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How Harmful are Adaptation Restrictions

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Summary
The dominant assumption in economic models of climate policy remains that adaptation will be implemented in an optimal manner. There are, however, several reasons why optimal levels of adaptation may not be attainable. This paper investigates the effects of suboptimal levels of adaptation, i.e. adaptation restrictions, on the composition and level of climate change costs and on welfare. Several adaptation restrictions are identified and then simulated in a revised DICE model, extended with adaptation (AD-DICE). We find that especially substantial over-investment in adaptation can be very harmful due to sharply increasing marginal adaptation costs. Furthermore the potential of mitigation to offset suboptimal adaptation is investigated. When adaptation is not possible at extreme levels of climate change, it is cost-effective to use more stringent mitigation policies in order to keep climate change limited, thereby making adaptation possible. Furthermore not adjusting the optimal level of mitigation to these adaptation restrictions may double the costs of adaptation restrictions, and thus in general it is very harmful to ignore existing restrictions on adaptation when devising (efficient) climate policies.

Keywords: Integrated Assessment Modelling, Adaptation, Climate Change

JEL Classification: Q25, Q28

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How harmful are restrictions on adapting to climate change?

1 Introduction

Emissions of greenhouse gasses are changing our global climate, precipitating damages worldwide. Adaptation can be a very powerful means of reducing the damages caused by climate change. Adaptation refers to adjustments in ecological, social or economic systems to moderate potential damages or to benefit from opportunities associated with climate change (Smit *et al.* 2001). Examples of adaptation are the building of dykes, the changing of crop types, and the use of mosquito nets against diseases such as malaria. It has been estimated that in some cases potential damages can be reduced by up to 80% (Mendelsohn 2000). The dominant assumption in economic models of climate policy remains that adaptation will be implemented in an optimal manner and in fact, most models only implicitly make this assumption by including adaptation into the estimate of damages (De Bruin et al., 2009a). There is reason to believe, however, that adaptation will not be undertaken automatically or optimally (see e.g. Smit et al.2003, Kelly and Adger 2000, Fankhauser 1998). Several reasons why optimal adaptation levels may not be attainable have been identified in the literature, such as capacity gaps, lack of information, or inertia in the decision making process. We refer to barriers or constraints resulting in suboptimal levels of adaptation as adaptation *restrictions*. The goal of this paper is to investigate these restrictions and their potential effects on setting optimal climate change policies. There is a significant gap in the literature regarding the effects of restrictions on adaptation. Where thousands of scenarios simulating sub-optimal mitigation are considered with varying degrees of mitigation or concentration targets, consistent economic analysis of suboptimal adaptation is virtually nonexistent. This is partly due to the fact that adaptation options are difficult to quantify and compare with each other. Where mitigation has a clear common performance indicator, adaptation does not (Lecocq and Shalizi, 2007). Furthermore as it can generally be assumed that adaptation has no externalities, it is assumed that it will be applied optimally. Hope et al (1993) and De Bruin et al. (2009a) look explicitly at adaptation and compare the effects of assuming no adaptation with optimal adaptation. Adaptation practices in the real world will, however, neither be optimal nor non-existent but likely somewhere in between. Including various scenarios with different restrictions on adaptation will better represent the real world situation and give us improved understanding of the costs and dynamics of adaptation restrictions. That is the aim of this paper.

Furthermore, besides the fact that there are many barriers to optimal adaptation there remains considerable uncertainty regarding climate change damages and how these can be avoided through adaptation. As a simplification, our model (and essentially all deterministic models) assumes that there is a policy lever that can set some macroeconomic "level of adaptation". In this paper, we investigate what the effects may be if this policy lever is not performing optimally, i.e. if the information on damages and adaptation costs is incorrect. Accordingly, we look at the consequences of misspecifying adaptation. This can give policymakers insights into the uncertainties regarding adaptation policies.

In this paper we use an Integrated Assessment Model (IAM), namely AD-DICE to simulate different adaptation restrictions that could occur. AD-DICE is a recently developed (de Bruin et al., 2009a, 2009b) extended version of the well-known DICE model (Nordhaus and Boyer 2000) that includes adaptation as a decision variable.

This paper attempts to answer several important questions. Firstly, what are the effects of different adaptation restrictions on the level and composition of climate change costs? Secondly, how do adaptation restrictions affect the optimal mitigation policies, i.e. how do optimal mitigation paths change due to the various restrictions? Thirdly, and linked to the previous question, how can flexible mitigation policies compensate for reduced adaptation and how costly is a "naive" mitigation policy that disregards existing restrictions on adaptation?

This paper is structured as follows. The second section briefly describes the AD-DICE model we use in our analysis. The third section will introduce different restrictions identified in the literature and describe how these are simulated in the model. The fourth section discusses the results and the final section concludes.

2 The AD-DICE Model

For this analysis we use the AD-DICE model as introduced in de Bruin et al. (2009a) and refined in de Bruin et al. (2009b) and de Bruin and Dellink (forthcoming). The model is based on the Dynamic Integrated model for Climate and the Economy (DICE) originally developed by Nordhaus (1994, 2007). The model calibration uses the latest adaptation literature as described in de Bruin and Dellink (forthcoming) and summarised in the annex. AD-DICE is a global model and includes economic growth functions as well as geophysical functions. In the model, utility, based on discounted consumption, is maximised. In each time period, consumption and savings/investment are endogenously chosen subject to available income, after the subtraction of the costs of climate change (residual damages, mitigation costs and adaptation costs). Climate change damages are represented by a damage function that depends on the temperature increase compared to 1900 levels. Mitigation decreases emissions per unit of output; the marginal costs of mitigation are decreasing over time and increasing with the magnitude of mitigation undertaken. In our model we use the discount rate assumptions of the DICE model, i.e. a Ramsey discounting method with a positive pure rate of time preference.

AD-DICE adds adaptation as a control variable to DICE as described in detail in de Bruin et al. (2009a,2009b) and briefly explained here. We define gross damages as the initial damages by climate change if no changes were to be made in social and economic systems. If these systems were to adapt to limit climate change damages, the damages would be lower. 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. Furthermore the net damages in the DICE model are assumed to be the *optimal mix* of adaptation costs and residual damages. Thus the net damage function given in DICE is unravelled into residual damages and adaptation costs in AD-DICE, yielding the level of adaptation as a new policy variable. Adaptation is 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, adaptation (denoted by P) is expressed as the fraction by which gross damages are reduced.

We assume that marginal adaptation costs increase at an increasing rate with the level of adaptation, as cheaper and more effective adaptation options will be applied first. The calibrated adaptation cost curve is represented in Figure 1[1].

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[1] We thus assume that adaptation costs in percentage of GDP for a given fraction of adaptation P are independent of the level of damages. This reflects two opposing mechanisms. Firstly, as gross damages increase we would expect adaptation to become more expensive. Gross damages increase over temperature change, which increases over output and time. Secondly, we would expect adaptation costs to increase less than proportional to output: as output increases the value you protect increases by a larger amount than the costs to protect it. The obvious example here is that of a dyke, where the value of the settlement behind the dyke increases with output increases whereas the costs of building a dyke increase only marginally. In our model we assume that these two effects generally even each other out and thus assume that adaptation costs grow at the same rate as output.

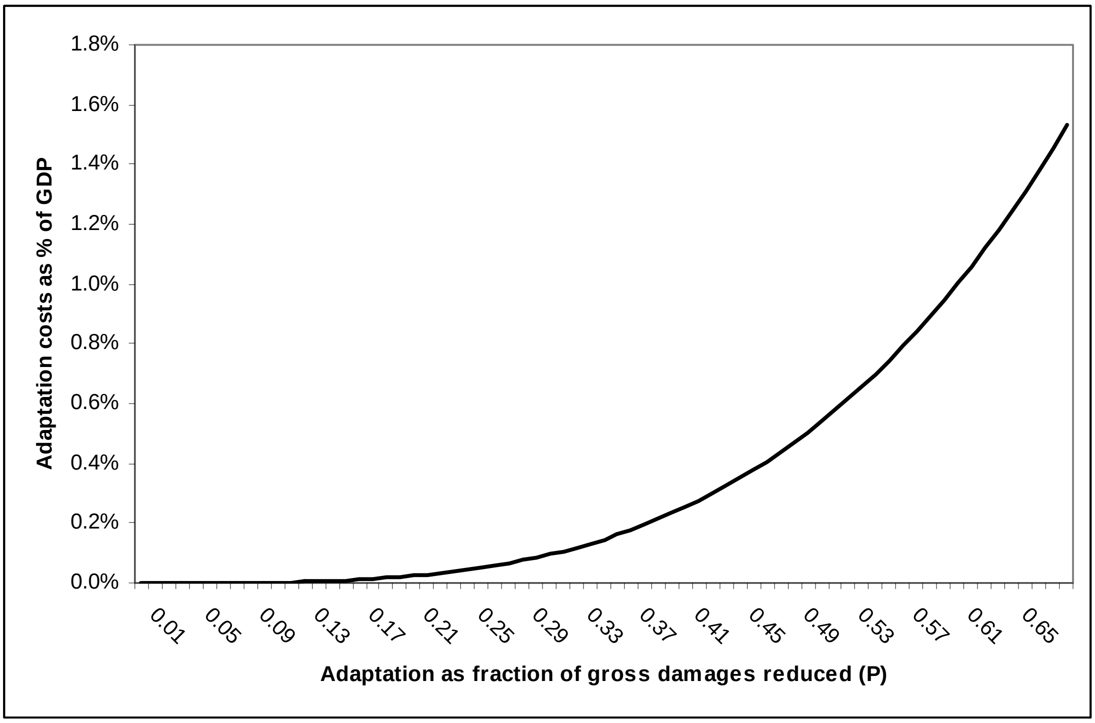

Figure 1: Calibrated adaptation cost curve.

The level of adaptation is chosen every time period (10 years). The level of adaptation in one time period does not affect damages in the next period, thus in each decade a similar 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 within the same time period. Many forms of adaptation have this 'flow' characteristic (e.g. air conditioning), although other forms require a build-up of adaptation stock. The restrictions we investigate in this paper capture the inertia related to the stock features indirectly[2], but we leave an analysis with adaptation explicitly as a stock variable (which reflects anticipatory investments in adaptation capital, such as the building of sea walls) for future research.

When optimal levels of adaptation are attainable, the results will stay unchanged when compared to DICE. The key innovation of the AD-DICE model is that it makes analysis of

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[2] Note, however, that we do consider all adaptation options when estimating the effectiveness of adaptation; capital goods investments are incorporated by calculating the associated annual capital costs.

suboptimal levels of adaptation possible. Thus, with this model we can control the level of adaptation to simulate restrictions or even completely exclude adaptation as an option for the sake of studying the effects of adaptation.

3 Adaptation restrictions

This section examines different restrictions, limits and barriers to adaptation. There are many reasons why the optimal level of adaptation may not be attainable, many of which are linked to the magnitude of climate change (see for example, Klein *et al*., 2007) and inertia in the physical, economic and social systems. This section discusses some of the key restrictions to adaptation, and "adaptation scenarios" are then constructed to simulate these restrictions in our Integrated Assessment Model framework. The scenarios are given in Box 1. Note that the numerical results will depend on the exact specification of the restrictions, and there is insufficient information to numerically determine these restrictions. Therefore we simulate a wide range of possible specifications per scenario in Section 4.

3.1 Restriction on the level of adaptation costs

The predominant adaptation restriction discussed in the literature is that of capacity gaps (e.g. Smit *et al*., 2003, Klein *et al*., 2005, Paavola and Adger, 2006). The amount of funds available for adaptation expenditures may be lacking. Many forms of adaptation need initial investments, and in many cases funds for these investments cannot be raised. This is often the case when large sums of money need to be invested in building adaptation options beforehand, i.e. before climate change occurs. For example a government may not be able to raise the funds required to build a sea wall or invest in climate proofing infrastructure. Also investments in early warning systems or research and development may involve sums of money that are not available to policy makers or may have to compete with other expenditures. Naturally this restriction is especially applicable to developing regions where there is a severe lack of funding for such purposes both on an individual as governmental level. Furthermore the adaptation expenditures have to compete with development expenditures which are direly needed (such as health care and education). This restriction is so important in developing regions that it has received international political attention where adaptation funds have been set up to support developing regions in funding their adaptation needs.

Furthermore the irreversibility of decisions to invest in adaptation under uncertain future climate impacts decreases the *ex ante* incentives to invest in adaptation. Policymakers therefore tend to be cautious in allocating funds when the level of future damages is uncertain. Another, but related, barrier is of a political or policy nature: it may be the case that adaptation is not undertaken when the benefits are less visible or further in the future. Governments may postpone such projects as the benefits will not be reaped within the governing period. This especially involves bigger, long term projects such as sea walls, setting up insurance schemes *etc.*

These forms of adaptation limitations are represented in AD-DICE by limiting the amounts of funds available for adaptation (i.e. adaptation costs) to a level below the optimal (scenario A1).

3.2 Restrictions on the level of adaptation

We distinguish between the level of adaptation and the funds spent on adaptation to differentiate between the effects of uncertainty regarding the effectiveness of adaptation and uncertainty regarding the costs. The restriction given in section 3.1 provides insight into the effects of misspecifying the adaptation costs or having a lack of funds, whereas here we look at the effects of misspecifying the avoided damages and thus choosing an incorrect level of adaptation. Note, however, that restrictions on the level of adaptation expenditure and the level of adaptation are closely linked through the interactions in the adaptation cost curves. Nonetheless because of the dynamic effects these are not exactly the same.

In this section, the actual level of adaptation (*P*) may be set at a suboptimal level, i.e. the fraction of gross damages that is prevented by adaptation is lower than optimal. There are many reasons why this may be the case. One such reason is a lack of knowledge. There remains a lot of uncertainty regarding the exact level and impacts of climate change, making it hard to employ the correct amount of adaptation. Note that a lack of information may have different effects than a lack of funds due to nonlinearities in the adaptation cost curves. Furthermore, the adaptation measures to be taken may not be known to the people concerned (Fankhauser et al, 1999). Moreover even if the (scientific) knowledge is available, there may be cognitive problems with the assimilation and understanding of this knowledge and the exact implications hereof. Also risk perception can limit adaptation, as individuals may not feel a sense of urgency (risk suppression), especially when simultaneously threatened by other risks. Adaptation may also be limited when there are other threats present (e.g. pollution, conflict and disease) which make ecosystems and people more vulnerable and less able to adapt. Technological limits may also play a role, for example many developing regions may not have access to the technology needed to adapt. Finally even though it is usually assumed that there are no externalities involved in adaptation decisions, this may not be the case, particularly on a smaller scale. When e.g. building sea walls against rising sea levels or forests against soil erosion, the benefits accrue to numerous people. If cooperation cannot take place between these individuals then adaptation may be set at a level below what is optimal. Finally, myopia, i.e. short-sightedness, may cause individuals not to consider the long-term effects of climate change, thus restricting proactive adaptation.

The key aspect that links all these restrictions in terms of our model, is that the amount of gross damages avoided is too low when compared to the optimal level, i.e. the adaptation level is too low. Thus, these limitations are mimicked, albeit in a crude fashion, in scenarios A2, where the amount of adaptation is limited to a level below optimal.

3.3 Restrictions on the level of residual damages

Up to now our restrictions have pertained to cases where not enough adaptation is deployed. It is, however, also imaginable that too much adaptation is undertaken. Due to loss aversion, i.e. people strongly prefer avoiding losses to acquiring gain, people may be inclined to over-protect their assets, i.e. over-adapt. Furthermore, people or policymakers may find it morally unjust to accept certain forms of climate change adaptation or certain amounts of residual damages. This is reflected in e.g. the social and cultural barriers which may exist when considering migration as a form of adaptation. It is often observed that in the case of natural disasters (such as floods), people are not willing to leave their houses regardless of the consequences; they have such strong ties to their homes that resettlement is not a socially viable option. Thus there are several reasons why people, or governments, may overinvest in adaptation to limit the residual damages. This is modelled in scenario A3 where residual damages are limited to a maximum level which is below the optimal level.

3.4 Restrictions on the timing of adaptation

A fourth issue that may constrain adaptation is inertia (cf. Burton 2005), i.e. there may be a problem of delayed reaction. Firstly, it might take considerable time to implement adaptation measures (Mendelsohn, 2000, and Berkhout et al., 2006). For example large scale adaptation projects such as sea wall construction need time to be set up and completed. Secondly, cultural and social aspects may cause delays in reacting to climate change due to slow adjustment phases. Societies need time to culturally accept that climate change is a problem and that certain adaptation measures are needed. Thirdly, inertia in the political systems and prolonged negotiations on international coordination of climate policies will further delay the implementation of adaptation. Finally, also a tendency to wait for improved information may postpone investments in adaptation. Scenario A4 reflects such inertia by assuming that adaptation is not applicable up to a certain point in time.

3.5 Restrictions on the flexibility of adaptation

It also may be the case that adaptation levels cannot change quickly over time. For example adaptation knowledge may need to be acquired over time in order to adapt as the climate changes. Thus changing the level of adaptation may be restricted due to the rate at which one can procure adaptation knowledge. Adaptation in its proactive sense also brings with it the idea that a stock of adaptation is built up over time. This stock cannot, however, accumulate or deplete very quickly over time. A similar type of inertia refers to physical and ecological limits. For instance, ecosystems need time to adjust (Klein et al, 2007). In scenario A5 we simulate this by restricting the change in adaptation levels over time, implying a gradual adjustment and preventing radical adjustment of adaptation policies.

3.6 Irreversible climate change (Tipping points)

Dramatic levels of climate change may also make it impossible to adapt (Nicholls and Tol, 2006, Tol *et al*. 2006, Tol and Yohe 2006). At lower levels of climate change we are able to gradually change our society, economic structure *etc.* in such a way as to limit the damages caused by the changing climate. If the climate system changes too much, this may no longer be possible. In the literature so called ‘tipping points’ have been identified, at which a small change in human activity can have large, long-term consequences for the Earth’s climate system. Many potential tipping points have been suggested in the climate change literature, the most known of these being the collapse of the West Antarctic ice sheet (at around 5-8 degrees) causing sea level rise of 5 meters and the collapse of the Atlantic thermohaline circulation (3 to 5 degrees) (Lenton *et al*. 2008). A whole new society and economic structure will be needed. Large ecosystems will be irreversibly disrupted and consequently these extreme damages cannot be adapted to within a reasonable time scale and will therefore have to be accepted. Irreversible climate changes may, however, occur already (although less dramatically) at lower levels of temperature change. We simulate this by assuming that as temperature increases (and thus gross damages) adaptation will become less effective.

Furthermore after a certain degree of temperature rise, adaptation becomes completely ineffective (the tipping point). This is simulated in scenario A6.

Box 1 summarises the adaptation scenarios. Box 2 shows how these restrictions are technically implemented into the model.

Adaptation Scenarios

A1 There is an upper limit on adaptation costs
A2 There is an upper limit on adaptation
A3 There is an upper limit on residual damages
A4 Adaptation cannot be implemented up to a certain time period
A5 Adaptation levels can only vary to a certain degree from one period to the next
A6 Adaptation becomes less effective as temperature rises

Box 1: Adaptation restrictions scenarios

A1: $PC_t \leq x$, where x is the limit in fraction of output

A2: $P_t \leq x$, where x is the limit in fraction of gross damages reduced

A3: $RD_t \leq x$, where x is in fraction of output

A4: $P_t = 0, \forall t \leq x$, where $x+1$ is the first time period in which adaptation can be implemented

A5: $\frac{P_t - P_{t-1}}{P_{t-1}} \leq x$, where x is fraction of change in adaptation from one time period to the next

A6: $RD_t = \left(1 - P_t \cdot \left[1 - \frac{\Delta temp}{x}\right]\right) \cdot GD_t$ where x is the temperature change where adaptation becomes completely ineffective (the tipping point)

where

P_t = adaptation in period t

PC_t = adaptation costs in period t, calculated as $PC_t = \gamma_1 \cdot P_t^{\gamma_2}$

GD_t = gross damages in period t

RD_t = residual damages in period t, calculated as $RD_t = (1 - P_t) \cdot GD_t$

$\Delta temp$ = temperature change compared 1990

Box 2: Implementation of the adaptation restrictions

4 Results

In this section we will present the results of our analysis. First the benchmark simulation, where we assume optimal adaptation, will briefly be presented; this provides the reference point for the evaluation of the various scenarios with adaptation restrictions. We then look at the effects of each restriction on the composition and level of climate change costs, assuming a responsive mitigation policy, i.e. mitigation levels can be adjusted to accommodate the adaptation restrictions. We then show how the optimal mitigation path is affected by the different restrictions. Finally we investigate the impact of naïve versus responsive mitigation policies for each scenario.

4.1 The Benchmark: optimal adaptation

We first present the case where there are no restrictions to adaptation. We call this the *optimal* case. All other scenarios include restrictions and thus are cases of constrained optimisation. Figure 2 shows the optimal path of adaptation over time without restrictions. As can be seen the level of adaptation increases steadily, due to increasing damage levels, and levels out at the end of the 22nd century when mitigation policies become more effective as a control option. Roughly speaking, in the first century it is optimal to avoid a quarter of all possible (gross) damages (P≈0.25) and afterwards optimal adaptation levels increase to nearly a half of gross damages (P≈0.44) on average.

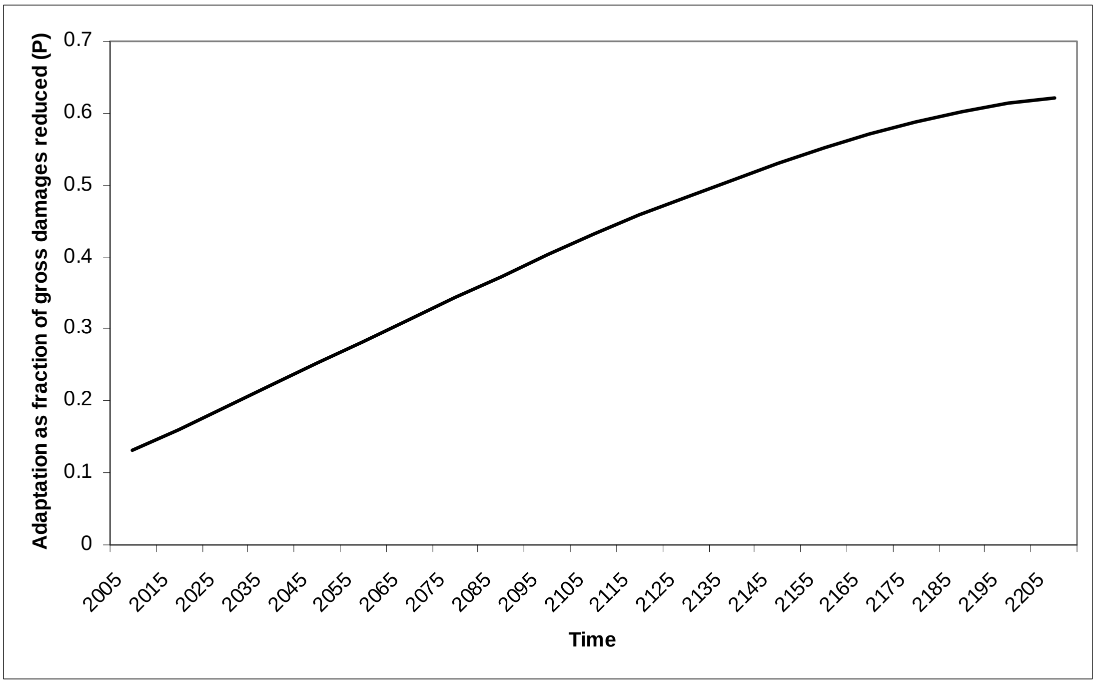

Figure 2: Level of optimal adaptation without restrictions over time.

The Net Present Value (NPV)[3] of total climate change costs (the discounted sum of adaptation costs, mitigation costs and residual damages over all periods), given as a percentage of NPV of output (GDP), are shown in Figure 3 for the optimal adaptation case and for the case where no adaptation is possible at all. The NPV of total climate change costs equals 0.9% of GDP when optimal adaptation is possible, and increases to 1.5% of GDP in the case of no adaptation. This shows the potential of adaptation to decrease climate change damages. By far the largest constituent part of climate costs are the residual damages, even in the case of optimal adaptation. This illustrates the trade-off that takes place at the margin: for every adaptation measure one has to weigh the additional benefits in terms of reduced damages with the additional costs of the measure. Thus, it is never optimal to completely eradicate all damages, and optimal climate policies are moderate in the use of both control options.

Figure 3 also illustrates the compensating effect mitigation can have. The case with no adaptation has much higher mitigation costs. Thus due to the lack of adaptation, damages cannot be reduced after climate change occurs but, will need to be reduced through limiting climate change, i.e. through mitigation. In other words as adaptation decreases, the marginal value of mitigation increases, increasing the level of mitigation and decreasing the damages.

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[3] While widely used as a convenient measure for comparing economic impacts of climate policies, the NPV of climate change costs is not a perfect measure of the welfare impacts of the policies (just as GDP is not a perfect indicator of welfare). However, it is convenient to study the components of climate change costs. We come back to this issue in the results section.

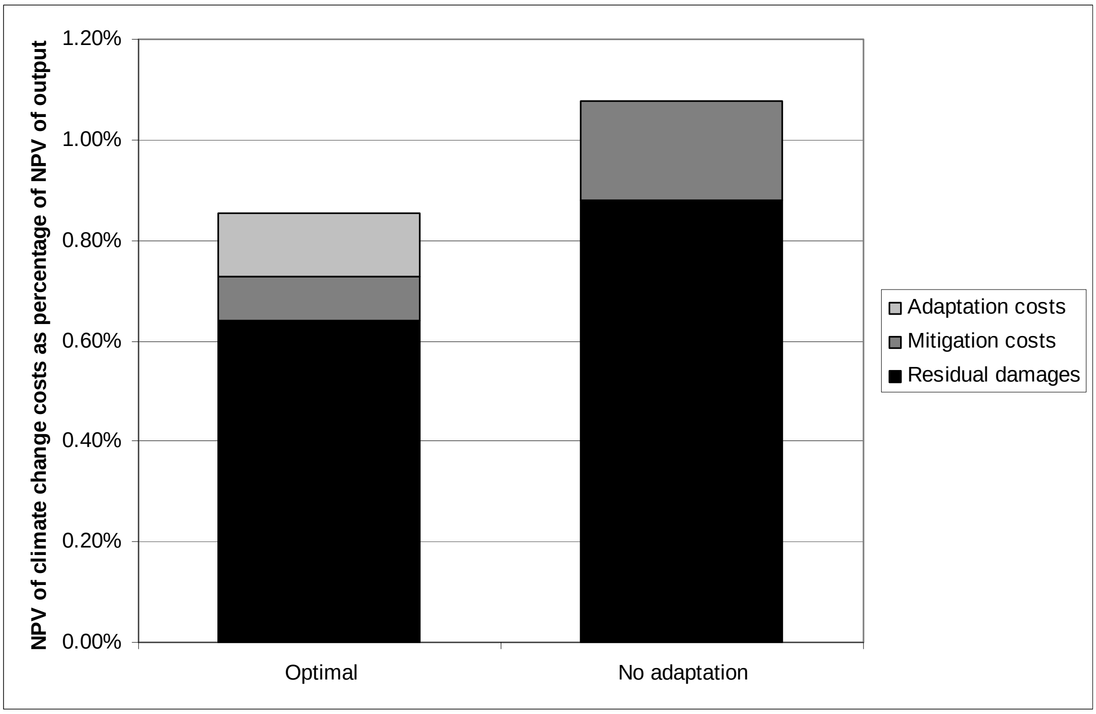

Figure 3: NPV of climate change costs components as a percentage of NPV of output for the optimal and no adaptation scenario.

4.2 The components of climate change costs with restrictions

Restrictions on the level of adaptation costs

In Figure 4 restrictions on the annual level of adaptation costs are examined, where adaptation costs have an upper limit (scenario A1). The right end of the graph reflects the unrestricted optimum. Here the left end of the x-axis shows the case where adaptation costs are completely limited, i.e. there is an upper limit of 0, resulting in total NPV of costs of 1.5% of NPV of GDP (as in the case of no adaptation). As the limit is increased, i.e. the restriction loosens (moving from left to right in the graph), adaptation costs increase while residual damages and mitigation costs decrease at a stronger rate, decreasing total climate change costs. One can see a sharp increase in climate change costs as the upper limit approaches 0, showing how powerful even small amounts spent on adaptation can be.

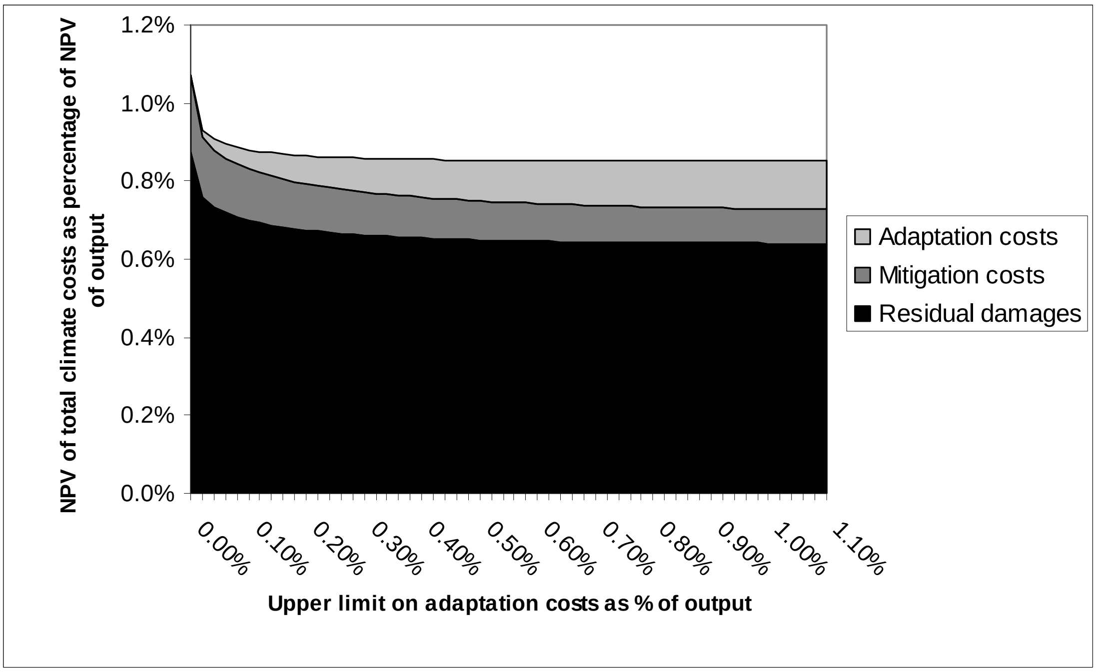

Figure 4 : NPV of climate change costs components as a percentage of NPV of output with upper limits on adaptation costs (A1)

Restrictions on the level of adaptation

Figure 5 looks at restrictions on the *level* of adaptation (A2) as opposed to the *costs* of adaptation in the previous subsection. As adaptation costs are an exponential function of the adaptation level the effects here are similar to Figure 4. The figure shows an upper limit on adaptation starting at 0 on the left hand side and increasing to the point where it is no longer binding on the right. We observe that increasing the upper limit reduces residual damages significantly while adaptation costs remain limited. This again shows how powerful low levels of adaptation can be.

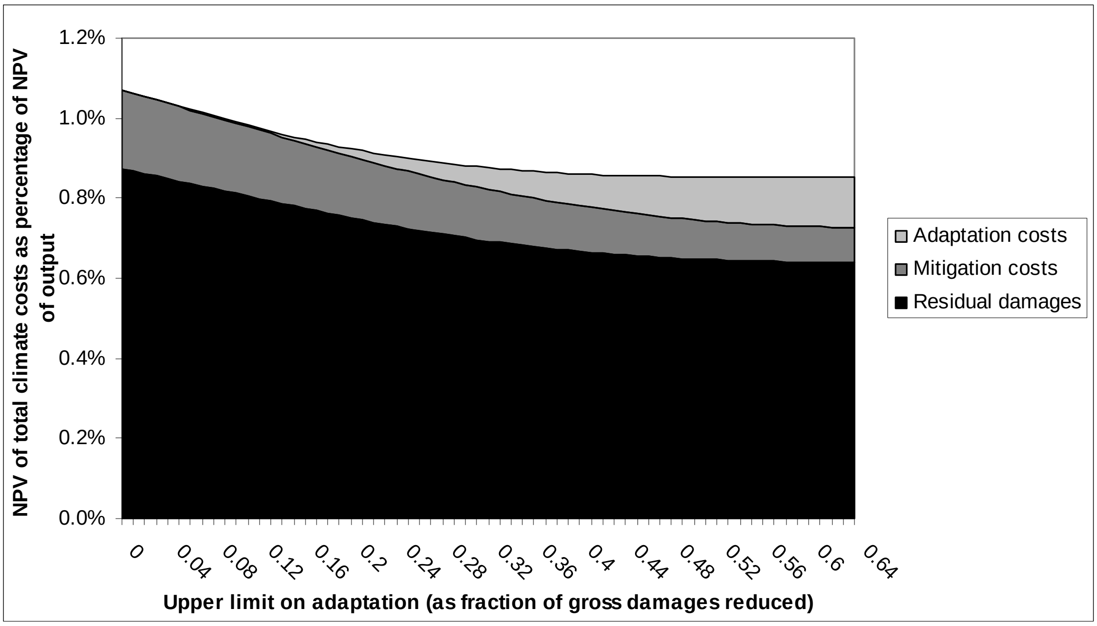

Figure 5 : NPV of climate change costs components as percentage of NPV of output with upper limits on the level of adaptation (A2).

Restrictions on the level of residual damages

Figure 6 shows the climate change costs for scenario A3, where there is an upper limit on residual damages. At the left of the figure no residual damages whatsoever are accepted. Going from left to right more residual damages are accepted. When the upper limit of residual damages reaches approximately 2 % of output the restriction is no longer binding and climate change costs are the same as in the optimum. We can see that over-investing in adaptation to restrict residual damages to a level below the optimum creates large increases in climate change costs (increasing total climate costs threefold in the most extreme case). In this case over-investing in adaptation creates larger costs than not adapting at all.

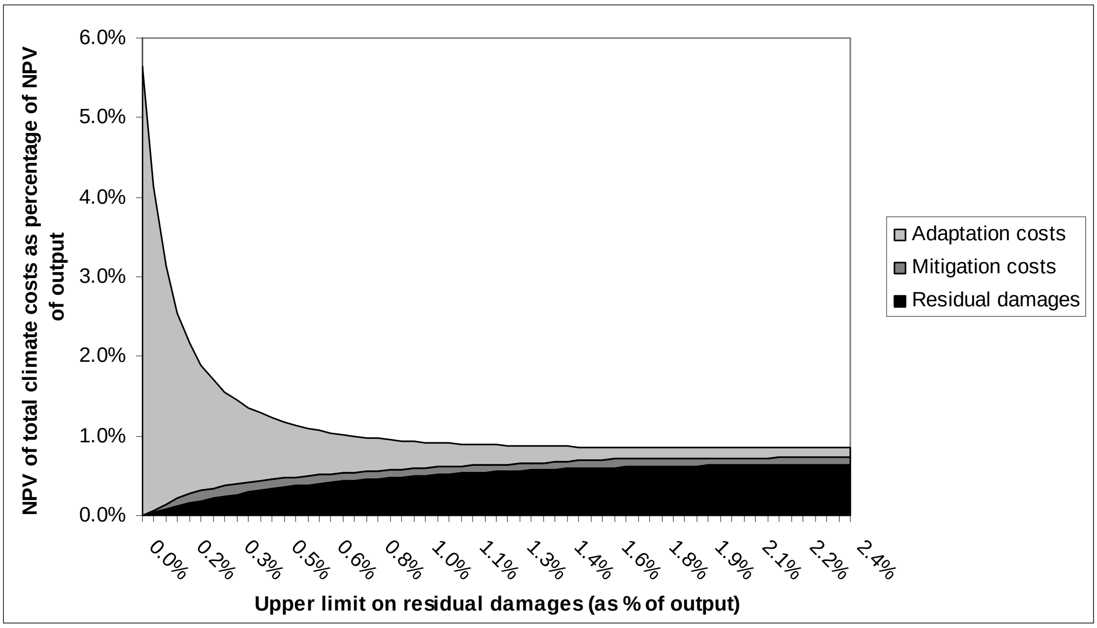

Figure 6: NPV of climate change costs components as a percentage of NPV of output with upper limits on the level of residual damages (A3).

Restrictions on the timing and flexibility of adaptation

Figure 7 shows the case where adaptation is not possible up to a certain point in time (scenario A4). We see that after approximately 200 years of no adaptation, climate change costs have reached the same level as when no adaptation is possible. This result is induced by the positive discount rate, making future damages (and thus future adaptation efforts) less important in net present value terms. Furthermore, restricting adaptation for the first couple of decades affects the composition and level of climate change costs to a small degree, i.e. the graph is relatively "flat". Two mechanisms are at work here. Firstly as time passes the degree to which the costs are discounted increases. Thus restrictions in earlier periods will *ceteris paribus* imply larger costs. Secondly, the global temperature also increases over time, increasing gross climate change damages and thus also increasing the effectiveness of adaptation. Thus in early periods when damages are low, adaptation will have lower benefits. The latter mechanism dominates in the first couple of decades.

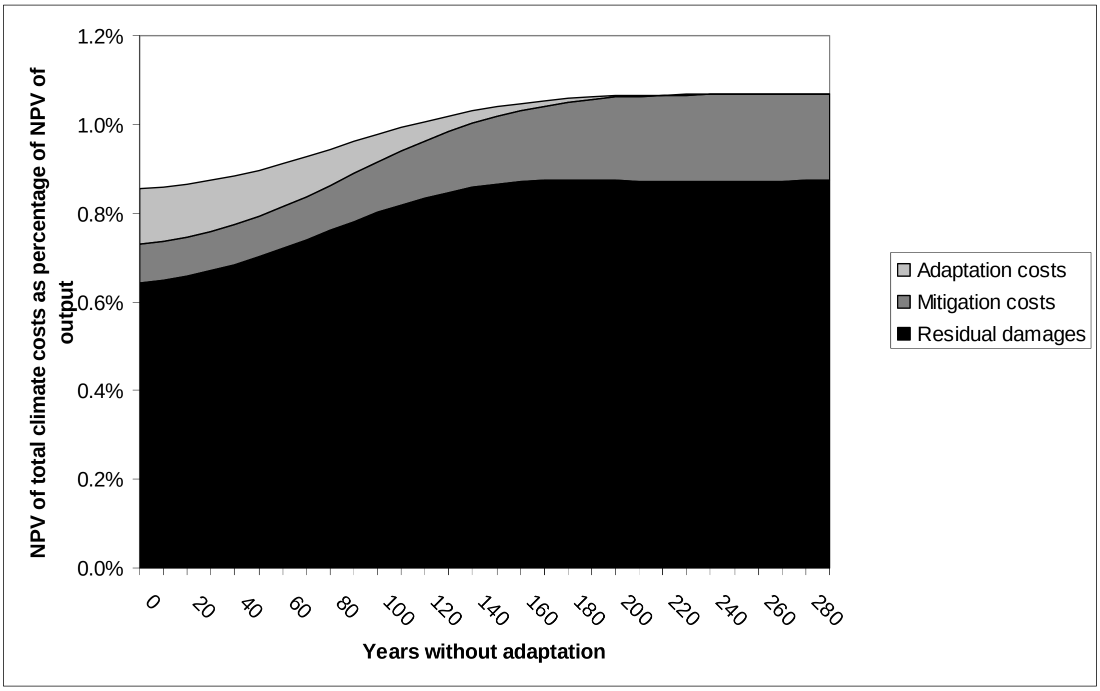

Figure 7: NPV of climate change costs components as a percentage of NPV of output with adaptation delays (A4).

The right-hand panel of Figure 8 shows the components of climate change costs when there is limited flexibility in adaptation over time (scenario A5). Adaptation cannot change more than a certain percentage from one time period to another, i.e. the growth rate of adaptation is restricted. As can be seen at the extreme right of the panel, losing intertemporal flexibility completely (when adaptation cannot change at all over time) increases total climate change costs somewhat, but mostly induces a different composition of these costs. When there is limited intertemporal flexibility it is optimal to choose a relatively low average rate of adaptation (equalling 25% of gross damages throughout the model horizon as opposed to the optimal average of 44%). This is because when there is less flexibility you will need to over- and/or under-invest in adaptation during some periods. Due to the exponential cost function of adaptation over-investing is more harmful than under-investing, and thus a lower level of adaptation is chosen.

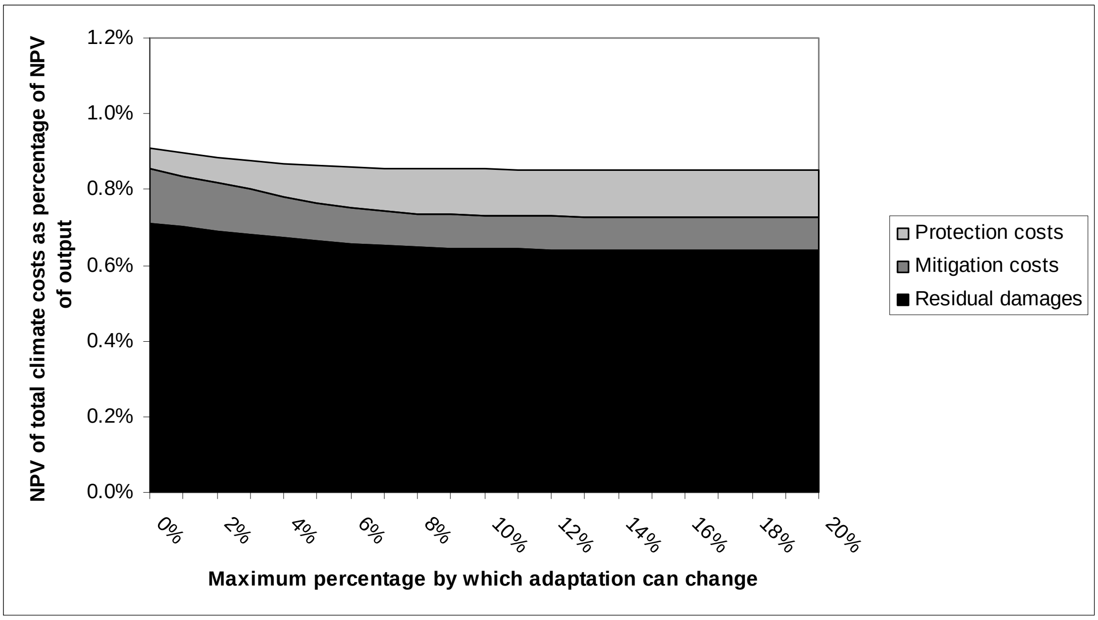

Figure 8: NPV of climate change costs components as a percentage of NPV of output with restrictions on the percentage by which adaptation can change over time (A5).

Restrictions due to irreversible climate change

Figure 9 shows the effects of not being able to adapt effectively at high levels of climate change (scenario A6). Here the climate change tipping point, i.e. the point at which adaptation is completely ineffective, is given on the horizontal axis. note that at adaptation already becomes less effective at lower levels of temperature change, as explained in Section 3.6. As we move from left to right and the tipping point of temperature change increases, we see that mitigation costs decrease, as do residual damages. Adaptation costs on the other hand increase as a higher tipping point implies more effective adaptation. Mitigation is applied with low tipping points to ensure that climate change is limited to less than the tipping point to enable effective adaptation.

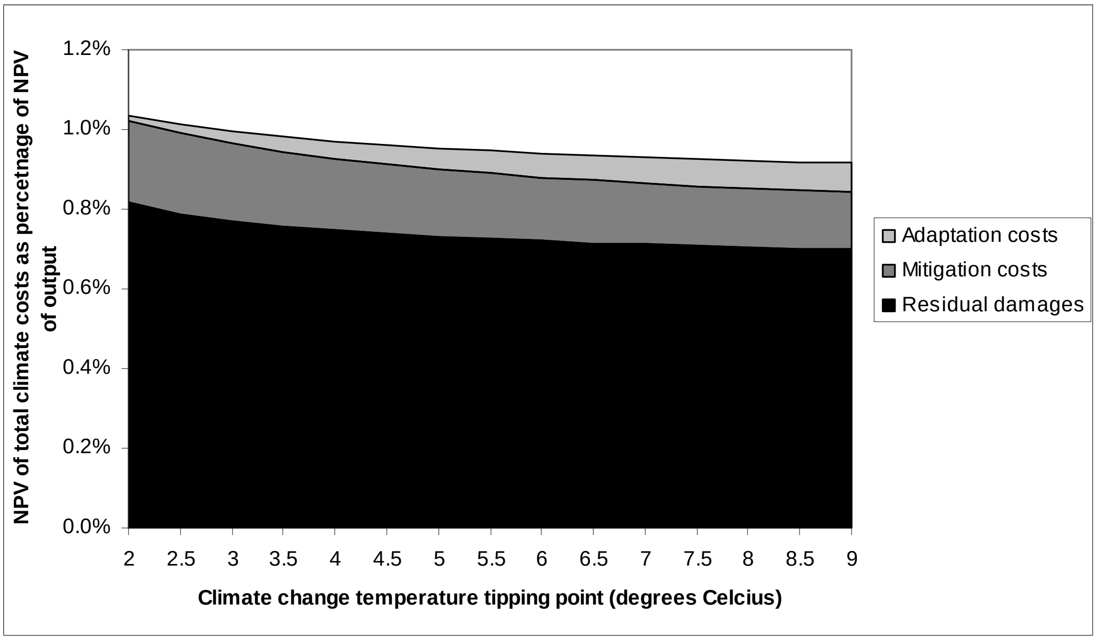

Figure 9: NPV of climate change costs components as a percentage of NPV of output with restrictions on adaptation with restrictions on adaptation due to irreversible climate change (A6)

4.3 Comparing restrictions

We now compare the effects of restrictions directly with each other in terms of welfare to get an idea which restrictions are the most harmful. As welfare losses are a more accurate indicator of the harmfulness of the restrictions than total climate costs, in figure 10 the utility index levels (where utility is normalised to 100 for the benchmark case with optimal adaptation), are plotted for the different restrictions. We look at 3 levels of restrictions for each type of restriction: a relatively weak, a medium and a strong restriction. These various restrictions are described in Table 1.

Table 1:Description of various restriction levels for each scenario

Scenario	Weak restriction[4]	Medium restriction	Strong restriction
A1	Adaptation costs upper limit is 100% of average optimal level	Adaptation costs upper limit is 75% of average optimal level	Adaptation costs upper limit is 50% of average optimal level
A2	Adaptation upper limit is 100% of average optimal level	Adaptation upper limit is 75% of average optimal level	Adaptation upper limit is 50% of average optimal level
A3	Residual damage lower limit is 100% of average optimal level	Residual damage lower limit is 75% of average optimal level	Residual damage lower limit is 50% of average optimal level
A4	Adaptation is not possible in first 30 years	Adaptation is not possible in first 60 years	Adaptation is not possible in first 90 years
A5	Adaptation cannot vary by more than 10 percent from one period to the next	Adaptation cannot vary by more than 5 percent from one period to the next	Adaptation cannot vary at all one period to the next
A6	Adaptation is ineffective after 7 degrees of climate change	Adaptation is ineffective after 5 degrees of climate change	Adaptation is ineffective after 3 degrees of climate change

Clearly, these restrictions cannot be easily compared, as they reflect very different types of restrictions, and the definition of what is "weak" and "strong" is necessarily somewhat ad-hoc. However, looking at Figure 10, we find that for some scenarios, the 'weak' restriction is already more harmful than a relatively strong restriction for another scenario. Thus, overinvestment in adaptation to limit residual damages, short term inaction in adaptation and, especially, decreasing effectiveness of adaptation due to increased temperature seem to be the most harmful restrictions. Furthermore restrictions on adaptation costs seem rather harmless compared to the other restrictions, reflecting the fact that there are many low cost adaptation options that can be employed even with a limited budget. In the case of adaptation (and this model) a little adaptation expenditure goes a long way.

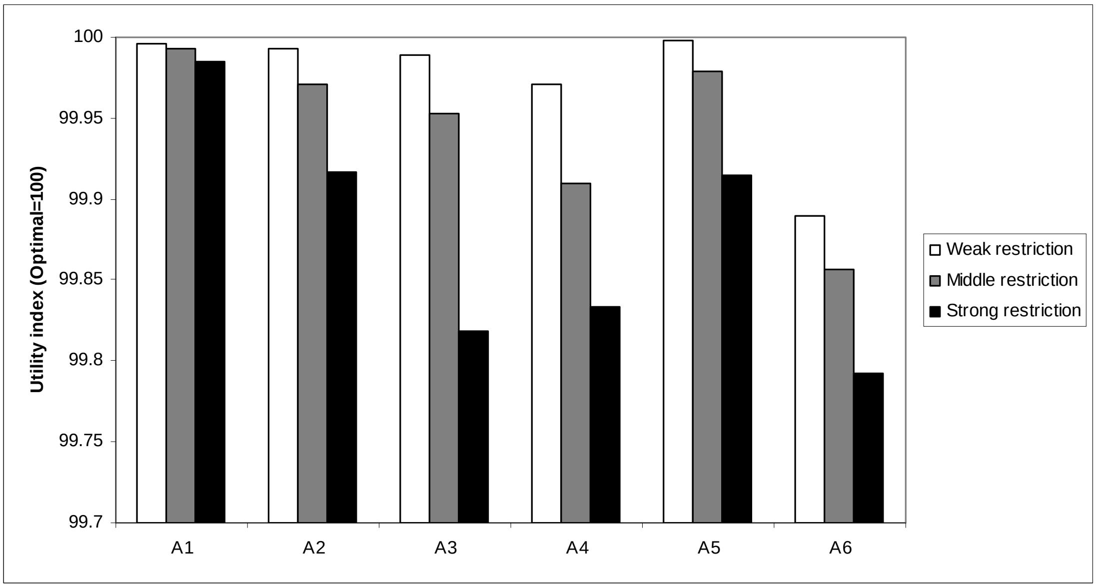

Figure 10: Utility index for various scenarios with 3 levels of restrictions: weak, middle and strong.

For weak restrictions, scenario A6 is the most harmful restriction, i.e. where adaptation becomes less effective as the temperature rises. A4 is the second most harmful restriction, where adaptation is not possible in the first 30 years. This reflects the high benefits of direct action regarding adaptation and the fact that mitigation cannot compensate for adaptation in the short term due to the time lags in the climate system. However, as the restrictions become stronger, limits on damages (A3) become more harmful compared to short term inaction (A4). An upper limit on adaptation costs (A1) on the other hand has small effects in all cases and the differences between the strictness of the restriction are small.

The effects on mitigation

The analysis in Sections 4.1 and 4.2 indicated that by changing the level of mitigation in response to limited adaptation, the increase in climate change costs can be limited. For instance, increased investments in mitigation are warranted when adaptation levels are too low, as the residual damages are larger and thus the productivity of mitigation increases.

Here, we further explore how mitigation responds to adaptation restrictions. We investigate how the optimal level of mitigation changes with different restrictions.

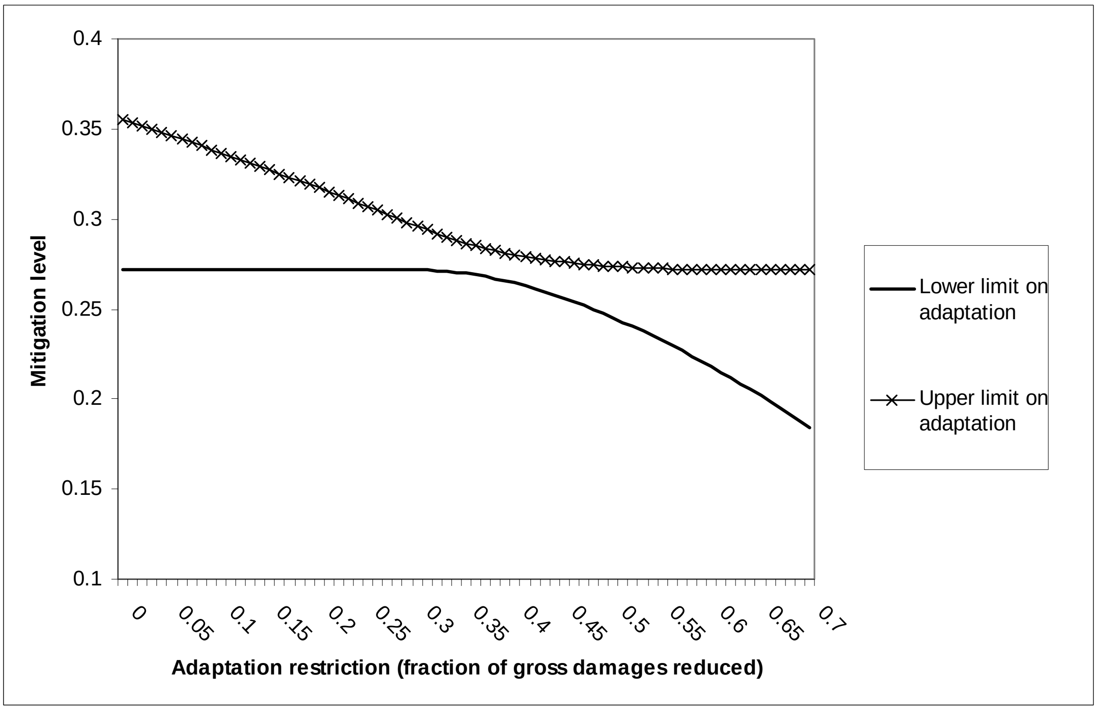

Figure 11: Mitigation level with upper and lower limits on adaptation for the year 2065

Figure 11 plots the optimal levels of mitigation in 2065 for different lower and upper limits on adaptation. In line with the observations made in Section 4.2, optimal mitigation levels are higher when adaptation is restricted below optimal and is lower when the restriction forces adaptation to be above optimal (note that the optimal level is approximately 0.22). We furthermore see that the effect of restricting adaptation on optimal mitigation seems more or less linear for the relevant range of restrictions.

We furthermore look at the path of mitigation over time with various adaptation restriction scenarios. Figure 12 shows the mitigation path when there is an upper limit on adaptation. One can see that as time passes the level of extra mitigation due to the adaptation restriction increases slightly: the mechanism is rather straightforward: restricting adaptation level further has a more or less linear positive effect on mitigation levels (at least until mitigation reaches its upper bound of 100%).

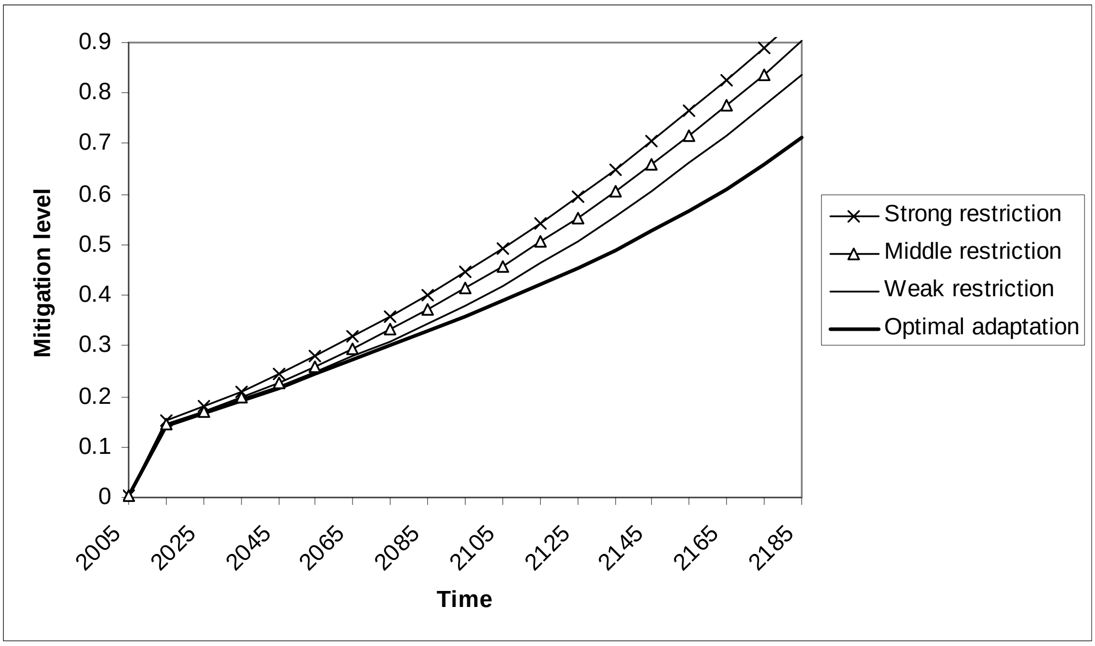

Figure 12: Optimal mitigation over time for various adaptation upper limit restrictions (scenario A2) and the optimal.

Figure 13 shows mitigation paths when residual damages have an upper limit. In the case of a weak restriction more mitigation is applied in the short term to reduce residual damages and hit the restriction at a later period. It does not pay, however, to have a permanently higher level of mitigation, as the trade-off between damages and mitigation has not substantially changed. Thus, the restriction acts as mechanism to change the optimal timing of mitigation: more early mitigation in order to postpone hitting the restriction on damages, and in later phases relying more on adaptation to cover the remaining impacts.. In the case of a medium restriction you see the same effect, but less pronounced. In the case of the strong restriction residual damages need to be restricted so much that mitigation is applied at a level above optimal over the whole horizon.

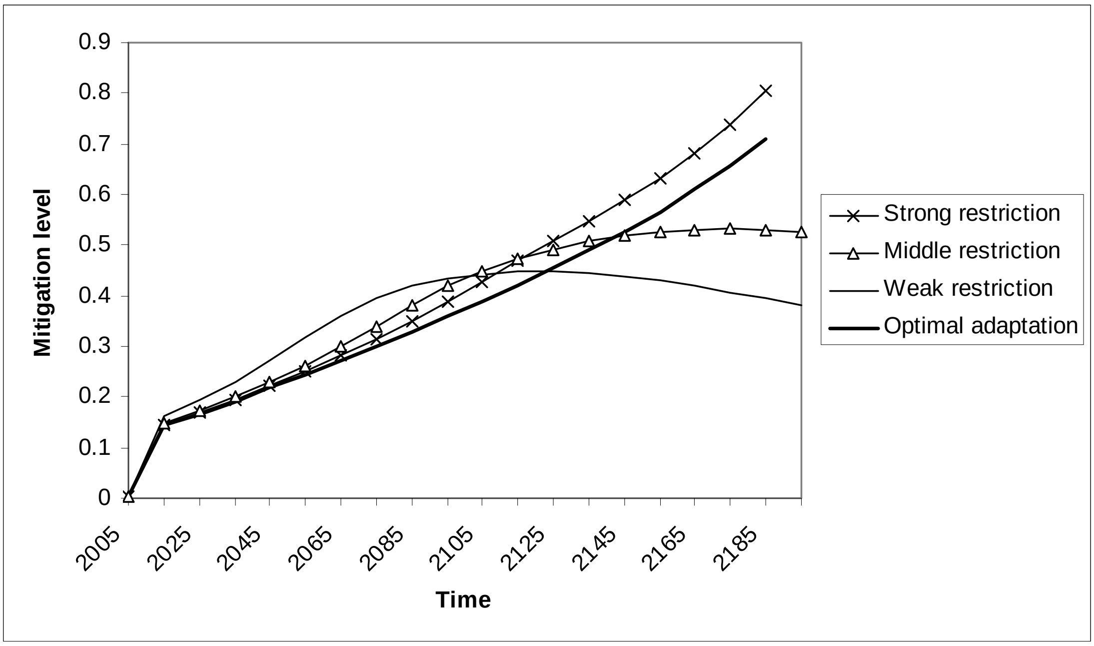

Figure 13: Optimal mitigation over time for residual damage upper limit restrictions (scenario A3) and the optimal

Figure 14 shows the optimal mitigation paths when adaptation is not possible in the short term. As can be seen in the figure, mitigation is higher in the earlier periods when the restriction applies, but the effect is temporary; and mitigation levels quickly return to their unrestricted optimal levels when adaptation becomes available.

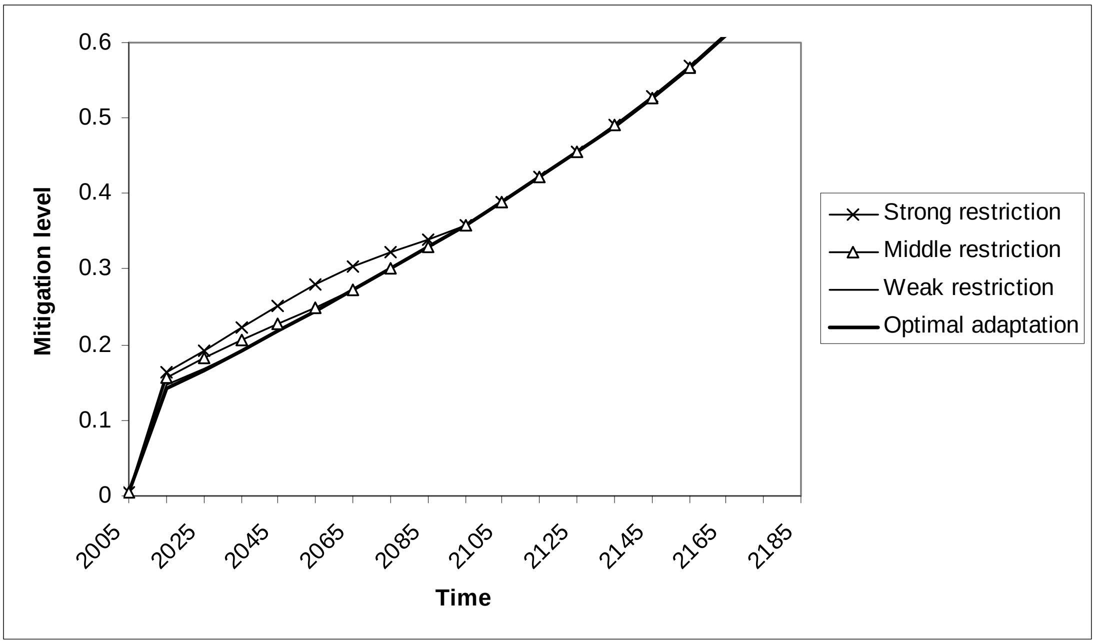

Figure 14: Optimal mitigation over time for various adaptation short term inaction restrictions (scenario A4) and the optimal.

The adaptation scenarios that affect the path of mitigation the most are those with irreversible climate change. Because adaptation becomes completely ineffective after a certain tipping point, mitigation is the primary policy instrument to keep temperature below that threshold level, even though in our simulation of this restriction adaptation is already less effective at lower levels of temperature change. This involves huge amounts of mitigation in early periods. In figure 15 we can see that mitigation reaches substantially higher levels much earlier than in the case of optimal adaptation.

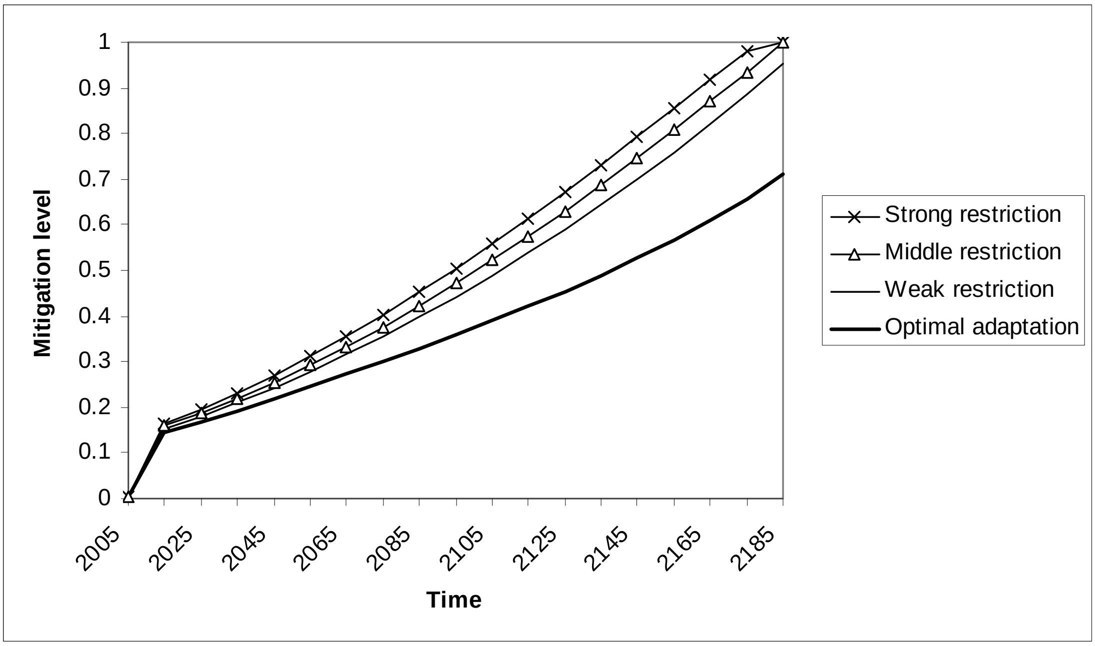

Figure 15: Optimal mitigation over time for various tipping point restrictions (scenario A6) and the optimal.

4.4 Naive versus responsive mitigation

In our analysis up to now, we have assumed that there is full information available about the restrictions of adaptation. This entails that the decision maker can adjust his level of other choice variables (consumption, investment and mitigation) to the lower level of adaptation, making the restriction less harmful. It may be the case, however, that the decision maker is not aware of these restrictions and assumes that adaptation is optimal, as commonly done when using IAMs to design policies. In this case there is no possibility to respond to the restrictions of adaptation and the levels of the other choice variables will not be adjusted to compensate for the limited adaptation. In this section we investigate what the effects are of not knowing that adaptation is limited. We focus on the choice variable mitigation as it is most likely to be formulated *ex ante* (e.g. in an international agreement) and thus naïve with respect to adaptation. Furthermore both mitigation and adaptation are used to combat climate change and can substitute each other. Thus their optimal levels are strongly linked to each other. We re-run all our previous scenarios, but now keeping the level of mitigation fixed at the level that would be optimal if adaptation was optimal.

When mitigation cannot be used to limit the effects of restricted adaptation, this leads in all scenarios to higher climate change costs than when mitigation is responsive. In Figure 16, the reduction in utility losses are given for the various scenarios (with medium level restriction) for the case responsive mitigation, relative to the utility losses for naïve mitigation case. As the strictness of the different restrictions may distort the comparison, this is most clearly illustrated by normalising the effects for the naïve case. The figure clearly shows the widely varying extent to which responsive mitigation can limit welfare costs of adaptation restrictions. The effects of responsive mitigation are greatest in the scenario A2 (upper limit on adaptation costs) and especially A1 (upper limit on adaptation). Leaving sufficient flexibility to vary either adaptation or mitigation levels may help to limit total climate costs. In some cases, however,, we see that adjusting mitigation to respond to adaptation restrictions is hardly beneficial for utility. This is the case in scenarios A3, A4, A5 and A6.In the case of A3 residual damages are limited and mitigation and adaptation can both be used to ensure this. Therefore flexibility in mitigation will have limited benefits, as there still remains flexibility in adaptation. For scenario A4, where adaptation is not possible for the first decades, responsive mitigation is virtually ineffective. This is logical, as the inertia in the climate system implies that additional early mitigation efforts will mostly affect later periods, where this restriction is no longer active

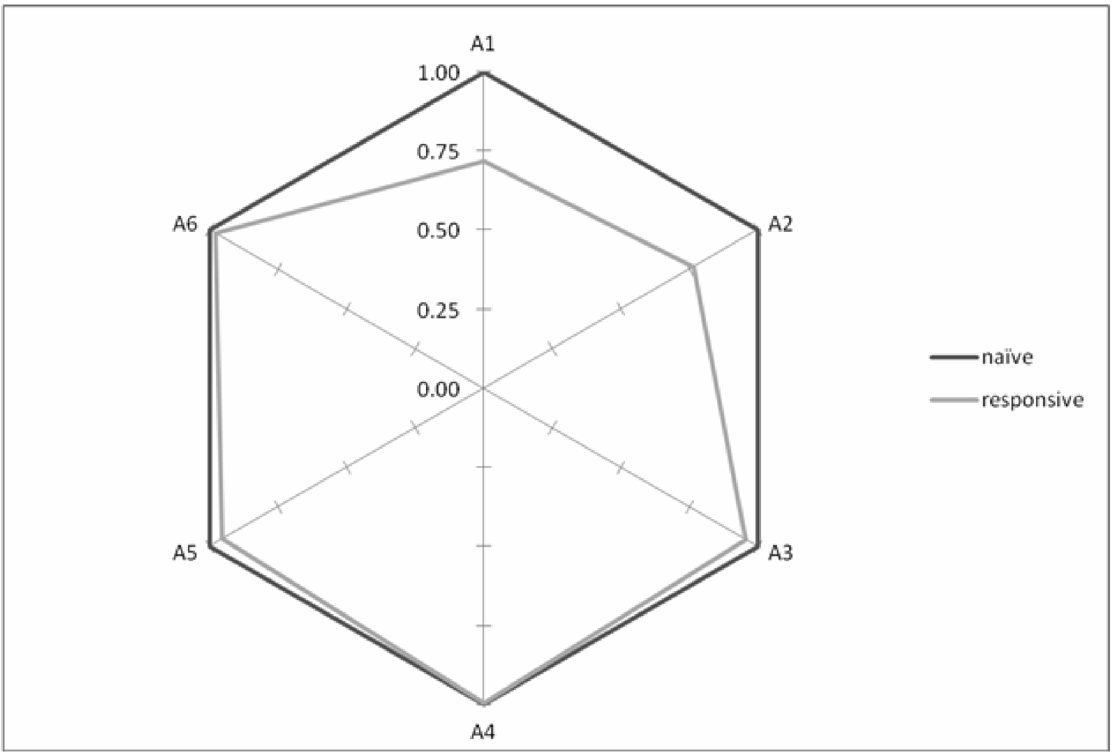

Figure 16: Utility loss index for the middle level of the restriction of the various scenarios with naive mitigation and responsive mitigation.

5 Final remarks

In this paper we look at the effects of adaptation restrictions. By adjusting our economic and social structures and activities to better fit the new climate we can substantially reduce potential damages of climate change. Virtually all economic models for climate change policy implicitly assume that optimal adaptation is possible and will be implemented. This means that all possible adaptation measures can be employed to the level at which their marginal benefits equals their marginal costs. There are many reasons to believe, however, that such “optimal” adaptation is not possible. Through lack of knowledge there may be under-investment, funds for adaptation may be limited and adaptation may not be possible at high (or extreme) levels of climate change. These are just a few examples of why adaptation may be restricted.

This paper firstly investigated how different adaptation restrictions affect the level of total climate change costs (the sum of adaptation costs, mitigation costs and residual damages). In this analysis, over-adapting to limit residual damages, short term inaction and ineffective adaptation due to irreversible climate change are most harmful. Particularly substantial over-adapting may increase total climate change costs hugely.

Secondly, this paper finds that having knowledge about the restrictions of adaptation and adjusting mitigation policies accordingly can be a means of keeping climate change costs low, but this effect should not be overestimated. When the restrictions are not taken into account when designing mitigation policies, adaptation restrictions become up to twice as harmful in terms of increased climate change costs. Integrated Assessment Models that are used to design mitigation policies nearly always assume optimal adaptation. Such an approach can be quite harmful when restrictions on adaptation are prominent, as empirical research suggests (cf. Fankhauser, 1998). This is especially the case when adaptation is restricted at higher levels of climate change and when adaptation is limited in the short term.

Thirdly, this paper finds that the mitigation paths are very different with the various restrictions. Compensating for adaptation restrictions by altering mitigation paths will therefore only be beneficial if the policymaker understands the restriction he is facing. This warrants more research in the exact adaptation capabilities.

Fourthly, from an adaptation policy perspective this paper gives insight into the effects of misspecifying adaptation costs and benefits. Uncertainties regarding adaptation are vast, and there are no clear policy levers to influence the macroeconomic level of adaptation, or even to measure an overall level of adaptation efforts and the corresponding avoided damages. Policymakers are somewhat in the dark when attempting to set adaptation policies. This paper shows the effects of these uncertainties. We see that in general reasonably sized deviations from the optimum have small effects, indicating that adaptation policies that are not optimal will most likely still be beneficial.

Fifthly, from the perspective of mitigation policy making, policy makers now often design mitigation policies based on an unwarranted assumption of optimal adaptation. Adjusting this assumption by explicitly considering suboptimal adaptation will lead to more effective mitigation policies.

There are several caveats and limitations to this study. Firstly this analysis is based on the AD-DICE model and has the same limitations as that model, and as the DICE model on which it is constructed. DICE and AD-DICE do not include certain important issues such as uncertainty and irreversibility. Moreover, the model assumes perfectly functioning markets and one aggregate impact function, rather than making a distinction between different sectors, although both damage and adaptation estimates are based on detailed sectoral studies (cf. the Annex). More detailed modelling of adaptation would also allow for a distinction between different restrictions and their exact effects. Furthermore, a single region model is used. Like sectors, different countries may have a qualitatively different response to climate change, and adaptation and adaptation restrictions may be very different. Nonetheless, de Bruin et al. (2009b) show that a global, single-sector model functions well as a first approximation of the effects that are likely to arise in a multiregional context.

It is also assumed that 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. Adaptation will however in many cases also have time-lags in costs and benefits. Examples of such measures are building seawalls and early warning systems. While such time-lags may have influence on the interactions between adaptation and mitigation, we feel it is less relevant for an investigation into the (macro-)economic effects of adaptation restrictions *per se* and leave this issue for future research.

Finally the restrictions we study are imposed exogenously and we do not model the causes of the restrictions directly, but limit ourselves to specifying scenarios for their likely impact on adaptation. To understand the full effects of certain restrictions the underlying causes for suboptimal adaptation would need to be modelled explicitly. Clearly, such an elaborate analysis would imply a major enlargement in terms of model specification and especially data requirements (for instance, it is not clear at all how a lack of information can be included consistently in the analysis). The current paper therefore provides a useful bridge between the overly simplistic models of optimal adaptation and more detailed but less general models of adaptation.

Annex: Data and calibration of adaptation costs curve in AD-DICE

In this Annex we describe the empirical foundation and calibration of the adaptation cost curve in the AD-DICE model. For a full description of the data and calibration method as applied to AD-DICE and AD-RICE see de Bruin and Dellink (forthcoming), here we only provide a summary. We use the sectoral breakdown of damages as used in the RICE model (Nordhaus and Boyer, 2000) to provide a more detailed estimation of the adaptation variables. In this calibration procedure we separate the AD-DICE2007 estimates of damages into residual damages and adaptation costs to create the AD-DICE model. To calibrate our model we assess each impact category described in the RICE model and use the relevant literature, supplemented with expert judgment where necessary, to estimate the (optimal) levels of the relevant adaptation variables (adaptation, adaptation costs, residual damages and gross damages). We thus assess each impact category, consider the main adaptation possibilities in that category and assess the related costs and benefits for each region. The RICE damage function is calibrated at the point where global atmosphere temperature has increased by 2.5 degrees compared to the 1900 level. We use the RICE sectoral breakdown but calibrated our damage function to replicate the DICE2007 damage function over the model horizon in the optimal case.

Very few empirical studies have focused on estimating the costs and benefits of adaptation. Furthermore, the few studies that do exist often focus on specific local adaptation options, because the costs and benefits of adaptation are often very location specific. Agrawala and Fankhauser (2008) give an excellent overview of the current literature available on adaptation costs and benefits. We have drawn strongly on this literature in our analysis and gathered other literature where possible.

The Nordhaus and Boyer damage function contains seven damage categories: Agriculture, Other Vulnerable Markets, Coastal, Health, Non Market Time Use, Catastrophic, and Settlements. The regional damages estimates for these seven categories are reproduced in Table A1. The empirically estimated levels of optimal adaptation (P) and the ratio of residual damages to protection costs (RD/PC) are also given in Table A1.

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. Assuming that crop production will be adjusted to the new climate, the damages are assessed. To estimate the adaptation in this sector we use regional estimates by Tan and Shibasaki (2003) and Rosenzweig and Parry (1994). Tan and Shibasaki estimate damages/benefits with and without adaptation for several world regions, but they only consider low cost adaptation measures. Rosenzweig also looks at more substantial adaptation options in developing and developed 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). To estimate the adaptation in this sector we use the FUND model (Tol 2007) which directly gives both the optimal protection level as costs and benefits of adaptation for more than 200 countries in the world. As can be seen in Table A1, the adaptation potential in this sector is high.

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. To estimate adaptation in this sector we use the study by Murray and Lopez (1996) on which Nordhaus and Boyer base their estimates. This study assumes a level of adaptation based on general improvements in health care etc. We also use data from the WHO malaria report 2008, which estimates the use of mosquito nets in various vulnerable regions.

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. Furthermore they estimate the willingness to pay to protect vulnerable ecosystems. Estimates of adaptation in this sector are based on expert judgment and Nordhaus and Boyer (2000).

The 'Other vulnerable markets' (OVM) 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. To estimate our adaptation variables in this sector we use expert judgment. We assume that dryer, hotter regions will have more trouble adapting. Furthermore, developing regions may lack the infrastructure to adapt.

'Non market time use' is a more abstract category and refers to the change in leisure activities. Due to a change in climate, people's leisure hours will be affected. In colder regions, a warmer climate will lead to extra enjoyment of outdoor leisure activities. In warmer climates, however, leisure activities will be more restricted if the amount of extremely hot days increases. Table A1 shows that most regions have benefits in this category. In this sector we rely on expert judgment to estimate the adaptation variables. Most of the impacts in this category will be adaptation costs as people will adapt their leisure activities to fit the new climate. Thus the net costs or benefits in this category are mostly changes in adaptation costs and not residual damages or benefits.

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. This does not include "minor" catastrophic events such as extreme weather events. Estimates of adaptation in this sector are based on expert judgment and Nordhaus and Boyer (2000). As the events considered in this category are large catastrophes, the potential to reduce their effects through adaptation is small.

Insert Table A1 here

Table A2 shows the resulting calibrated values of the gross damage function and adaptation cost function in AD-DICE[5], where the gross damage (GD) and adaptation cost (PC) function are as follows:

$$\frac{GD_{r,t}}{Y_{r,t}} = \alpha_{1_r} \Delta T_t + \alpha_{2_r} \Delta T_t^{\alpha_{3_r}}$$

$$\frac{PC_{r,t}}{Y_{r,t}} = \gamma_{1_r} P_{r,t}^{\gamma_{2_r}}$$

Insert Table A2 here

[5] Note that the form of the adaptation cost curve is also influenced by the form of the DICE damage function.

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SD	36.2009	Markus Kinateder (lxxxv): Team Formation in a Network
SD	37.2009	Constanza Fosco and Friederike Mengel (lxxxv): Cooperation through Imitation and Exclusion in Networks
SD	38.2009	Berno Buechel and Tim Hellmann (lxxxv): Under-connected and Over-connected Networks
SD	39.2009	Alexey Kushnir (lxxxv): Matching Markets with Signals
SD	40.2009	Alessandro Tavoni (lxxxv): Incorporating Fairness Motives into the Impulse Balance Equilibrium and Quantal Response Equilibrium Concepts: An Application to 2x2 Games
SD	41.2009	Steven J. Brams and D. Marc Kilgour (lxxxv): Kingmakers and Leaders in Coalition Formation
SD	42.2009	Dotan Persitz (lxxxv): Power in the Heterogeneous Connections Model: The Emergence of Core-Periphery Networks
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IM	57.2009	Emmanuel Farhi and Jean Tirole: Collective Moral Hazard, Maturity Mismatch and Systemic Bailouts
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