptation scenario damages are smaller in the beginning periods compared to the no control scenario. The optimal scenario distributes the damages more evenly over time. At certain points in time it is less beneficial than a scenario with only adaptation, but overall this scenario has the least discounted damages.

Insert Figure 6 here

5.3 Mitigation and adaptation

We first look at the effect adaptation and mitigation have on each other. We compare the optimal level of mitigation with and without adaptation. This is shown in Figure 7. In figure 8 we show the optimal level of adaptation with and without the option of mitigation. In both cases we see that adding the other control option decreases the optimal level of the initial control option. Mitigation seems more sensitive to the addition of adaptation than vice versa. The optimal level of adaptation in early periods hardly changes when adding mitigation, this is because mitigation only effects the climate with a delay, whereas adaptation immediately reduces the profitability of mitigation efforts.

Insert Figure 7 here

Insert Figure 8 here

To examine the dynamics of adaptation and mitigation in more detail, we look at the net benefits of adaptation and mitigation over time (both as a percentage of output) in Figure 9. We see that adaptation has higher benefits until 2140 than does mitigation. After that, however, mitigation becomes much more beneficial than adaptation. Thus even though it is optimal to invest in mitigation, few of these benefits will be felt in the first 60 years – largely because of the slow workings of the energy sector, carbon cycle and climate.

Insert Figure 9 here

We now look at how adaptation and mitigation affect each other. In Figure 10, the net benefits of the optimal amount of mitigation for each period are given for the case when only mitigation is an option and for the case where adaptation is also possible. We see that including adaptation as an option leads to higher benefits of the optimal path of mitigation until 2120 but lower benefits later. This is because adding adaptation as a control option will decrease the optimal level of mitigation (as shown in Figure 7). Because of this, costs of mitigation in the beginning periods will be avoided, but this also entails that benefits of mitigation in later periods are lost.

Insert Figure 10 here

There is a chance that policymakers do not look at the optimal control over time but only consider the near future, that is the world may have 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, that is 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). However, a side benefit in this respect is that the net damages of the optimal level of mitigation in the earlier periods are lower and even become benefits when adaptation is included as a control option.

We see that mitigation only has a “negative” effect on adaptation. In Figure 11 we see that the optimal level of 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.

Insert Figure 11 here

6 Sensitivity analysis

In this section we conduct a sensitivity analysis. We have already seen that our model is robust to changes in the scenario used in the calibration, see Figure 1. AD-DICE replicates DICE in all scenarios where adaptation is optimal. Next we check if our model is robust to changes in the climate sensitivity and the discount rate used.

6.1 Discount rate

We run both the DICE and AD-DICE model with 3 alternative utility discount rates, namely a low level, an original, middle level and a high level. The original discount rate is 0.03 and decreases over time, the low level discount rate is 50% of the original level (0.015) and the high level is 150% of the original level (0.045). The corresponding climate change costs and mitigation are shown in Figure 12 and 13. We see that the AD-DICE model adjusts to changes in the discount rate in the same way as the DICE for all relevant variables, here we show the total climate change costs and the mitigation level. Again we see that the AD-DICE model has slightly lower levels of mitigation.

Insert Figure 12 here

Insert Figure 13 here

Insert Figure 14 here

In Figure 13 and 14, we see that a higher (lower) discount rate increases (decreases) the level of adaptation but decreases (increase) the level of mitigation. This is quite intuitive as the benefits of mitigation are only felt in later periods. A higher (lower) discount rate would shift policy from mitigation (adaptation) to adaptation (mitigation).

6.2 Climate sensitivity

We do the same with 3 levels of climate sensitivity i.e. the equilibrium warming for a doubling of the atmospheric concentration of carbon dioxide. The original climate-equation coefficient, that is the effect of radiative forcing on the atmospheric temperature, is 0.226, the low level coefficient is 50% of the original level (0.113) and the high level is 150% of the original level (0.339). Again we see that AD-DICE adjusts in the same manner as DICE with lower mitigation levels in later periods. This is shown in Figures 15 and 16.

Insert Figure 15 here

Insert Figure 16 here

Insert Figure 17 here

In Figure 16 we see that lower (higher) climate sensitivity will decrease (increase) mitigation. In Figure 17 we see that lower (higher) climate sensitivity will decrease (increase) adaptation until the year 2190 and increase (decrease) it after that. This is because if emissions cause less climate change, there will be lower damages. This will lead to lower levels of mitigation and adaptation. After some time due to the lower level of mitigation, damages will reach a level where a high level of adaptation will again become optimal.

6.3 Protection costs

Finally we look at the results if we use another specification for the protection costs function. We give the PC_t function as

(9) $\frac{PC_t}{Y_t} = \gamma_1 \left(\frac{1}{1-P_t} \right)^{\gamma_2}$, where $\gamma_1 > 0$ and $\gamma_2 > 1$.

This full analysis is given in the Appendix, here we discuss the results only. The adaptation curves of both specifications are not identical, see figure A1 in Appendix. Using the alternative specification leads to a higher lying adaptation cost curve that translates into higher protection costs. The curve also becomes very steep at P=0.3 with extremely high costs at adaptation levels above that.

We again look at the policy scenarios with the new specification. The results are given in Figure 18. The results show the same order of policies; however, the utility of the scenarios with no adaptation are slightly higher than before.

Insert Figure 18 here

We also check to see whether the costs of climate change under the different control options develop in the same way as before and if the results are not sensitive to changes in specifications. In Figure 19, we see that the climate cost curves of the different options have the same form as before. The only adaptation curve is slightly higher in this specification because adaptation is more expensive. Also because adaptation is less beneficial in this specification the no control curve is slightly lower than before. We thus can conclude that our results on the policy options are robust to these changes.

Insert Figure 19 here

Adaptation and mitigation are still affected by each other in the same way is in the original PC_t specification. Adaptation increases the benefits of mitigation then decreases them. Mitigation decreases the benefits of adaptation.

Conclusions

In this paper we set up a framework that can model adaptation as a decision variable in IAMs. We then use this framework to create a model AD-DICE that includes adaptation as a decision variable in the DICE model of Nordhaus (1994). In the DICE model adaptation is assumed to be optimal and included in the damage function. Relaxing this assumption, several conclusions with regard to adaptation can be made.

We adopt a framework in which adaptation and mitigation decisions are separable: the adaptation level is chosen to minimise net damages plus adaptation costs, while the mitigation level is chosen to minimise the aggregate of net damages and adaptation costs plus mitigation costs. We find that in our specification, AD-DICE can mimic the original DICE model. This holds by definition for the optimal control scenario, as the AD-DICE model parameters are calibrated to this end. But our specification is robust with respect to the other mitigation policy scenarios employed in DICE as well. This shows the generality of our approach and illustrates that our framework can be used for other models and settings as well.

Our results show that both adaptation and mitigation can reduce a large amount of the costs of climate change. When applied optimally, adaptation will reduce gross damages of climate change by on average 33% (as calibrated). We see that applying only adaptation is more beneficial than applying only mitigation, illustrating the importance of adaptation as a control option in combating climate change. We also conclude that adaptation is the main climate change cost reducer in the first periods (up to the year 2100) after which mitigation reduces the bulk of the damages. Thus to combat climate change in the cost effective 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. If policy makers focus on the short run benefits and costs an underinvestment in mitigation and overinvestment in adaptation may take place as benefits of adaptation are higher than those of mitigation until 2130. Adding adaptation as a control option however, does have the positive side effect on mitigation that the optimal mitigation path becomes beneficial earlier than without adaptation. These results are robust to variations in key parameters.

The results in this paper by and large confirm the main policy conclusions of the DICE model, even though AD-DICE is only calibrated to one scenario of DICE. This shows that while adaptation may not be explicitly represented in most existing Integrated Assessment models, there are no grounds to reject the policy conclusions from these models, as long as mitigation and adaptation decisions are separable (as in AD-DICE). That is, while these models cannot be used to investigate optimal adaptation strategies, there are not necessarily biased in their analysis of mitigation strategies. To challenge the conclusions from AD-DICE and other IAMs, more research is needed. Firstly, we ignore uncertainty. However, the way we calibrated the gross damage and adaptation functions makes them respond in the same way to key parameter variations as the original DICE model. This suggests that the behaviour of AD-DICE would be similar to that of DICE, also under uncertainty. Secondly, we ignore irreversibility. Should greenhouse gas emissions set in motion a shutdown of the thermohaline circulation or a collapse of the Greenland or West-Antarctic Ice Sheet, adaptation may be the only policy option. In the same way adaptation may not be possible in the presence of certain irreversibilities and mitigation may be the only option. Thirdly, we use perfectly functioning markets and one aggregate impact function, rather than making a distinction between different sectors. In some sectors, adaptation is relatively easy. In other sectors, it is more difficult. Fourthly, we use a single region model. Like sectors, different countries may have a qualitatively different response to climate change, and adaptation may be very different. Furthermore, with different countries, countries may cooperate on mitigation, on adaptation, or both – while the original RICE model has only one instrument of international cooperation. All this is deferred to future work, which can build upon the framework developed in this paper.

Appendix: An alternative specification of the adaptation cost function

In this appendix we show the calibration of the AD-DICE model using another specification of the PC_t function. This specification is based on the idea that the RD_t function takes another form, i.e.

(7) $RD_t = \frac{GD_t}{PR_t}$, where $PR_t > 1$. The level of protection is given by PR_t. Thus, instead of assuming that protection directly reduces gross damages on a one to one basis, we assume that adaptation

becomes less effective as the level of adaptation rises. The costs of this protection we assume to be given by a power function:

$$(8)\ \frac{PC_t}{Y_t} = \gamma_1 PR_t^{\gamma_2}\text{, where } \gamma_1 > 0 \text{ and } \gamma_2 > 1.$$

To be able to use the logical interpretation of P_t and to thus keep the original RD_t function (3), we rewrite (8) as a function of P_t, this results in the following PC_t function:

$$(9)\ \frac{PC_t}{Y_t} = \gamma_1 \left(\frac{1}{1-P_t} \right)^{\gamma_2}\text{, where } \gamma_1 > 0 \text{ and } \gamma_2 > 1.$$

The results of the calibration with this specification are given in table 4. In figure A1 the adaptation curves under both specifications are given.

Insert Table A1 here

Insert Figure A1 here

Notes

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[i] Examples of such models are: MERGE (Manne et al 2005), FUND (Tol, 2006) and IGSM (Sokolov et al 2005)

[ii] According to Nordhaus and Boyer (2000), adaptation is included in the damage estimates and it is implicitly assumed that this is the optimal adaptation

[iii] We assume in this paper that net climate change damages are positive, that is climate change will have a negative effect. Note that this may not be the case for several regions of the world (e.g. Tol, 2001).

[iv] In the Appendix another representation is presented and used to calibrate the AD-DICE model.

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Figures

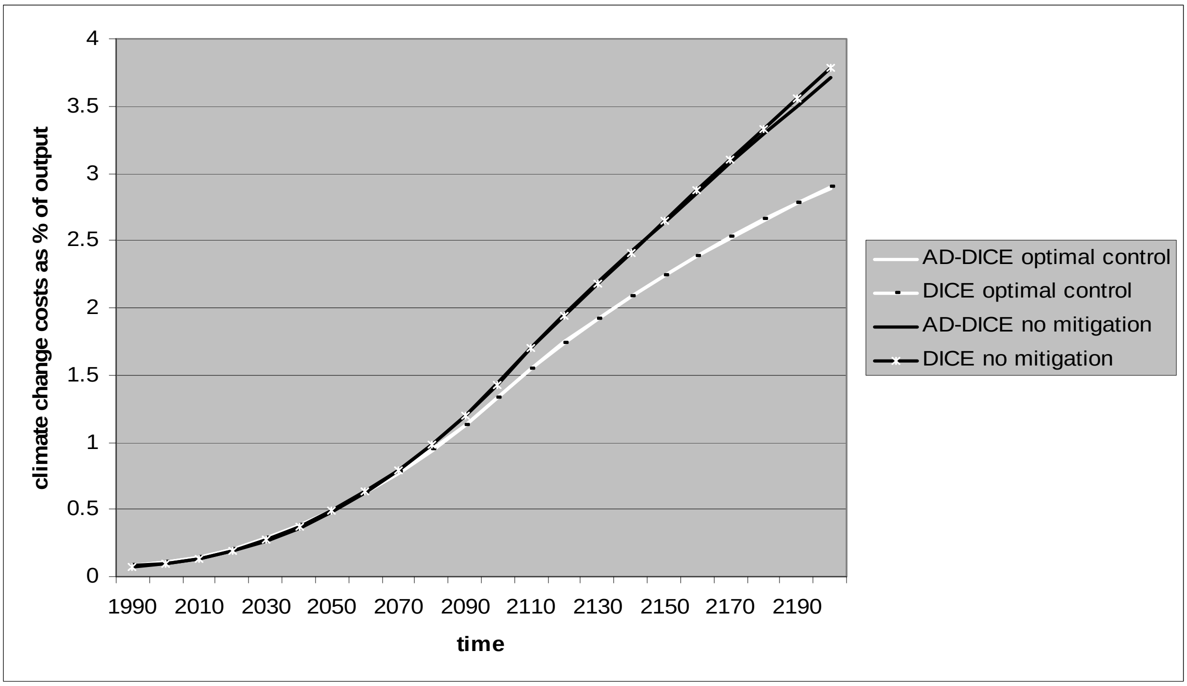

Figure 1: net climate change costs estimated by AD-DICE and DICE: optimal scenario, no mitigation scenario

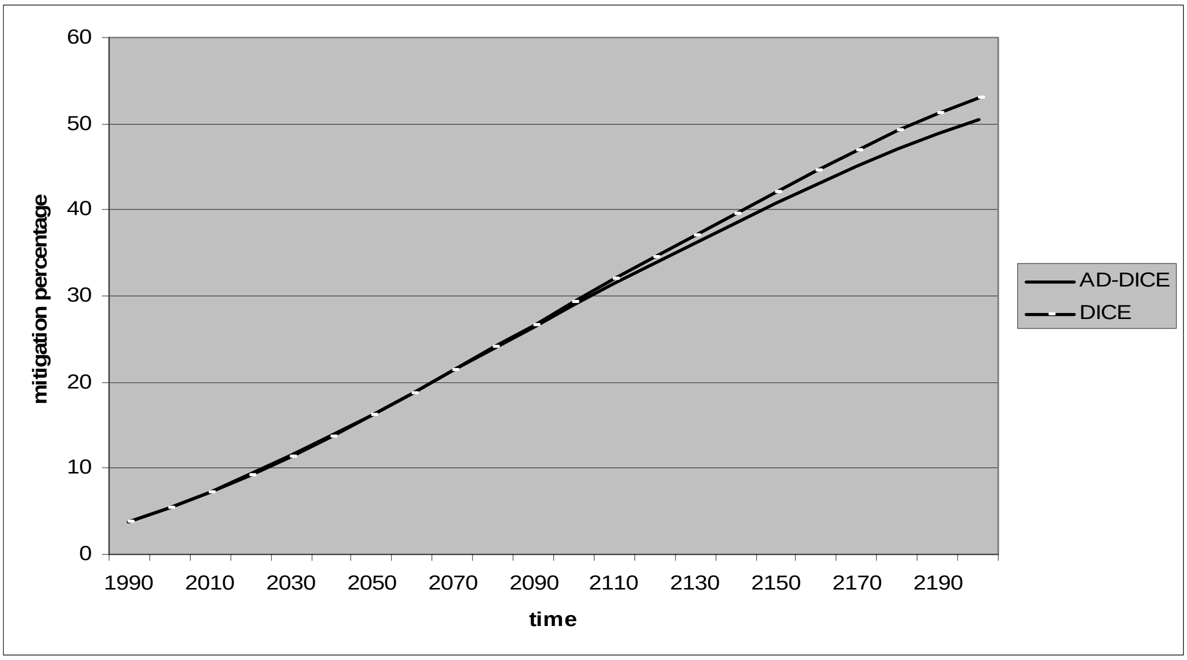

Figure 2: mitigation level in the AD-DICE and DICE models.

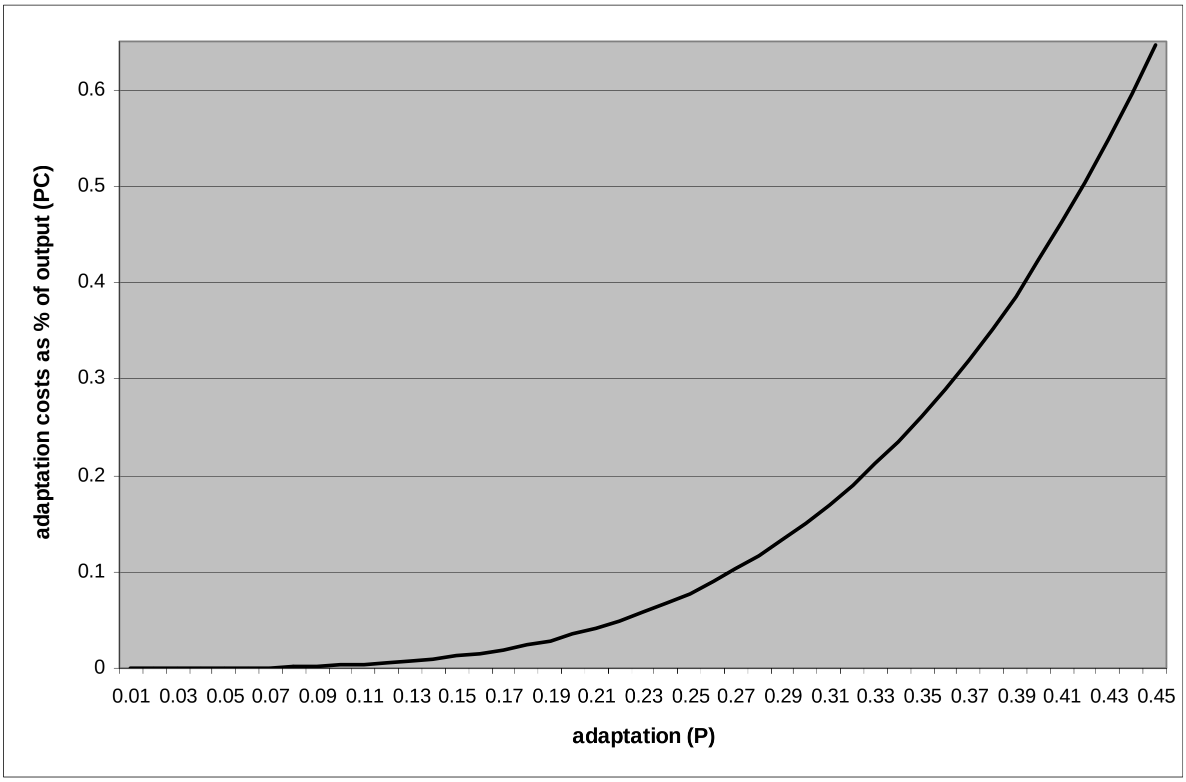

Figure 3: the adaptation cost curve implicit in the DICE model (range 0.15-0.4).

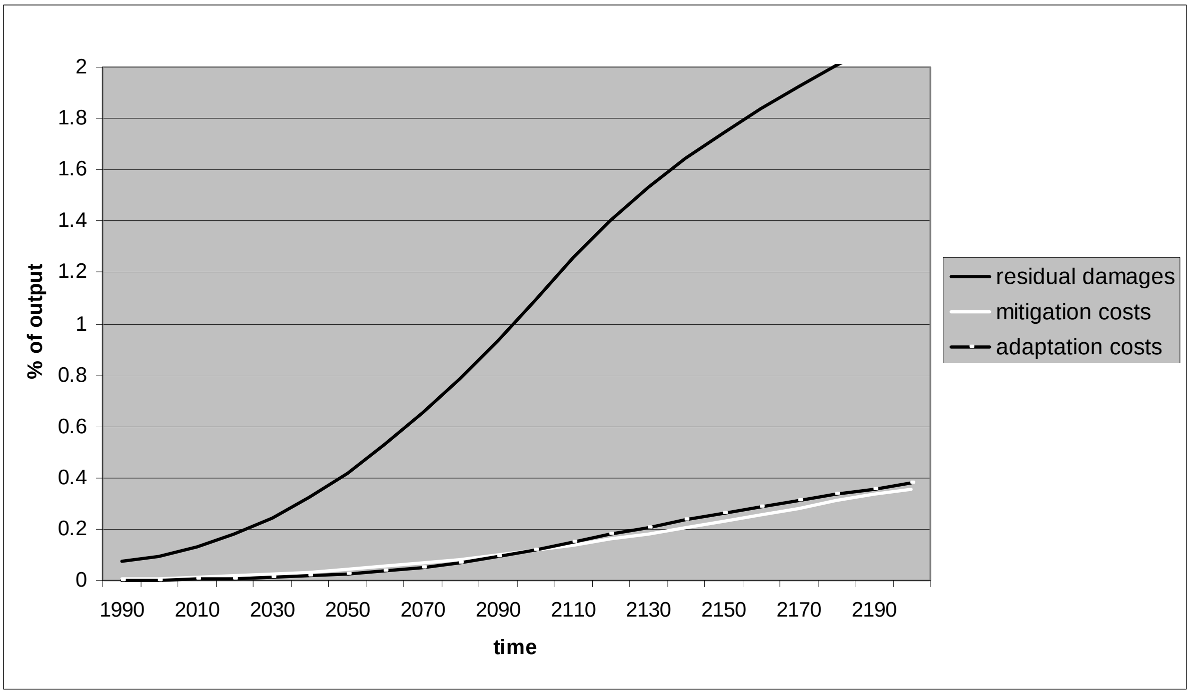

Figure 4: composition of climate change costs in the optimal scenario.

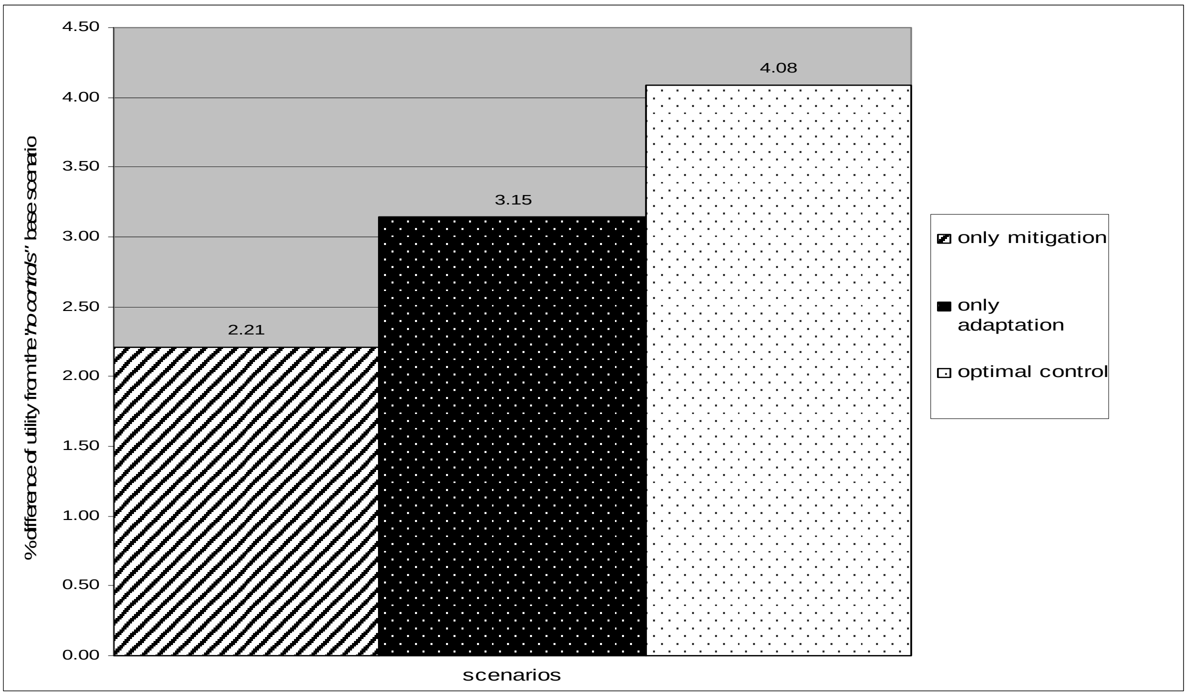

Figure 5: The differences in utility of the different scenarios compared to the base case.

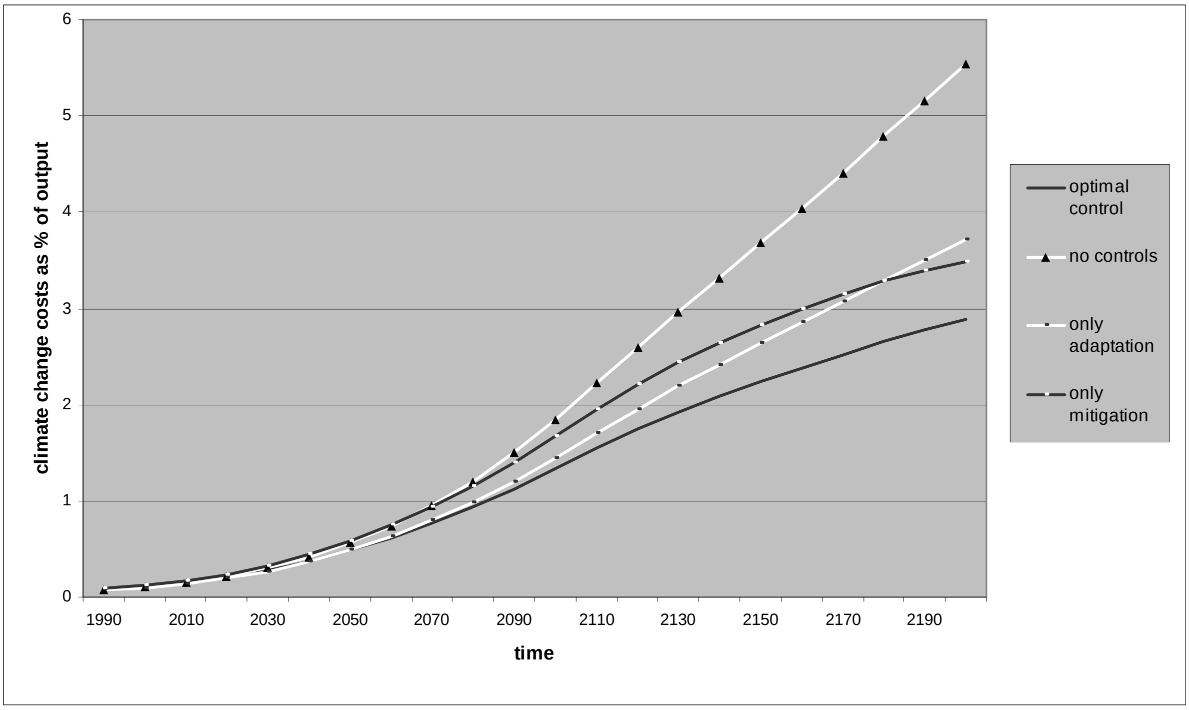

Figure 6: climate change costs of different policy scenarios

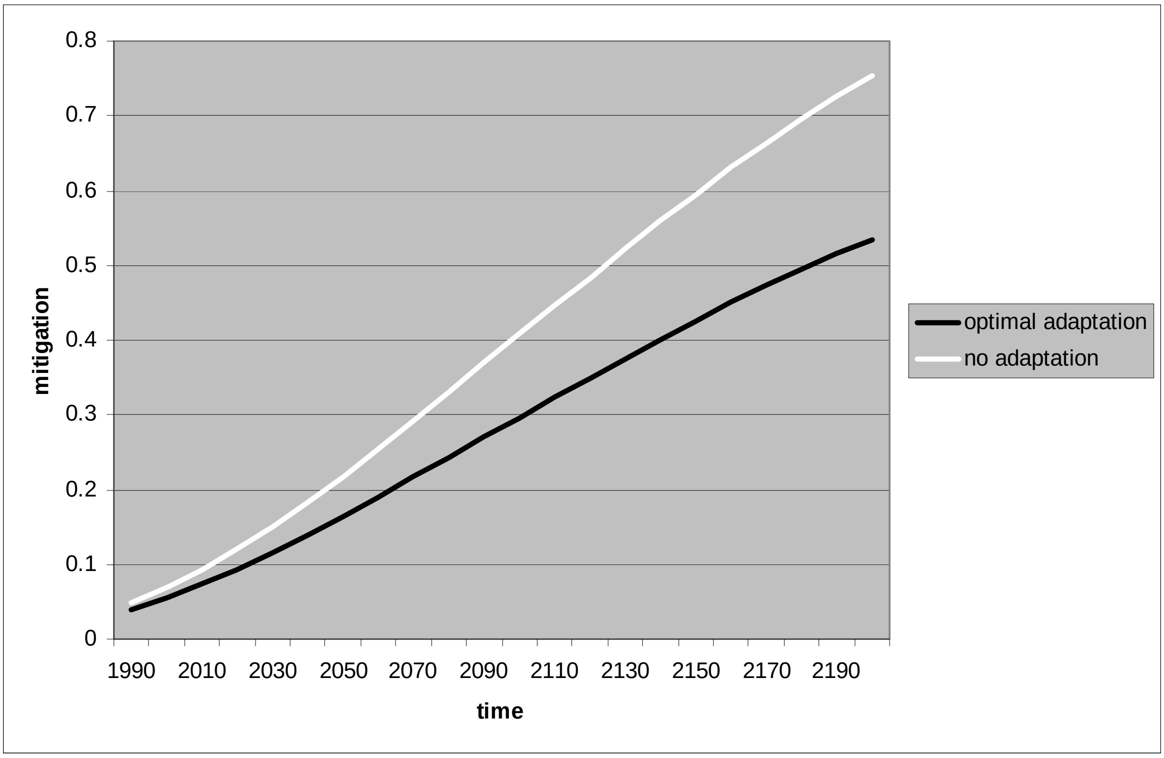

Figure 7: Optimal level of mitigation with and without adaptation

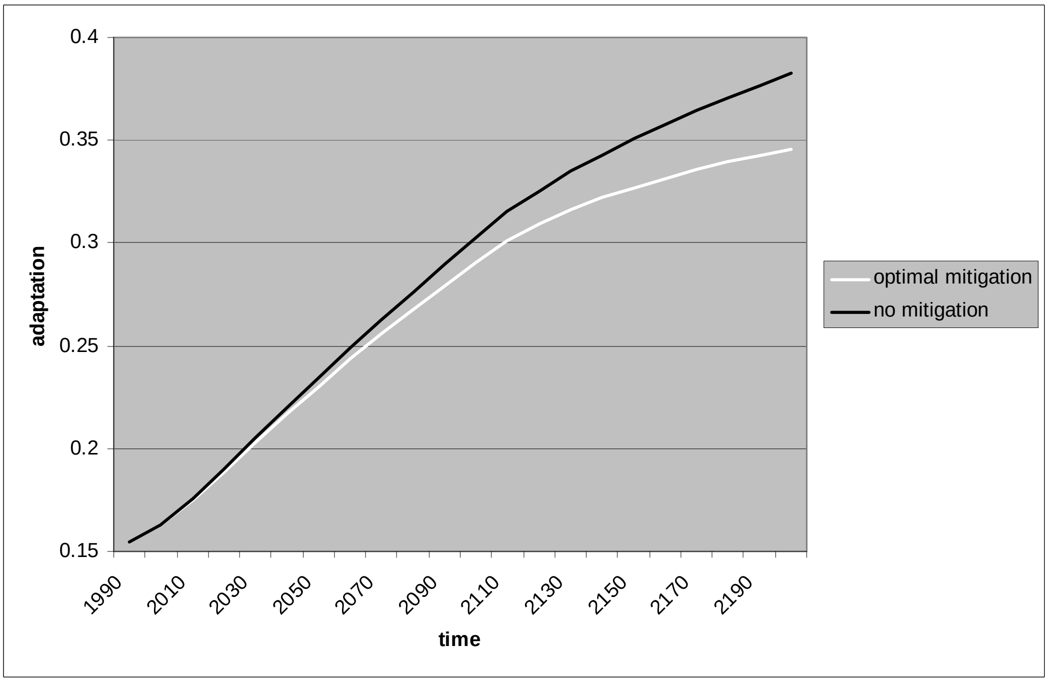

Figure 8: Optimal level of adaptation with and without mitigation

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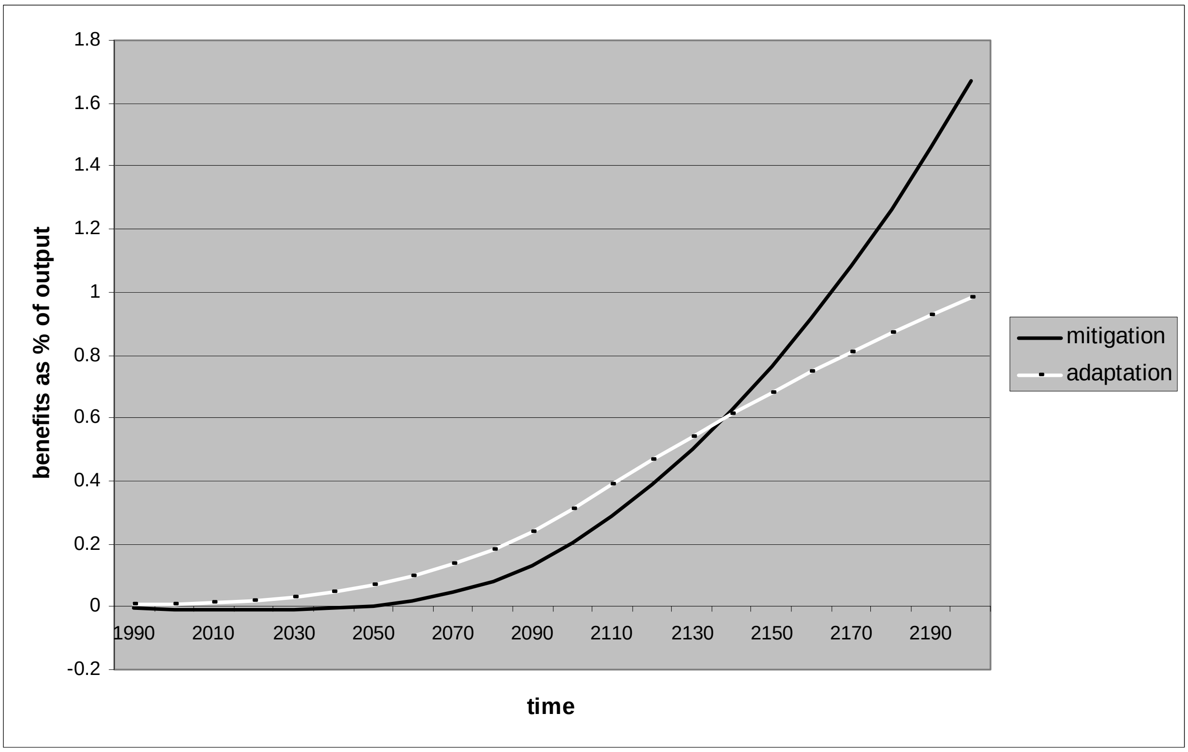

Figure 9: net benefits of optimal adaptation and optimal mitigation over time.

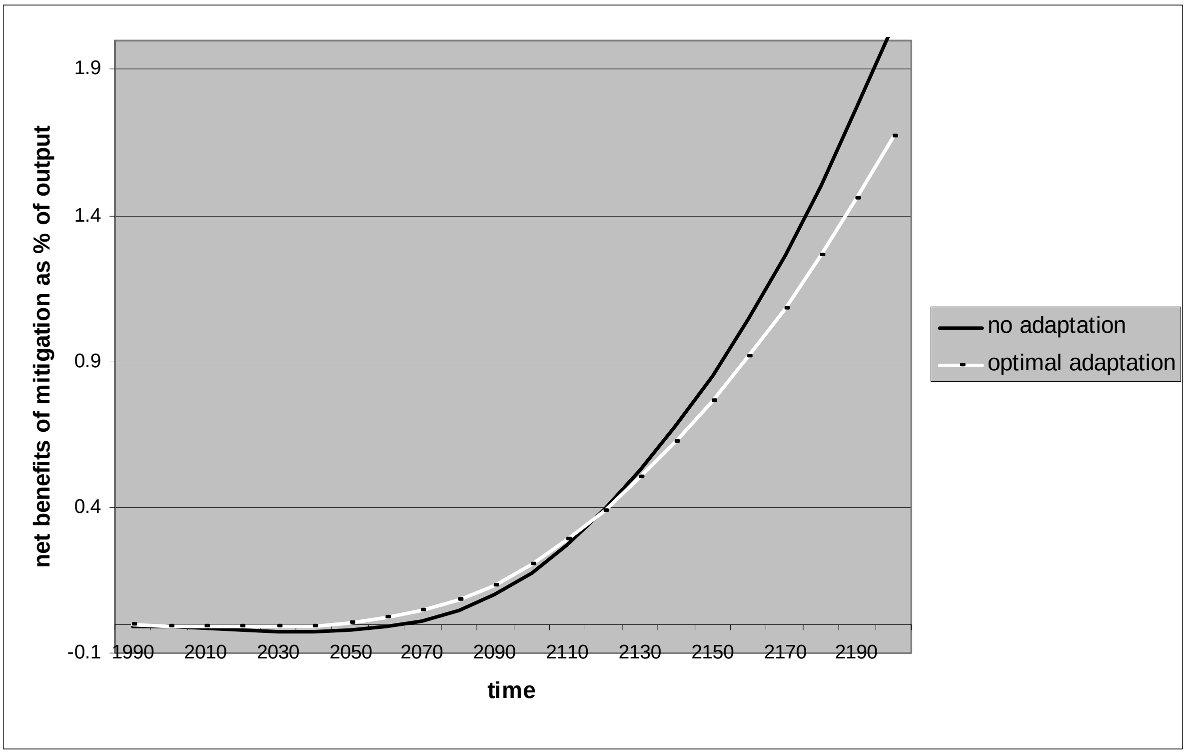

Figure 10: The net benefits of optimal mitigation as a % of output with and without adaptation.

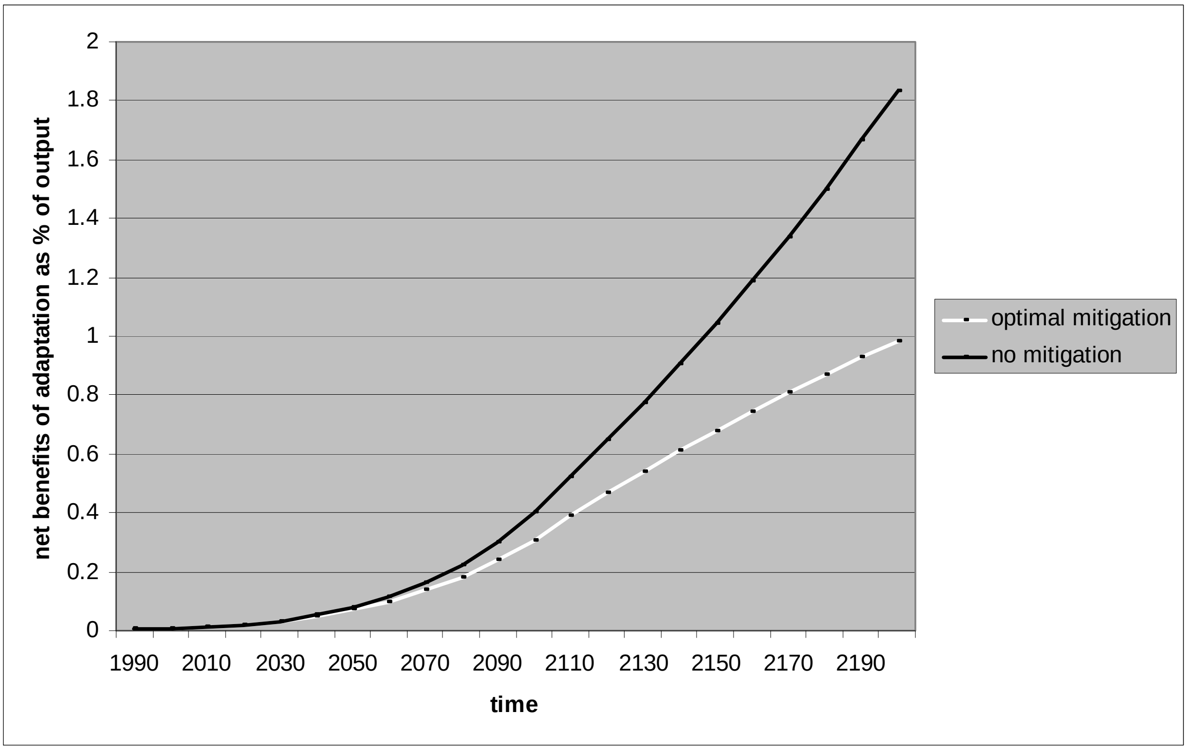

Figure 11: The net benefits of optimal adaptation as a % of output with and without mitigation.

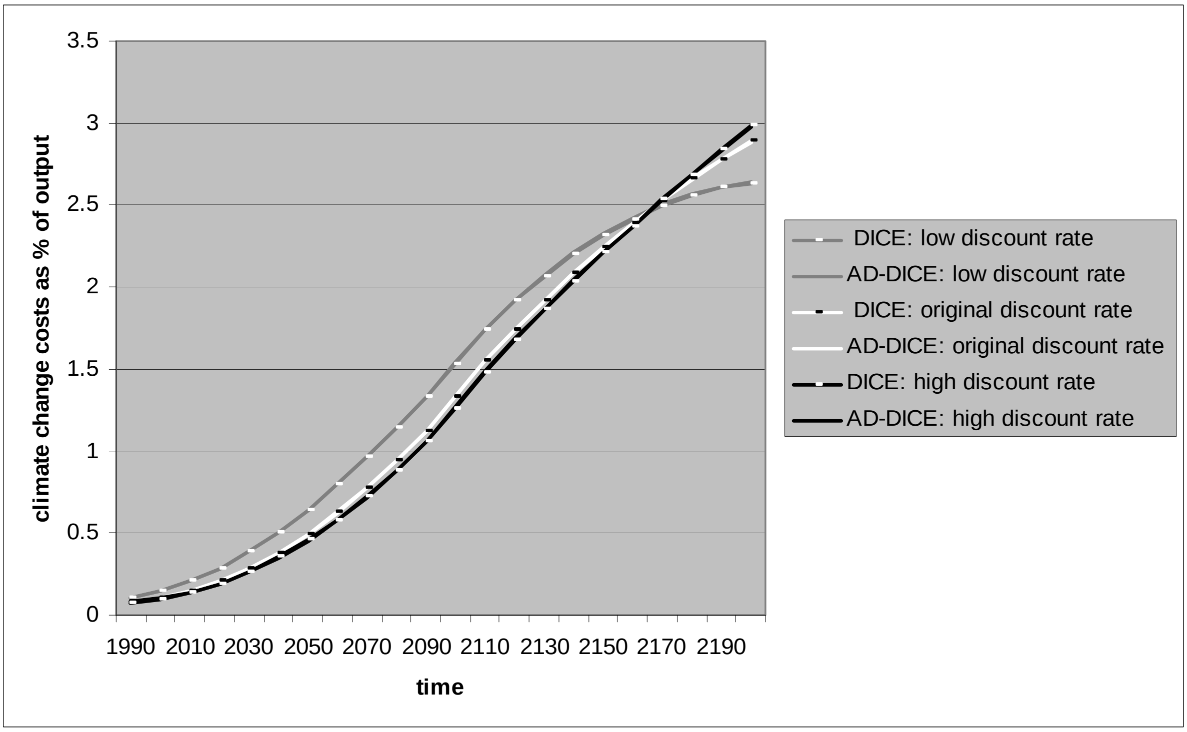

Figure 12: climate change costs as % of output with different discount rates.

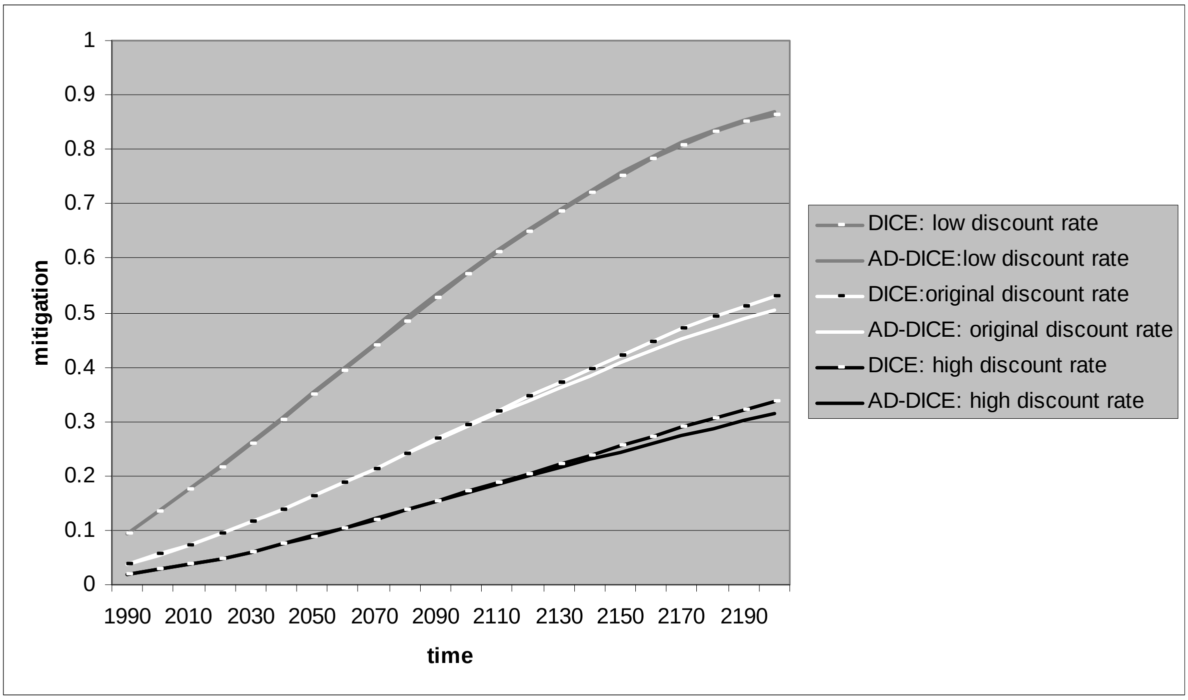

Figure 13: mitigation level with different discount rates.

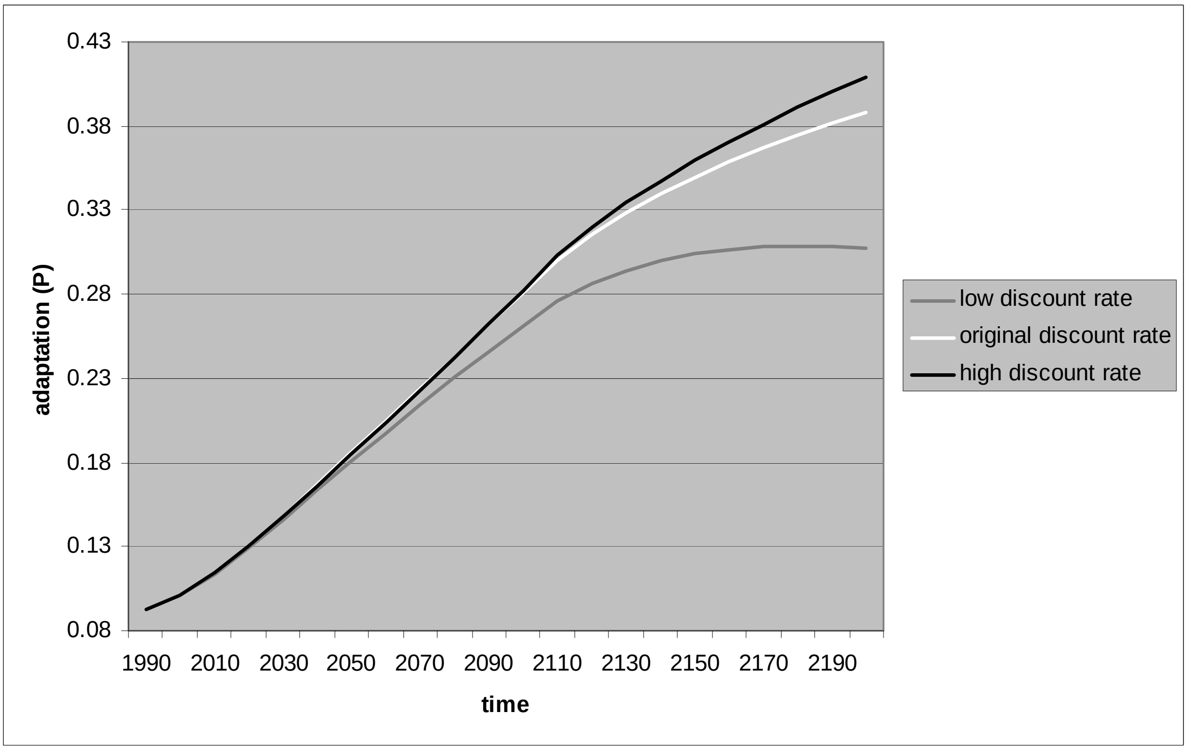

Figure 14: adaptation level with different discount rates

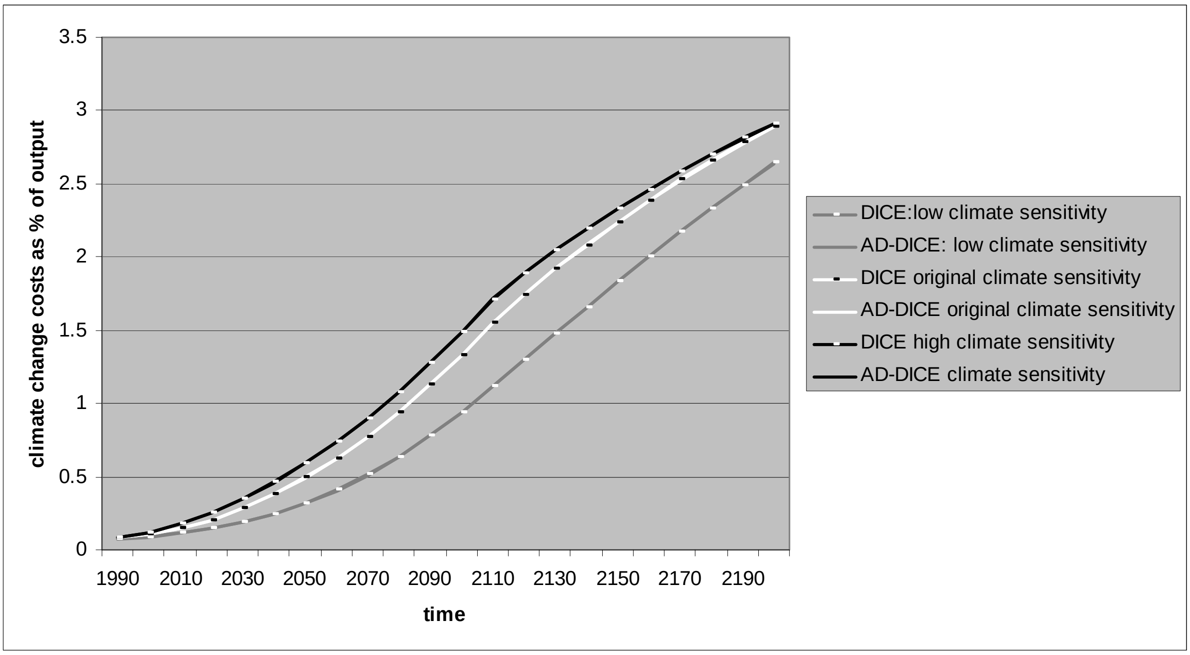

Figure 15: climate change costs as % of output with different climate sensitivities.

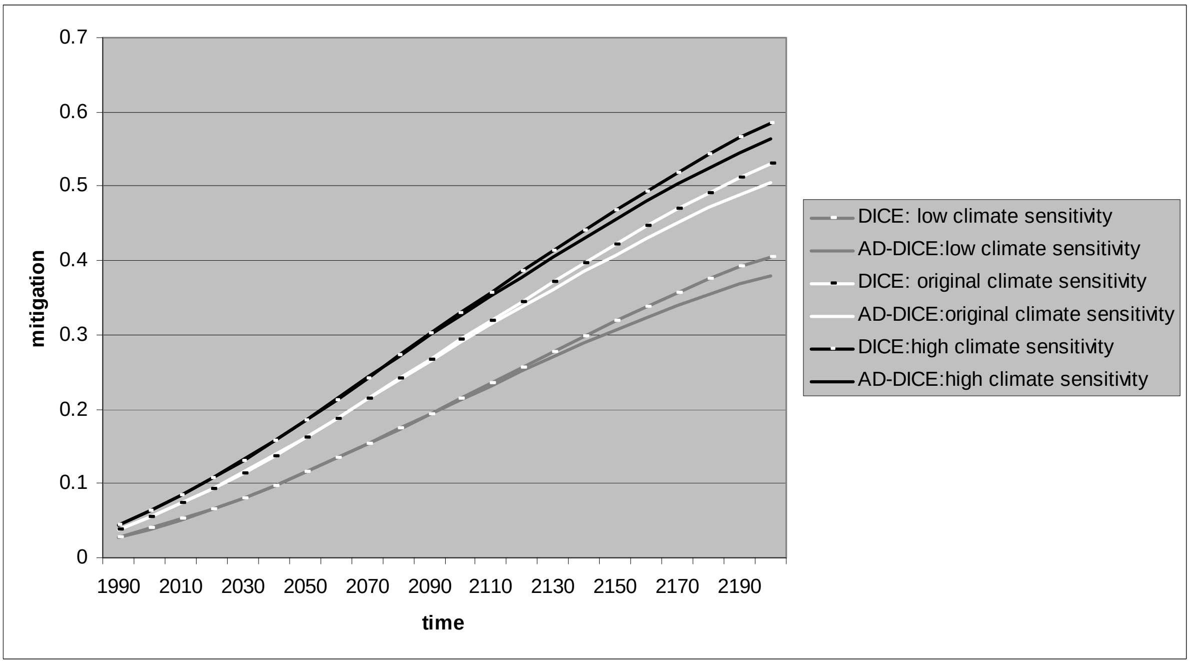

Figure 16: mitigation level with different climate sensitivities.

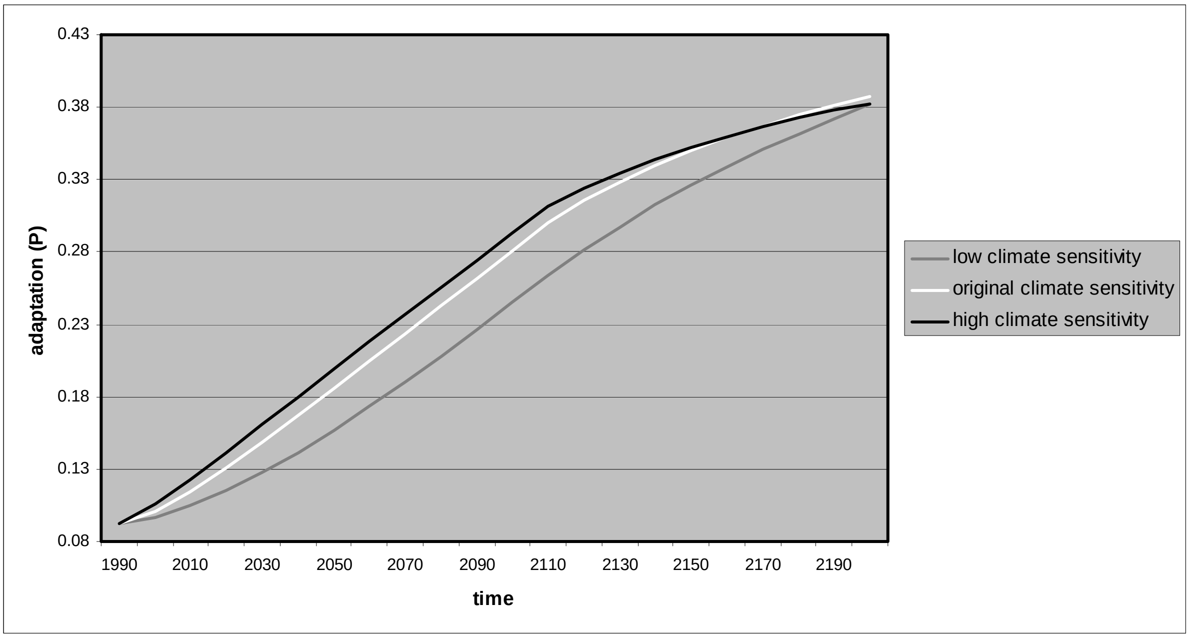

Figure 17: adaptation level with different climate sensitivities.

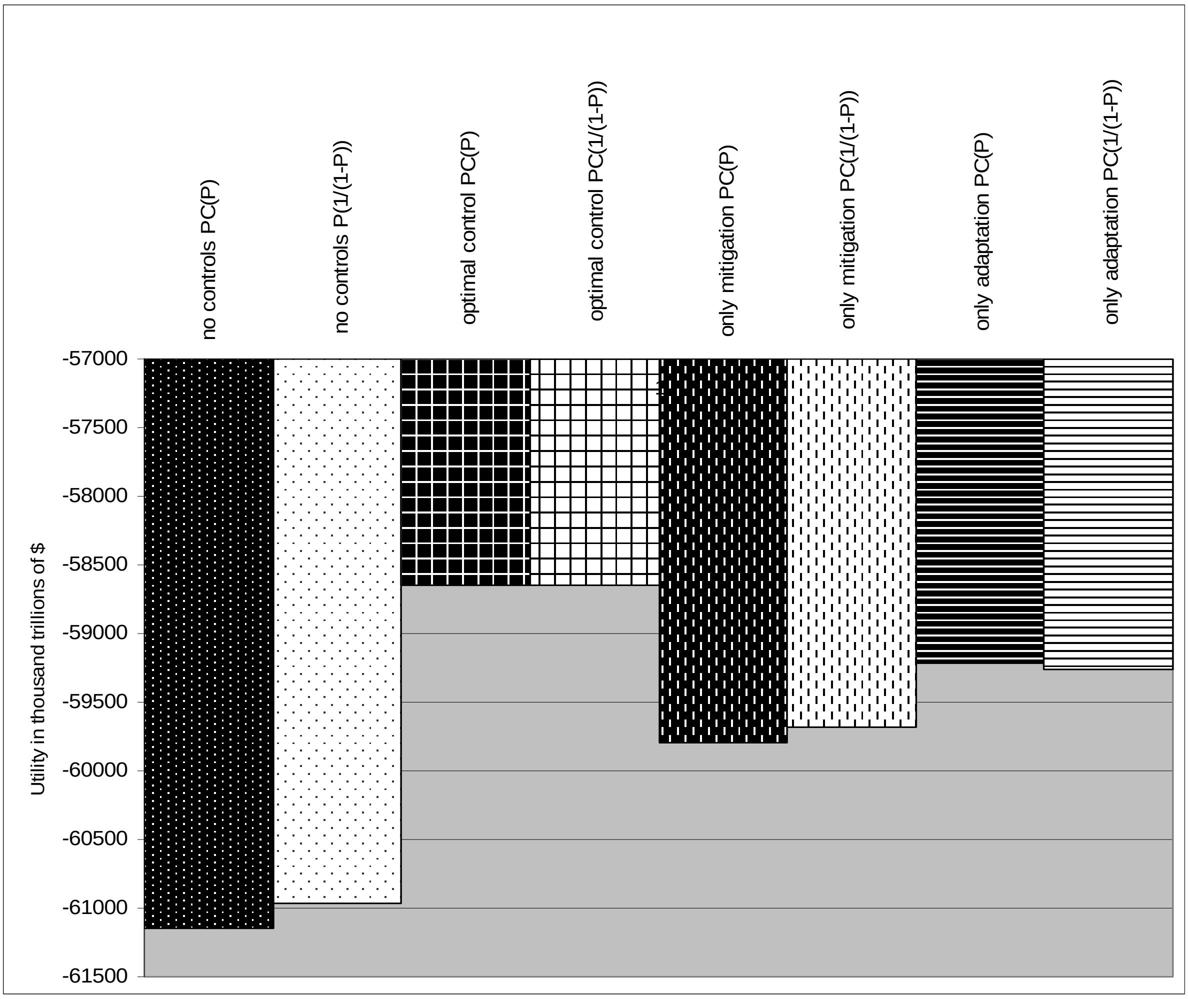

Figure 18: utility of different scenarios with each specification of protection costs.

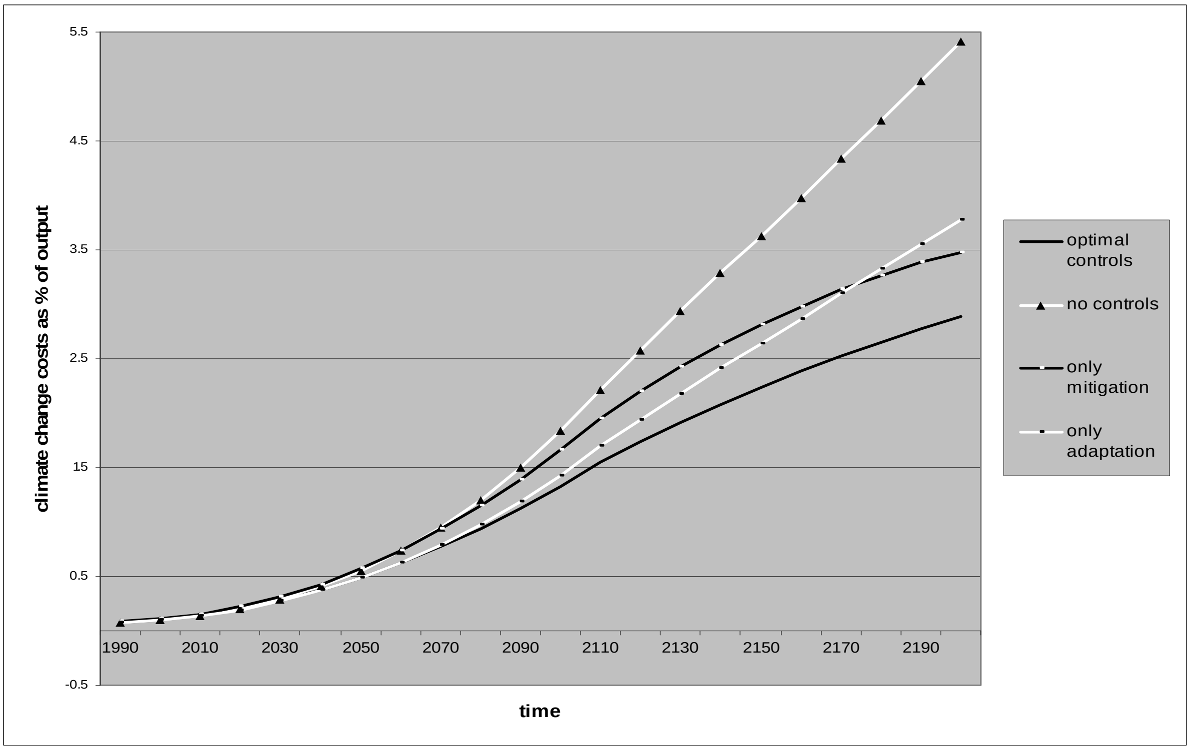

Figure 19: Climate change costs of different scenarios with each PC_t specification.

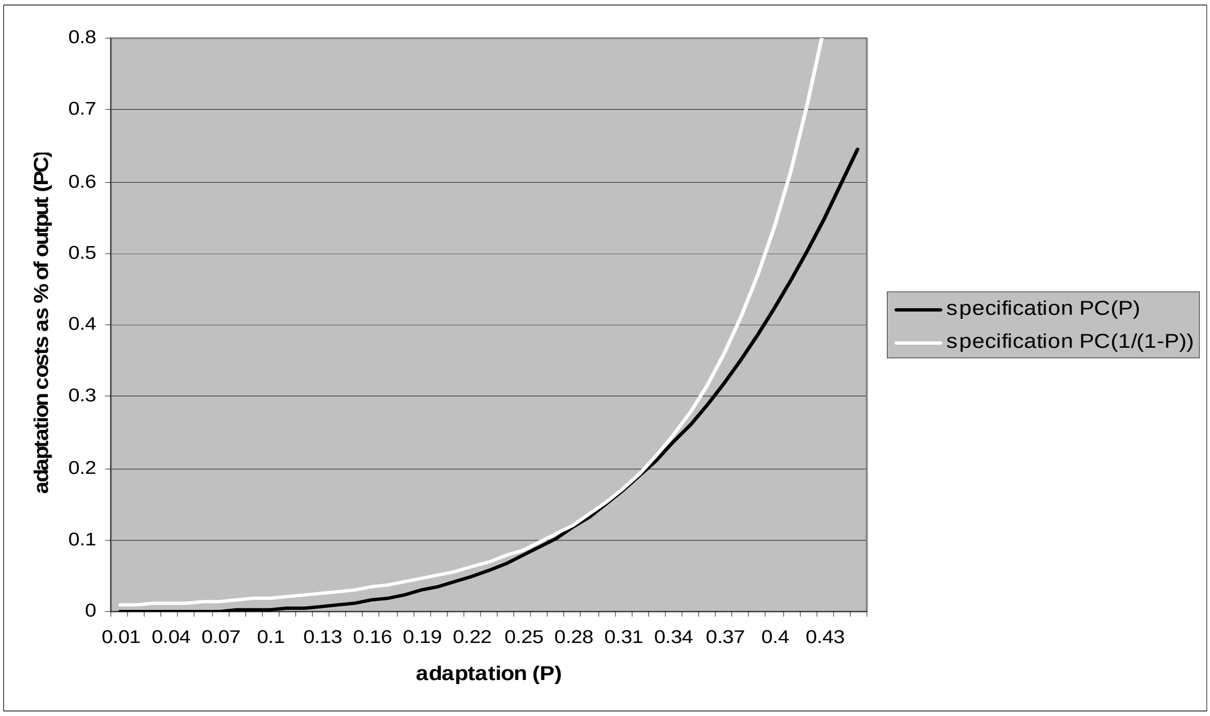

Figure A1 Adaptation curves for both PC specifications

Tables

parameter	α_1	α_2	α_3	γ_1	γ_2	p-value
value	0.0012	0.0023	2.32	0.115	3.60	0.99

Table 1: parameter values from AD-DICE in the optimal scenario calibration.

Scenario	α_1	α_2	α_3	γ_1	γ_2	p-value
Optimal	0.00058	0.0027	2.20	0.000082	8.19	0.99

Table A1: Parameter values from AD-DICE using the PC(1/(1-P)) specification

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