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# Distinguishing Between Proactive (Stock) and Reactive (Flow) Adaptation

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## 1 Introduction

To combat climate change in an efficient and effective way in both the short and long term, both adaptation and mitigation are needed. Adaptation is an effective option especially to combat the short run effects of climate change, whereas mitigation is needed to limit climate change to an acceptable level in the long run. Due to past emissions of greenhouse gases a certain degree of climate change will take place, independent of the stringency of mitigation policies. Therefore adaptation is needed to limit the impacts associated with climate change and is increasingly being recognised as an equal and complementary response to greenhouse gas (GHG) mitigation to address the risks posed by climate change.

Climate change involves many interrelated processes belonging to different disciplines. Human activity contributes to GHG emissions; atmospheric, oceanic and biological processes link these emissions to atmospheric concentrations of GHGs. These concentrations influence climatic and radiative processes resulting in changes in climate. These changes in climate result in biophysical and socio-economic impacts. Integrated Assessment Models (IAMs) represent the above mentioned component processes as well as associated policy responses to climate change within a formalised modelling framework. Mitigation is studied in IAMs, where the costs are weighed against the benefits (i.e. avoided climate change and thus avoided damages). In this way IAMs are an important tool for policy makers to determine mitigation policies. Whereas IAMs have studied mitigation policies extensively, policies of adaptation are not often considered.

IAMS have been developed in the past years (e.g Bosello 2004; de Bruin et al. 2009; de Bruin and Dellink forthcoming). The drawback, however, of these analyses is that adaptation is modeled either solely as a *flow* variable, where adaptation costs and benefits fall within the same period (e.g de Bruin et al. 2009; de Bruin and Dellink forthcoming) or solely as a stock variable, where adaptation cost now create a flow of benefits in the future (e.g Bosello 2004). Furthermore these analyses are based on a limited empirical estimates of costs and benefits. Adaptation can be modelled both as a flow variable (replicating the characteristics of reactive adaptation) and as a *stock* (replicating the characteristics of proactive adaptation). Reactive adaptation refers to adaptation which takes place after climate change damages have occurred or while they occur. Examples of such measures are the use of air-conditioning , the adaptation of new heat resistant crops or adjusting the planting times of crops. Anticipatory adaptation refers to adaptation measures which are taken before the climate change damages are felt and should be modelled as an adaptation stock. Such measures often involve investments beforehand which build adaptation capital or infrastructure which limit the damages associated with climate change when it occurs. Examples of such adaptation measures are the building of sea walls and early warning systems.

Assuming that all adaptation is either reactive or proactive oversimplifies the nature of adaptation. From an inter-temporal integrated assessment modelling perspective, it is important to distinguish between adaptation investments where both costs and benefits accrue in the same time period and those where initial investments offer benefits that extend beyond the time period when the costs were incurred (Lecocq and Shalizi 2007). The time lag between costs and benefits will change the optimal time profile of adaptation. Furthermore, the optimal mix of adaptation and mitigation depends crucially on the discount rate, as the cost-to-benefit time lag of mitigation is (much) larger than that of adaptation. Introducing a time-lag for a share of the adaptation benefits will affect this relationship.

Due to the increasing attention given to the financing of adaptation there is a need for a better understanding of the costs and benefits of adaptation. Local project partners are interested in the local costs and benefits whereas policymakers will particularly be interested in the costs and benefits at the aggregate level. Financing adaptation which was key to the negotiations at the Fifteenth Conference of the Parties (COP 15) to the United Nations Framework Convention on Climate Change (UNFCCC) and is a prominent element of the Copenhagen Accord. It continues to be a core element in the ongoing international negotiations on climate change. Consequently there has been considerable analytical effort in recent years in estimating the aggregate costs of adaptation (cf. Parry et al. 2009; Stern 2007; UNDP 2007; UNFCCC 2007a; WB 2009a). These estimates have a very narrow empirical base, however, and/or are generally static, whereas the estimates in this paper are based on extensive empirical literature and are dynamic. Furthermore, estimates can be made of the optimal stock and flow adaptation paths.

The objective of this paper is twofold. The first objective is to distinguish between both forms of adaptation and create an IAM (AD-DICE09) with this differentiation implemented, accomplishing a more detailed representation of adaptation in an IAM framework. Secondly, distinguishing between stock and flow adaptation can answer some important questions concerning adaptation and its interactions with mitigation. The second objective is to examine the following questions; how much capital is needed to adapt? What are the optimal mixes of stock adaptation, flow adaptation and mitigation over time? What interactions are there between stock and flow adaptation and mitigation? How can stock and flow adaptation compensate for suboptimal mitigation and vice versa? Finally how do the chosen discount rate and other important parameters affect the choice between the two forms of adaptation and mitigation?

This paper is structured into six sections. The second section describes the characteristics of stock adaptation and flow adaptation in more detail. The third section develops a framework that combines the stock and flow approaches to adaptation and calibrates a new gross damage function, the optimal adaptation level and the costs and benefits of different forms of adaptation. The fourth section presents the results of the simulations with the AD-DICE09 model. In the fifth section a sensitivity analysis is presented and the final section concludes.

## 2 Stock and Flow Adaptation

To reduce climate change damages different forms of adaptation can be applied. These forms of adaptation differ in various ways, and hence alternative classifications of adaptation are possible. Adaptation can be categorised based on many criteria, e.g. who adapts (*public* vs. *private*), when adaptation occurs (*anticipatory (proactive)* vs. *reactive*), how it occurs (*autonomous* vs. *planned*) etc. (Smit

1993; Smit et al. 2000; UNFCCC 2007a). From an economic modelling perspective we make a distinction between adaptation based on the time lag between the costs and benefits of applying adaptation. In other words: if one invests in adaptation now and instantaneously incurs costs for that, when will the benefits be reaped of this investment?

Flow adaptation has the characteristic that adaptation costs and benefits fall within the same period. Furthermore, benefits are only felt for one period. For example as the climate gets warmer, farmers may choose to plant new heat resistant crops. The farmer will incur the costs of the new crops and reap the benefits in the same period, which in most IAMs consist of 5 or 10 years. This form of adaptation generally falls within the category of *reactive adaptation*, which refers to adaptation done in reaction to actual climate change stimuli. Flow adaptation is also often *autonomous* (applied automatically) and *private* (applied by individuals). As we assume flow adaptation is synonymous to reactive adaptation, in this paper we will use the former term.

Stock adaptation is characterised by a build-up of stock through investments, similar to the build-up of ordinary capital goods (effectively, the adaptation stock is just a special type of capital stock). In this case the costs of adaptation are borne before the benefits (by at least one period). The benefits are, however, reaped for as long as the stock is in place, i.e. for more than one period. The stock of adaptation is increased by investments in adaptation stock and decreases every period due to depreciation. Due to the timeframe involved, stock adaptation mostly falls within the category of *proactive adaptation*. Proactive adaptation refers to adaptation strategies which are undertaken in anticipation of climate change. Proactive adaptation is *planned* and generally *public*. For example, sea walls should be put in place by governments before sea level rise becomes threatening.

Both forms of adaptation reduce the residual damages of climate change and can be used to combat climate change. For example, in agriculture to deal with the decreased amount of water available, one can build irrigation infrastructure to ensure there is enough water for the crops. In this case investments are made in a capital good which will create a stream of benefits over the periods to come. However, one can also change the planting dates or crop types to decrease the amount of water needed. This is a flow form of adaptation. There are some damages that can be reduced much more effectively with either stock or flow adaptation. For example it is hard to think of a flow substitute to a seawall.

Thus stock and flow adaptation can substitute each other to a certain degree, but are definitely not perfect substitutes.

## 3 Data and Calibration

To be able to formulate optimal policies regarding adaptation and mitigation within an integrated assessment framework, the impacts[1] of climate change need to be assessed and monetarised, i.e. given a monetary value. In this manner the benefits of policies, namely avoided climate change damage can be compared with the costs. Many different forms of impacts may occur making the process of assessing these damages difficult. There have, however, been several attempts to do so, where a direct relationship between temperature change and impacts as a fraction of GDP is estimated. The most notable of these impact assessments are that of Nordhaus in the DICE/RICE model (Nordhaus 2008; Nordhaus and Boyer 2000), that of Tol in the FUND model (Tol 2005; Tol et al. 1998), that of Hope in the PAGE model (Hope 2003) and that of Mendelsohn and Neumann (1999). Many other models, such as MERGE and WITCH, incorporate an impact function based on that of DICE/RICE.

To assess the climate change impacts in a comprehensive manner, they are furthermore, often divided into different categories. The impacts are then estimated per category and aggregated. These estimates are often based on regional studies that are extrapolated to the whole globe. Adaptation options are often region specific, which brings into question whether such extrapolations are credible. A thorough bottom-up analysis would lead to a better representation of real world adaptation option and climate change damages. Such an analysis is, however, not yet possible due to a lack of data.

In the appendix we describe our calibration procedure where we separate the DICE and RICE damages into residual damages and stock adaptation costs and flow adaptation costs. To calibrate our model we assess each impact sector described in the DICE/RICE models. We first describe each sector that is used by Nordhaus and Boyer (2000) and how impacts are estimated in this category, we then identify relevant literature or where necessary use expert judgment to estimate the levels of the adaptation variables. As the damages from climate change in DICE represent the global aggregate of the regions in the RICE model,

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[1] Impacts can be both positive and negative. Because in most cases impacts are negative, we also refer to them as damages.

we need to first estimate the regional adaptation costs and benefits and then aggregate these. As will be described in more detail in the next section; the net damages of Nordhaus and Boyer consist of residual damages, stock adaptation costs and flow adaptation costs. Besides estimating these variables we need to estimate the levels of gross damages, i.e. damages before adaptation. We do this by estimating the effectiveness of the different forms of adaptation, i.e. which fraction of the gross damages can be reduced through adaptation in each impact sector. To simplify our estimation we use an intuitive indicator of adaptation, namely $P_t$. The adaptation level ($P_t$) indicates the ratio of gross damages that are avoided as a result of the adaptation measure. The adaptation level is expressed on a 0-1 scale, with 1 implying that 100% of the gross damages were avoided. Estimating the optimal level of adaptation will allow us to understand what the damage would be if adaptation did not take place and what the benefits of adaptation are.

Very few empirical estimates exist on the costs and benefits of adaptation. This is because the costs and benefits of adaptation are often very location specific. Several studies have been carried out on the aggregate costs of adaptation (cf. Oxfam 2007; Stern 2007; UNDP 2007; UNFCCC 2007b; WB 2009b). A major advantage of adaptation cost curves presented here over these adaptation cost estimates is that they can provide a dynamic profile of adaptation costs. This is important, as projections of damages, adaptation and mitigation are expected to increase substantially over time. Furthermore, in AD-DICE the costs are mapped onto the benefits that might result from investing in adaptation. The other recent estimates generally do not quantify the benefits. The estimates presented here, however, should still be interpreted with caution. Due to the large uncertainty involved in the estimation of climate change and its effects estimating exact numbers for adaptation costs remains difficult.

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. We then assess the various variables: gross damages, residual damages, flow adaptation costs, stock adaptation costs, optimal flow adaptation and optimal stock adaptation. The DICE/RICE damage function is calibrated at the point where temperature has increased by 2.5 degrees compared to the 1900 level. We calibrate our damage function to replicate the Nordhaus and Boyer damage function over the whole model horizons of DICE and RICE, in the optimal scenario. We

| **Net damages (N&B)** *(% of output)* | **Optimal flow adapt.** *(fraction)* | **Optimal stock adapt.** *(fraction)* | **Flow adapt. costs** *(% of output)* | **Stock adapt. costs** *(% of output)* | **Residual damages** *(% of output)* | **Gross damages** *(% of output)* |
|---|---|---|---|---|---|---|
| 1.5 | 0.27 | 0.19 | 0.17 | 0.21 | 1.21 | 2.25 |

Table 1: Global adaptation estimates derived from an aggregation of the RICE regions

Source: own calculations based on Nordhaus and Boyer (2000)

present the damage weighted totals of the adaptation variables in Table 1 for all regions, derived from the data assessment given in the appendix. Furthermore the global aggregates are presented based on the damage (in $ terms) weighted average of all the regions. These global estimates are then used in Section 4 to calibrate the parameters of AD-DICE09 model.

| **Equation 2** | | | **Equation 4** | | | | **Equation 5** |
|---|---|---|---|---|---|---|---|
| $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\rho$ | $\delta_k$ |
| 0.003 | 0.0007 | 3.62 | 68 | 0.46 | 0.71 | 0.5 | 0.1 |

Table 2: Calibrated parameter values

| **Adaptation cost ratio** ($PC/RD$) | | **Adaptation level** ($P$) | | **Net damages** ($RD + PC$) | |
|---|---|---|---|---|---|
| estimated | calibrated | estimated | calibrated | DICE | calibrated |
| 0.32 | 0.32 | 0.49 | 0.48 | 1.78% | 1.78% |

Table 3: Calibration fit of AD-DICE09: data estimates compared with calibrated values at calibration point

## 4 Stock and Flow Modelling Framework (AD-DICE09)

In this section an IAM framework including both stock and flow adaptation is presented. We use the DICE model but substitute the original damage function with a series of equations describing the costs and benefits of both stock ($SAD$) and flow ($FAD$) adaptation. Then our empirical estimates are used to calibrate the parameters of these equations and create the AD-DICE09 model.

In DICE net climate change damages are represented by a quadratic function as follows:

$$D_t = a_1 \cdot TATM_t + a_2 \cdot TATM_t^2, \tag{1}$$

where the subscript $j$ represents the region and the subscript $t$ the time period , which is defined as 10 years. $a_1$ and $a_2$ are regional damage coefficients and $TATM_t$ is the degrees of climate change compared to 1900 levels. Note that in more recent versions of the DICE model (DICE2007) $a_1$ is set at 0. This damage function represents the net damages when assuming optimal adaptation. The damages are given as a fraction of GDP, and we assume that all damage-related variables we introduce ($RD_t$ ,$PC_t$, $GD_t$, $FAD_t$, $SAD_t$, $IA_t$) are also given as a fraction of GDP.

We define a new approach which consists of six equations. Firstly the gross damages are defined as follows:

$$GD_t = \alpha_1 \cdot TATM_t + \alpha_2 \cdot TATM_t^{\alpha_3}. \tag{2}$$

This is the most commonly used form for damage costs of climate change in IAMS, where $\alpha_3$ generally takes a value between 1 and 3 (Tol et al. 1998). This is a generalised version of equation (1), where $\alpha_3$ is not assumed to be 2 as in the RICE/DICE model, but is left to be determined through calibration. These are the damages that occur if no adaptation takes place, and are thus higher than the net damages. These damages can be reduced through the use of adaptation. We assume the following relationship:[2]

$$RD_t = \frac{GD_t}{1 + PT_t}, \tag{3}$$

where $PT_t$ is the total level of adaptation measures (stock and flow) and $RD_t$ are the residual damages. Note that $PT_t$ differs from the level of adaptation $P_t$, which represents the fraction of gross damages reduced as introduced in the previous section and appendix. The functional form of equation (3) is chosen because it limits the fraction by which the gross damages can be reduced to the interval of 0 to 1. When total adaptation reaches infinity, all gross damages are reduced (the residual damages are zero) and when no adaptation is undertaken no gross damages are reduced (residual damages equal gross damages). This functional form also ensures decreasing marginal benefits of adaptation, that is the more adaptation is used the less effective additional adaptation will be. This

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[2] de Bruin et al. 2009 provides some insight into the implications of this functional form, contrasts it with a specification of $RD_t = GD_t \cdot (1 - P_t)$, and finds that the differences are limited.

is assumed as more cost effective measures of adaptation will be applied first whereas less cost effective measures will be applied after that.

We now define how the two forms of adaptation (stock and flow) together create the total level of adaptation measures. The two forms of adaptation are aggregated together using a Constant Elasticity of Substitution (CES) function. Here the elasticity of substitution can be chosen to reflect the observed relationship between the both forms of adaptation. We assume that both forms are imperfect substitutes for each other and estimate that $\rho = 0.5$ [3]. The total level of adaptation options is then given by:

$$PT_t = \beta_1 \cdot \left(\beta_2 \cdot SAD_t^{\rho} + (1-\beta_2) \cdot FAD_t^{\rho}\right)^{\beta_3/\rho}, \tag{4}$$

where $SAD_t$ is the total amount of adaptation capital stock. $FAD_t$ is the amount spent on flow adaptation in that period. Furthermore $\rho = \frac{\sigma - 1}{\sigma}$, where $\sigma$is the (constant) elasticity of substitution. Adaptation capital stock is built up as follows:

$$SAD_{t+1} = (1-\delta_k) SAD_t + IAD_t \tag{5}$$

where $\delta_k$ is the depreciation rate and $IAD_t$ are the investments in adaptation stock ($SAD_t$). For the depreciaton rate of capital the same value is chosen as for capital in the DICE model. The total adaptation costs in each period are thus:

$$PC_t = FAD_t + IAD_t. \tag{6}$$

As mentioned before the net damages given by equation (1) represent the optimal mix of residual damages and adaptation costs. Therefore, combining equations (3) and (6) with the calibration equation that the sum of residual damages and adaptation costs need to equal the original damages from the DICE model, we have:

$$D_t = RD_t^* + PC_t^* = \frac{GD_t^*}{1 + PT_t^*} + FAD_t^* + IAD_t^*. \tag{7}$$

where the asterisks indicate that these are the optimal levels of these variables. In this framework of climate change damages there are two choice variables

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[3] This value is chosen based on aggregated estimates of both the substitution between stock and flow in each impact sector as well as the substitution between impacts sector.

namely investments in stock adaptation ($IAD_t$) and expenditures on flow adaptation ($FAD_t$). The choice of these two variables in turn determine the levels of $PT_t$, $RD_t$, $SAD_t$.

The calibrated values of the parameters of the gross damage equation (3), the total protection equation (4) and the adaptation capital stock equation (3) are given in Table 2. In Table 3, we assess the calibration fit of the AD-DICE09 concerning both the replication of the original DICE damages and the replication of the empirical estimates described in the appendix and summarised in otal protection equation (4) and the adaptation capital stock equation (3) are given in Table 6. The calibrated ratio of residual damages to adaptation costs and the level of adaptation with the estimated values based on the literature review are both given as well as the AD-DICE09 net damages and the original DICE net damages.

## 5 Results

To understand the effects of adaptation and mitigation policies we define six reference scenarios for AD-DICE09: no controls, optimal controls, no adaptation and no mitigation, no flow adaptation, no stock adaptation. In the no controls scenario, adaptation and mitigation levels are set at zero.[4] This is the case where no climate change policies are undertaken and business as usual is assumed. In the optimal controls scenario, both adaptation and mitigation levels are determined endogenously within the model to maximise social welfare (utility), i.e. for both variables optimal levels are chosen. In the no adaptation scenario, mitigation is at its optimal level while the adaptation level is zero. In the no mitigation scenario, adaptation is at its optimal level while the mitigation level is zero. In the no flow adaptation scenario, mitigation and stock adaptation are at their optimal levels while flow adaptation levels are zero. In the no stock adaptation scenario, mitigation and flow adaptation are at their optimal levels while investments in stock adaptation are not made. When one of the climate change controls (mitigation, stock adaptation and flow adaptation) is not applied, this can be compensated by an increase in the other controls. We use the AD-DICE09 model to firstly investigate the composition of climate change costs (consisting

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

of adaptation costs, mitigation costs and residual damages) in the different reference scenarios. Secondly, adaptation costs and benefits are studied. Finally the effects of the discount rate, damage level and depreciation rate are investigated in a sensitivity analysis.

## 5.1 Composition of Climate Change Costs

Our AD-DICE09 model results can be used to investigate the composition of climate change costs. Total climate change costs consists of mitigation costs, flow adaptation costs, stock adaptation costs and residual damages. Applying the reference scenarios we can get a better understanding how mitigation and the different forms of adaptation interact with each other and affect total climate change costs.

Figure 1 illustrates the effects of different policies in terms of the NPV of climate change costs as a percentage of the NPV of GDP. When comparing the no controls scenario and the optimal control scenario it is clear that adaptation and mitigation can severely decrease the costs associated with climate change. Furthermore, the climate change costs in all scenarios mostly consist of residual damages. The optimal controls scenario logically results in the lowest climate change costs. The other reference scenarios can be ranked from the lowest associated climate change costs to the highest as follows; no flow adaptation, no stock adaptation, no adaptation, no mitigation scenario and no controls scenario. According to the results of this model it is best to apply both adaptation and mitigation. However, if only adaptation or mitigation can be applied, only mitigation results in lower climate change costs. In NPV terms, aggregated over the entire model horizon, and given the discount rate, mitigation is thus more effective than adaptation in combating climate change in this specification. Naturally, a lower chosen discount rate will increase the role that mitigation plays compared to adaptation, and a higher discount rate will have the opposite effect.

Furthermore, only applying stock adaptation results in lower climate change costs than only applying flow adaptation, suggesting that over the model horizon stock adaptation plays a more important role in damage reduction than flow adaptation. This result is driven by the data assessment described in the appendix, where especially sea level rise damages can be combated (cost) effectively by stock adaptation (such as seawalls).

When comparing the optimal controls scenario with the no mitigation scenario (thus studying the effect of taking away the option of mitigation) we see that the share of stock adaptation increases more than that of flow adaptation to compensate the lack of mitigation. When mitigation is limited, stock adaptation serves as a better substitute for mitigation than flow adaptation. Adaptation strategies have a shorter delay between their costs and benefits than mitigation and have shorter lived benefits. Flow adaptation even has no delay at all and no benefits beyond the period in which it is applied. Stock adaptation, however, does have a delay between its costs and benefits and has a stream of benefits over time. The time profile of the costs and benefits of stock adaptation therefore resemble that of mitigation more compared to flow adaptation and stock adaptation is a better substitute for mitigation.

When one form of adaptation is limited, the other form of adaptation acts as a better substitute than mitigation, i.e. the other form of adaptation increases relatively more than mitigation. This is because the time lag between the costs and benefits of stock and flow adaptation are closer than that of mitigation. Though mitigation and stock adaptation both involve the build-up of a stock with a stream of benefits, the benefit stream of stock adaptation starts after one period whereas the bulk of mitigation benefits only after several periods. Flow adaptation has direct benefits and therefore it more closely represents the characteristics of stock adaptation than mitigation does.

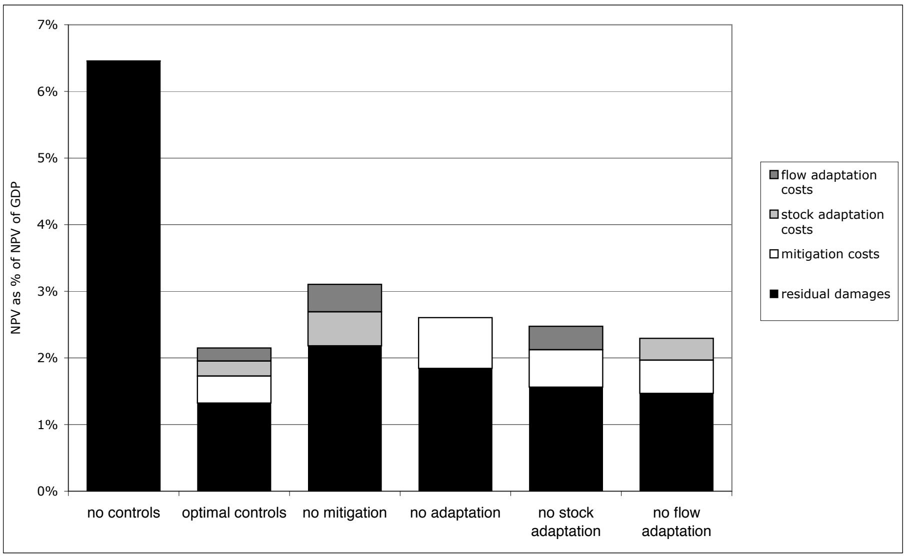

Figure 1: Composition of climate change costs in NPV as percentage of NPV of GDP over the next two centuries

Figure 2 shows the total climate change costs for the reference scenarios over time. When comparing the no controls scenario and the optimal control scenario it can be seen that adaptation and mitigation have an increasingly important effect over time. Furthermore, adaptation and mitigation affect the time profile of climate change costs in different ways. On the one hand applying mitigation (as can be seen in the no adaptation scenario) decreases costs specifically in the longer run and slightly increasing costs in the first periods. On the other hand adaptation decreases costs more in the earlier periods, and less in later periods compared to mitigation.

When both controls are applied (in the optimal scenario) climate change costs are spread more evenly over time. Moreover when mitigation and either stock or flow adaptation are available, the climate change costs are spread over time largely in the same manner as in the optimal scenario. That is to say using mitigation as a long term control and either form of adaptation as a short term control will spread the climate change costs in the same manner as in the optimum. This reflects that both forms of adaptation are good substitutes for each other. Thus, the differences between adaptation and mitigation are so large that even when adaptation is modeled as a stock, it much more closely represents flow adaptation than mitigation. Furthermore, it can tentatively be concluded that in this setting though representing adaptation both as a stock and flow variable is a better reflection of the real world, the results concerning the climate change costs over time will generally not be greatly affected by this further specification.

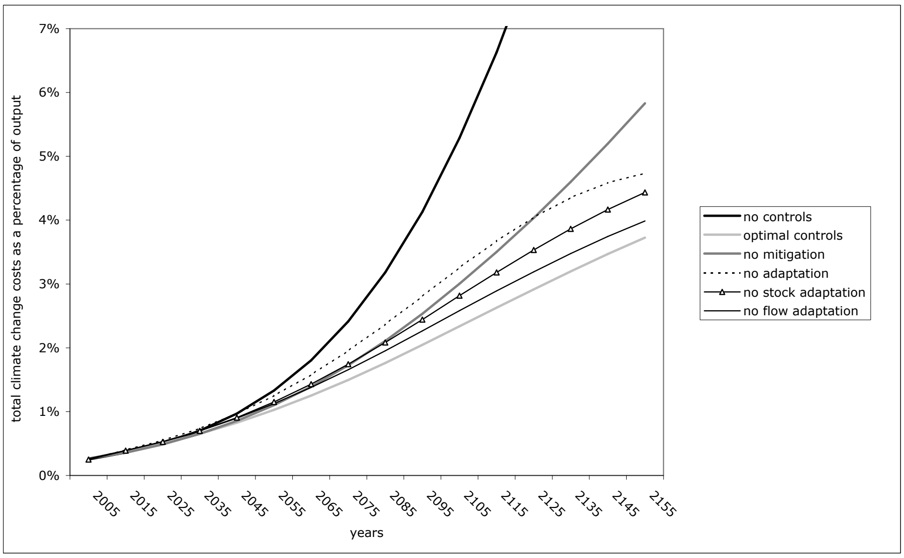

Figure 2: Total climate change costs over time for the reference scenarios

## 5.2 Adaptation Costs and Benefits

Using the same set of stylised scenarios we can plot adaptation costs as a function of the level of adaptation. The level of adaptation, expressed as a fraction of gross damages reduced, can be interpreted as the benefits of adaptation. The benefits and costs of both stock and flow adaptation are given, where the costs are expressed in percentage of GDP. The adaptation cost curves can give an indication of the relation between adaptation costs and benefits in each scenario run. The resulting adaptation cost curves for each reference scenario are given in Figure 3. These cost curves represent the adaptation costs associated with a specific level of adaptation in the scenarios, i.e. the adaptation costs are given over adaptation levels and not time.

The optimal scenario results in the lowest lying adaptation cost curve. In the optimal scenario both forms of adaptation are applied at their optimal level without having to compensate for sub optimal levels of mitigation. When mitigation is not possible, adaptation compensates resulting in a quicker build up of adaptation capital than would otherwise be optimal. This increases the costs of adaptation relatively more than the benefits. Note that at low levels of adaptation (and thus in earlier periods) the difference between the optimal and no mitigation adaptation cost curve is small as restricting mitigation will predominately have effects in the longer run.

As it is most cost effective to apply both forms of adaptation, when one form is not applied adaptation costs will increase for each level of adaptation. The CES function describes in section 4, will then only have one possible input, decreasing the level of total adaptation measures associated with adaptation costs. In our framework stock adaptation plays a greater role in decreasing damages of climate change, resulting in a higher adaptation cost curve without stock adaptation compared to the adaptation cost curve without flow adaptation.

The net benefits of adaptation are high. The NPV of the costs of adaptation in the no mitigation scenario are 0.9% of the NPV of world GDP. The benefits of adaptation (calculated as difference in between the gross and residual damages) are 4.3% of the NPV of world GDP. Therefore, the net benefits of adaptation are 3.4% of the NPV of world GDP and the benefit-cost ratio of adaptation in the no mitigation scenario is around 4.6. Thus adaptation is highly cost-effective. The benefit-cost ratio of adaptation when mitigation is also applied is lower at a level of 1.2. Adaptation is thus more beneficial when mitigation is not used in

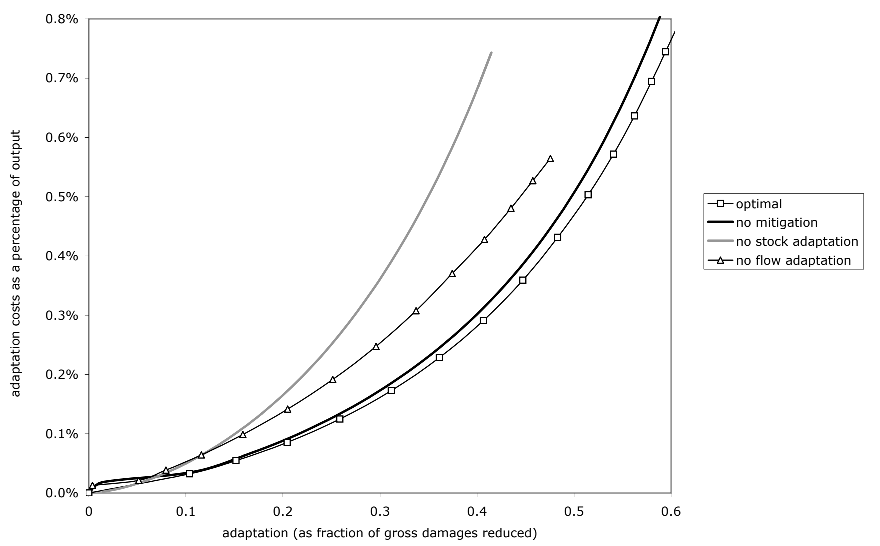

Figure 3: Adaptation costs curves in the reference scenarios over the next two centuries[a]

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[a] All curves do not span the whole range of adaptation levels, as the curves can only be drawn for adaptation levels applied in the corresponding scenario.

NPV terms, whereas in Figure 3 we saw that for a given level of adaptation expenditures the adaptation benefits are lower in terms of fraction of gross damages reduced when mitigation is not applied. When mitigation is not applied the same amount of adaptation reduces a lower fraction of a much higher level of gross damages.

Figure 4 examines the relative importance and evolution of stock and flow adaptation costs in the optimal scenario. Note that adaptation, and especially stock adaptation, starts immediately, even if at low levels. The total adaptation costs build up slowly in the first few decades of this century but rise as climate damages increase in the latter half of the century. In the year 2100, the total adaptation costs compose 0.8% of world GDP in the AD-DICE09 model. At the end of the 22nd century both adaptation costs decrease, however, the decline of stock adaptation is before that of flow. Stock adaptation needs at least one period to build up and the benefits are felt for several periods, hence stock adaptation costs decline before flow.

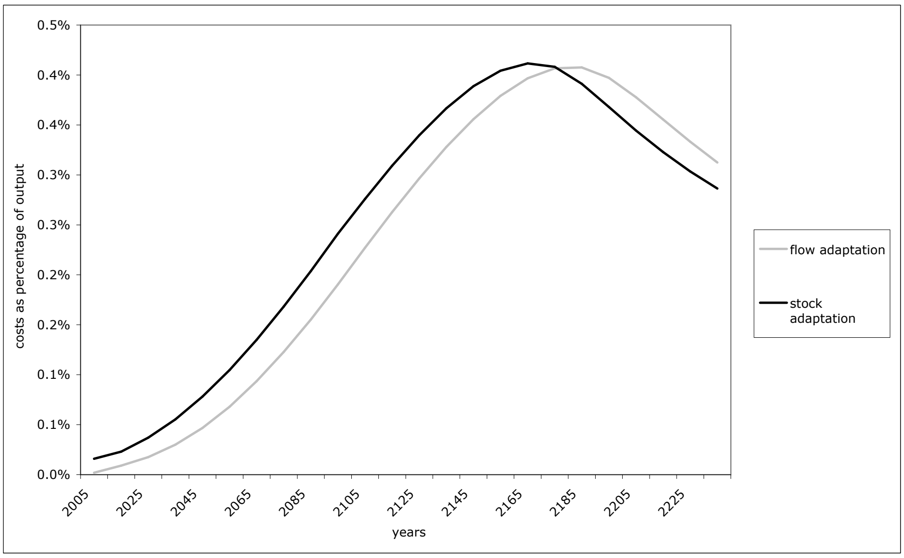

Figure 4: Stock and flow adaptation costs over time in the optimal scenario

# 6 Sensitivity Analysis

To understand the robustness of our results and to what degree they depend on certain parameter values, a sensitivity analysis is conducted here. The discount rate, damage level and depreciation rate are discussed.

## 6.1 Discount Rate

One of the most debated issues in the economic analysis of climate change is the choice of discount rate (Weitzman 2001). The results and policy suggestions of IAMS are highly dependent on the discount rate. On the one hand e.g. the Stern review has a relatively low discount rate, weighing future generations virtually equal to our generation and this suggests immediate stringent climate policies. Nordhaus on the other hand assumes a relatively high discount rate in his DICE model reflecting consumer time preference and suggests less stringent near-term policies. As a lower discount rate is chosen, increasing importance is put on future generations, i.e. those who feel the benefits of mitigation. Mitigation will thus be increased as a lower discount rate is chosen. The discount rate will also affect the levels of adaptation, as a lower discount rate is chosen adaptation will decrease and mitigation increase. Furthermore, the relative importance of stock adaptation with respect to flow adaptation will increase as the discount rate decreases. This is because the benefits of stock adaptation are also reaped

| Method | $\mu$ = elasticity of marginal utility of consumption | $\rho$ =pure rate of time preference |
|---|---|---|
| AD-DICE | 2 | 1.5 |
| UK Treasury | 1 | 1.5 |
| Stern | 1 | 0.1 |

Table 4: The parameter values assumed in the different discounting methods

with a delay, thus a lower discount rate will result in higher benefits in NPV terms.

To test the effect of the discount rate assumptions we run our model using different discount rate specifications. We have chosen to use two alternative discount rates, that suggested by the UK treasury and that applied in the Stern Review. We have chosen these because the Stern Review has an opposing view to DICE, namely a low discount rate. The UK Green treasury is an intermediate rate suggested by the UK treasury for the costs-benefit analysis of climate change investments.

The discount rates are based on the Ramsey equation (Ramsey 1928). This equation states that the discount rate is equal to $\rho + \mu g$, where $\rho$ is the rate of pure time preference, $\mu$ represents the negative of the elasticity of marginal utility with respect to consumption per capita, and $g$ the per capita growth rate of consumption. The first term $\rho$ in the Ramsey equation reflects the discount rate that would apply if future generations had the same wealth as the current generation. The second term $\mu g$ is the wealth-based component and reflects the assumption that one extra dollar is worth more to a person with a low income than to a person with a high income. The different assumptions on these parameters for the different discounting methods are given in Table 4. Note that because DICE endogenously estimates economic growth, the assumptions about that are not changed within the model.

Figure 5 shows the composition of total climate change costs for the three different discount rates Figure 5 shows that as a lower discount rate is chosen, the share of mitigation costs increase and the share of residual damages and adaptation costs decrease. Furthermore, stock adaptation costs decrease by much less than flow adaptation costs because the benefit of stock adaptation (which lies in the future) is valued more with a lower discount rate.

The choice of discount rate has an interesting effect on the optimal paths and relative importance of stock and flow adaptation. Figure 6 shows the op-

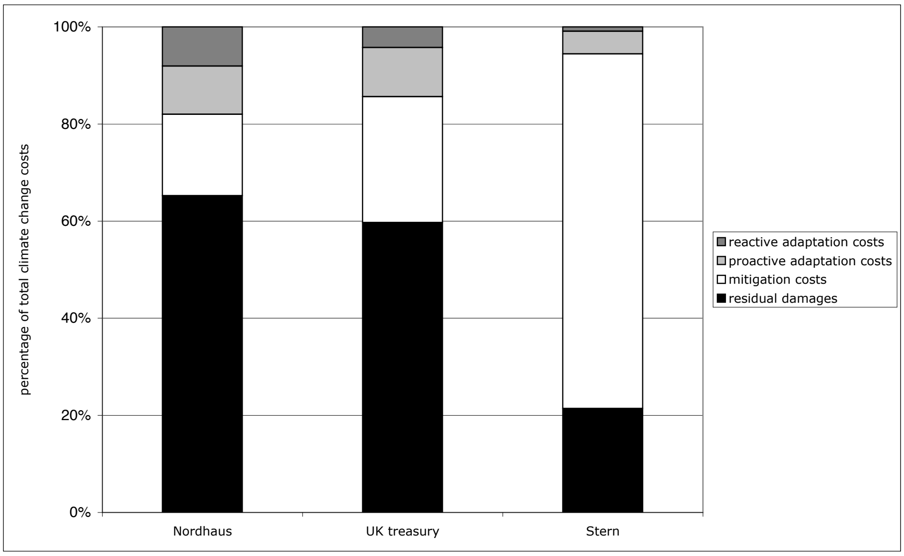

Figure 5: Composition of climate change costs in percentage (calculated based on NPV divided by NPV of GDP) for the Stern, UK Treasury and Nordhaus discount rates

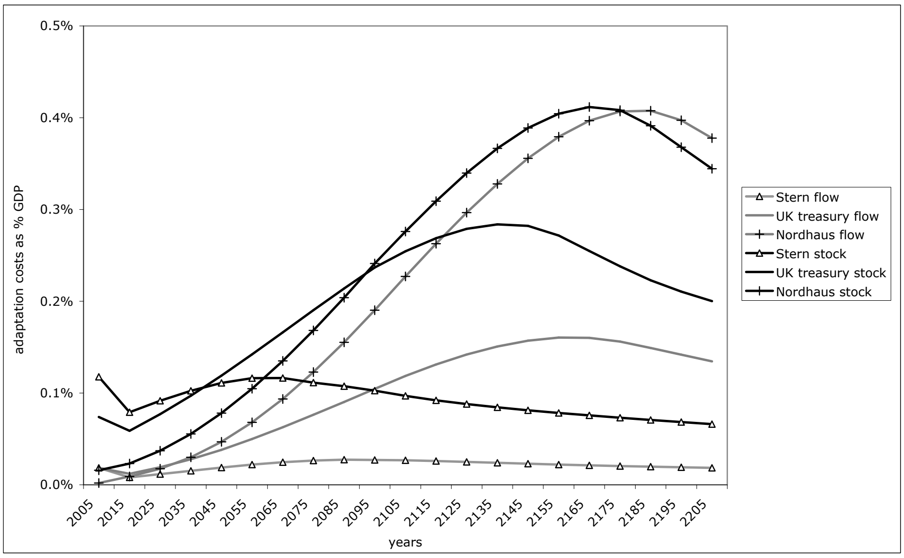

Figure 6: Optimal stock and flow adaptation cost paths for the Stern, UK Treasury and Nordhaus discount rates

timal paths of stock and flow adaptation costs over the next centuries; several observations can be made. Firstly, as a lower discount rate is chosen, the benefits of mitigation increase and therefore also the level of mitigation, decreasing both stock and flow adaptation costs. This is the case in later periods when mitigation plays an important role and mitigation substitutes adaptation.

Secondly, as a lower discount rate is applied flow adaptation becomes relatively less important compared to stock adaptation. This is due to the increased weight put on the benefits of stock adaptation with a lower discount rate. This results in higher stock adaptation costs in the beginning periods as stock adaptation substitutes flow adaptation.

Finally, the peak of the optimal paths shifts forward in time as the discount rate decreases. Thus adaptation investments are shifted to earlier periods as the discount rate increases. Note that the level of stock adaptation is high in the first period for the Stern and UK treasury discount rates and sharply decreases in the second period. This is due to the assumption made in the DICE model that the level of mitigation is fixed in the first period to a level lower than optimal for these discount rates. Adaptation thus compensates in the first period for the lack of mitigation.

## 6.2 Damage Level

The DICE and RICE models are often criticized for having too low damages. We look at the effects of using a damage function that has higher damages. Recent estimates by Hanemann (2008) suggest that damages could be 2.5 times higher than the DICE2007 model suggests. We rerun some key scenarios with a gross damage function that is scaled up 2.5 times. Figure 7 shows the optimal levels of adaptation and mitigation adaptation using the original and the higher damage function in DICE. As can be seen both the adaptation and mitigation levels increase substantially when the gross damage function is scaled up. Furthermore, the level of adaptation increases much more in beginning years than that of mitigation, while mitigation increases much more in later periods. Due to the large time lapse between the costs and benefits of mitigation and the decreasing positive discount rate mitigation efforts are shifted to later periods.

## 6.3 Depreciation Rate of Adaptation Capital

This section investigates how the choice of adaptation capital depreciation rate influences the choice between policy measures over time. In DICE capital is depreciated at a rate of 10% per year, which is what we assume for adaptation capital as well. We conduct this sensitivity analysis, however, as the adaptation capital depreciation rate is debatable. The AD-DICE09 model is recalibrated with

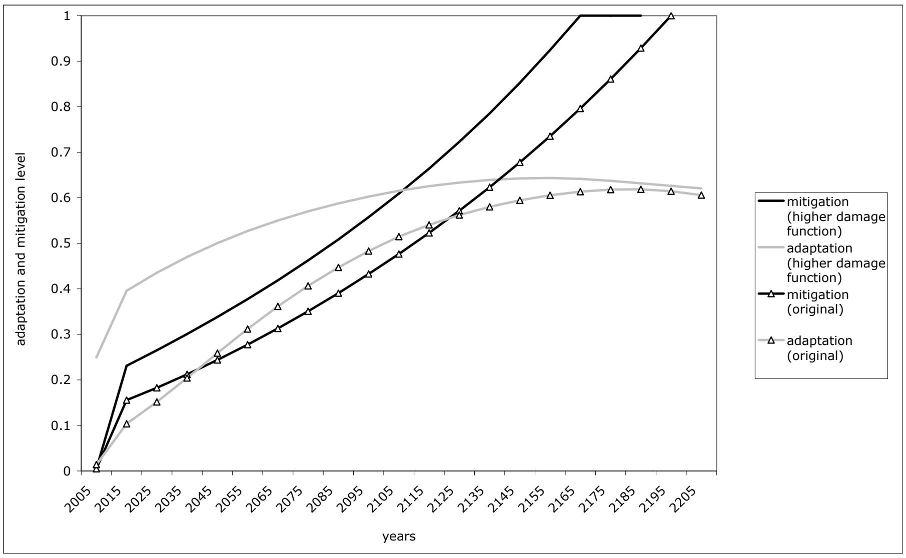

Figure 7: Optimal adaptation and mitigation levels (in percentages) with the original and upscaled damage functions

two alternative annual depreciation rates for comparison, namely 5% and 15%.[5] We examine the effects on the optimal paths of stock and flow adaptation and on the composition of climate change costs in NPV.

The first panel of Figure 8 shows the optimal stock adaptation investment path whereas the second panel shows the optimal flow adaptation expenditure path for the three different depreciation levels. Particularly the flow adaptation expenditures are sensitive to the chosen depreciation rate. As a higher capital depreciation rate is chosen stock adaptation investments decrease, as these are less profitable. This translates into a slower build-up of adaptation capital resulting in increasingly lower levels of adaptation capital stock over time compared to a lower depreciation rate. Flow adaptation expenditures increase to compensate for lower levels of adaptation stock. Therefore, though stock adaptation investments decrease somewhat evenly over the first century as a higher depreciation rate is chosen, flow adaptation expenditures decrease at an increasing rate. Due to the high level of mitigation after the first century, both stock and flow adaptation starts to decrease due to the decreased gross damages and hence decreased adaptation benefits. With a lower chosen depreciation rate of adaptation capital, stock adaptation investments will decrease faster as the benefits of adaptation stock in the future will be lower due to the high level of mitigation.

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[5] Note that the depreciation rate of physical capital remains the same: at 10%.

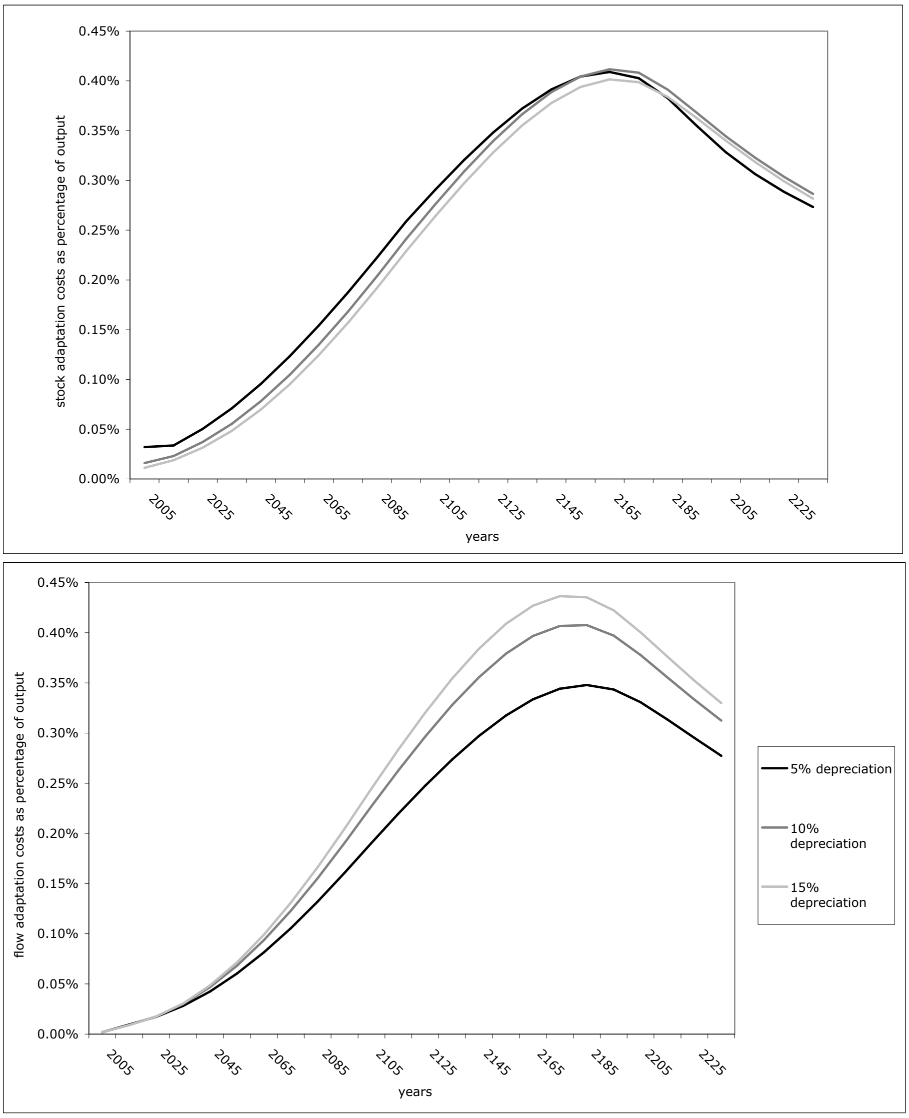

Figure 8: Optimal stock and flow adaptation paths for alternative adaptation capital depreciation rates

Figure 9 shows the NPV of the components of climate change costs for the three depreciation rates for the optimal scenario and the no mitigation scenario. With a higher depreciation rate of stock adaptation, stock adaptation investments decrease as the benefits of stock adaptation last less long as the capital depreciates faster. Flow adaptation and mitigation increase to compensate for the lower effectiveness of stock adaptation investments. This effect is stronger for flow adaptation than mitigation. Residual damages also increase as it becomes optimal to accept more damages as opposed to combating them with controls.

When mitigation is not applied, we again see an increase in flow adaptation and residual damages as the depreciation rate of stock adaptation increases. These changes are larger than in the optimal case and more so for residual damages. This again reflects the role mitigation can play in compensating for lower levels of stock adaptation.

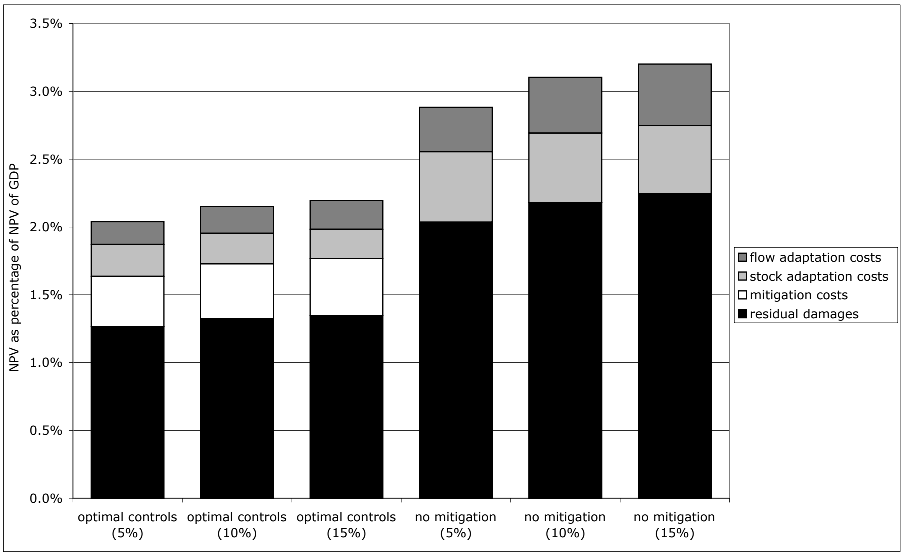

Figure 9: Difference in stock and flow adaptation costs compared to base specification for alternative depreciation rates

## 7 Conclusion

The purpose of this paper is to create a framework with which the optimal mix of emission reduction, reactive (flow) adaptation and proactive (stock) adaptation can be investigated. An Integrated Assessment Model is developed, namely AD-DICE09. Though previous frameworks to model adaptation have been developed such as in previous AD-DICE models, this model includes *both* reactive adaptation actions and investments in adaptation stocks. Consequently, the dynamic aspects of adaptation, as well as the interactions between adaptation and mitigation can be much better understood using this new model. This paper applies AD-DICE09 to investigate various questions concerning climate change policies and draws the following conclusions.

Firstly, both adaptation and mitigation are important in responding to climate change and should be part of a climate policy portfolio. The timing of adaptation and mitigation expenditure is also very important, a gradual build-up of mitigation expenditures is optimal. For adaptation, this implies that there would be a greater emphasis on adaptation in earlier decades in response to the impacts of climatic changes that are already locked-in. In the optimal mix climate change costs consists for a large part of residual damages. Total adaptation costs and mitigation costs are of the same magnitude, where flow adaptation costs are slightly larger than stock adaptation costs.

Secondly, this analysis demonstrates that both types of adaptation options are important in offsetting some of the adverse impacts of climate change. These range from autonomous, reactive measures (flow adaptation) at one end to anticipatory investments in adaptation stock (stock adaptation) such as coastal adaptation infrastructure on the other. The costs and the policy mix of these investments, however, vary considerably across regions, over time, and depend upon the level of mitigation as well as assumptions about climate damages and discount rates. These numerical estimates of adaptation costs should thus be considered preliminary and critically dependent upon the specification of the climate damages used. There is an urgent need for a comprehensive effort to update information on regional damages that are used as inputs into IAMS to reflect more recent information. More important than the specific numbers, this paper seeks to highlight the key drivers behind the choice of policy options.

Thirdly, the three different climate policy options are substitutes. Though any least-cost policy response to climate change will need to involve substantial amounts of mitigation efforts, investments in adaptation stock and reactive adaptation measures to limit the remaining damages. These options are substitutes as they compete for limited resources and can substitute each other when one option is limited, e.g. increased adaptation can limit the damages of no mitigation action. Furthermore stock adaptation, flow adaptation and mitigation negatively affect the marginal benefits of each other. Increased mitigation will decrease the benefits of adaptation by decreasing the gross damages. Adaptation decreases the benefits of mitigation as it decreases gross damages to residual damages. Furthermore increased reactive adaptation will decrease the marginal benefits of stock adaptation and vice versa.

Fourthly, when one climate change policy option is limited, the most similar available option will play a more important role in compensating. Due to increasing marginal costs, however, both available options will be applied. If flow adaptation is limited e.g., the stock adaptation compensates for this to a higher degree than mitigation does. In the case of limited mitigation, stock adaptation is the most similar due to the delay of benefits.

Finally, in our sensitivity analysis we investigated how robust our findings are. We found that the choice of discount rate has immense effects on the results and policy prescriptions of our model. The optimal mix of the three climate policy options depends primarily on the discount rate. A lower discount rate will result in a shift of importance away from flow adaptation and towards mitigation. The Stern discount rate suggests aggressive mitigation action, whereas higher discount rates suggest less aggressive policies where adaptation and mitigation both play an important role. Furthermore, an increased damage level increases the levels of both adaptation and mitigation in the optimum, and the effect on adaptation is stronger particularly in early periods. Finally, a higher depreciation rate of adaptation capital results in higher investments in stock adaptation to compensate. Furthermore, flow adaptation compensates for the decreased effectiveness of stock adaptation. A lower depreciation rate has the opposite effect.

# A Appendix

Nordhaus and Boyer (2000) estimate climate change impacts for 13 regions divided into 7 categories. The regions included in the RICE model are; Japan, USA, Europe,[6] Other High Income Countries (OHI),[7] High Income Oil-Exporting Regions (HIO),[8] Middle Income Countries (MI),[9] Russia, Low-Middle-Income Countries (LMI),[10] Eastern Europe (EE), Low-Income Countries (LI),[11] China, India and Africa.[12]

We use these categories to estimate the costs and benefits of adaptation per region and for the globe as a whole. We do not re-estimate climate change damages but unravel the net climate change damages of the DICE2007 model into stock adaptation costs, flow adaptation costs and residual damages. We will discuss each category in turn and how the adaptation variables were estimated. paper

**Agriculture** Nordhaus and Boyer use sub-regional agricultural impact estimates (in most cases from Darwin et al. (1995) but also from Dinar et al. (1998)) and estimates of sub-regional temperature to produce a relationship between agricultural damage and temperature change. The damages in agriculture as a fraction of GDP are given as a willingness to pay (WTP) function for each region. These damage estimates reflect the adaptation incorporated in the Darwin et al. (1995) study. This includes farmers selecting the most profitable mix of inputs and outputs on existing cropland, adjustments in domestic markets and international trade, and increases in the amount of land under cultivation. Incorporating all of these adaptation options leads to a slight increase (0.2-1.2%) in world cereals production under the climate change scenarios Darwin et al. (1995) consider. It should be noted that $CO_2$ fertilization is excluded

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

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

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

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

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

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

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

| RICE Regions | Tan and Shibasaki regions | Optimal Adaptation level |
|---|---|---|
| USA | NORTH AMERICA | 0.48 |
| CHINA | ASIA | 0.33 |
| JAPAN | ASIA | 0.33 |
| EUROPE | EUROPE | 0.43 |
| RUSSIA | EUROPE | 0.43 |
| INDIA | ASIA | 0.33 |
| OHI | AUSTRALIA | 0.27 |
| HIO | Average EUROPE and AFRICA | 0.33 |
| EE | EUROPE | 0.43 |
| MI | SOUTH AMERICA | 0.38 |
| LMI | Average ASIA and SOUTH AMERICA | 0.355 |
| AFRICA | AFRICA | 0.23 |
| LI | Average AFRICA and ASIA | 0.28 |

Table 5: Adaptation estimates in the agricultural sector

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

in this study.

Adaptation can be very effective in combating the effects of climate change in agriculture. Measures such as irrigation, crop planting time changes, crop changes, and the use previously inarable land can decrease the damages or increase the benefits in agriculture. Many studies include the effects of adaptation in reducing the agricultural damages (or enhancing the benefits) of climate change (e.g Kane et al. 1992; Reilly 1994; Rosenzweig and Parry 1994). More recent studies include Cline (2007); Easterling et al. (2007).

For consistency we use one study (as opposed to various regional studies) to estimate the effects of adaptation. We use the estimates by Tan and Shibasaki (2003) as this study includes various world regions. They estimate the effects of climate change on the amount of crop yield for various regions for the year 2050. Table 5 shows the effect of adaptation for the various regions of Tan and Shibasaki (2003) and how they have been translated into the RICE regions. The form of adaptation that Tan and Shibasaki (2003) consider is the changing of crop planting dates.

Tan and Shibasaki consider the amount of water available in regions without irrigation and assume that water is available for regions that do have irrigation facilities. They do not estimate the extra costs of water needed in these regions or the costs of changing the planting timing as they assume these are very small.

Consequently, we assume here that the percentage of adaptation costs in total net damages is 10% (and thus residual damages constitute 90%). Table 6 gives the different estimates of the adaptation variables.

As Tan and Shibasaki only consider certain low cost adaptation options, we extend our assessment with estimates by Rosenzweig and Parry (1994), who include two forms of adaptation, one including small changes in agricultural systems and other more substantial changes. The first form of adaptation corresponds to that of Tan and Shibasaki, we therefore additionally include only the second form of adaptation including `more substantial change to agricultural systems, possibly requiring resources beyond the farmers' means, investment in regional and national agricultural infrastructure and policy changes. Such measures include large shifts in planting dates (> 1 month), increased fertilizer application, installation of irrigation systems and the development of new varieties. Table 6 gives the breakdown of net damages in residual damages and adaptation costs for the various regions for the agricultural sector.

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

To our knowledge there are no quantative estimates of the effects of adaptation in this sector. Cooling and heating have a great potential to decrease damages and enhance benefits of climate change. Exposure to heat can cause discomfort, illness and even death, which cooling can prevent (Martens 1998; Martens and McMichael 2002). This form of adaptation in relatively easy to apply as it is mostly an extension of regular behaviour (heating and cooling); we therefore estimate the adaptation potential to be high. We assume that the optimal level of adaptation is 0.8. That is, by consuming more energy one can decrease 80% of the discomfort and sickness caused by the warmer climate. Adaptation will mostly be of the flow variety as the infrastructure (energy supply)

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

Table 6: Adaptation estimates for the RICE regions in the agricultural sector for a 2.5 °C increase in temperature

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

is often already in place. Investments in infrastructure may be needed, especially so in developing regions where energy demand is growing fast.

Because most gross damages can be reduced, we assume that most costs in this category are adaptation costs, i.e. adaptation costs compose 80% of total net damages. Note that some regions have benefits in this sector, i.e. the costs of increased air-conditioning are lower than the costs saved due to decreased heating. The corresponding estimates are given in Table 7.

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

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

To estimate the adaptation costs, adaptation level and residual damages, we use the FUND 2.9 model. The FUND model uses the framework proposed by Fankhauser (1994) to calculate the optimal level of coastal adaptation. The methodology used in FUND 2.9 is described in detail in Tol (1995). This model estimates the costs of wetland loss, dryland loss, adaptation costs, migration costs and the adaptation level for more than 200 countries. Wetland losses are caused by both the rising sea level and the building of adaptation measures. Dryland losses and wetland losses due to sea level rise together constitute the residual damages. The adaptation costs and wetland losses due to adaptation and migration costs as given by FUND are totaled to get adaptation costs. The migration costs, however, are extremely low compared to sea wall construction costs. The FUND estimates of adaptation costs differ from those of the RICE model, as they are more recent. Because we want to replicate the original RICE damage function and divide it into residual damages and adaptation costs, we

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

Table 7: Adaptation estimates for the RICE regions in the other vulnerable markets sector for a 2.5 °C increase in temperature

Source: Own calculations based on Nordhaus and Boyer (2000).

will use the FUND data only to estimate the ratio of adaptation costs and residual damages and retain the total net damages of the RICE model.

Table 8 gives the results obtained concerning the adaptation variables. As can be seen from Table 8, the level of adaptation in the coastal sector is extremely high for most regions. This is because these are the optimal adaptation levels where the costs of protecting land are much lower than the costs of losing that land due to sea level rise. For Russia the level of adaptation is 0, as it has no vulnerable coastlines and thus no coastal damages to protect itself against. The levels of Europe and Other High Income countries are also relatively low. These regions have coastal areas where the costs of protecting are higher than the costs of losing land, creating a lower optimal adaptation level. There is a negligible amount of flow adaptation, as most coastal adaptation is stock, i.e. building of seawalls, strengthening coastlines, etcetera.

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

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

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

Table 8: Adaptation estimates for the RICE regions in the coastal sector for a 2.5 °C increase in temperature

Source: own calculations based on Nordhaus and Boyer (2000) and FUND 2.9.

public education.

The estimates regarding adaptation costs and benefits when assuming the same adaptation level as in Murray and Lopez (1996) are given in Table 9. In the case of diseases adaptation is relatively cheap as compared to the damages created by the diseases. For example the costs of losing a year of a life due to malaria is two times the GDP per capita of that person (Murray and Lopez 1996), whereas a mosquito net costs 4 dollars and will likely prevent malaria. In this case we assume that adaptation costs are 20% of net damages in the case of diseases and 0.3 in the case of pollution. Adapting to pollution will be more costly and less effective and we assume that adaptation costs will be some 30% of net damages. Most adaptation strategies in this category are reactive strategies. General facilities such as hospitals and institutions will, however, be needed to adapt effectively. In developing regions health infrastructure is severely lacking.

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

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

We assume that adaptation here is virtually cost free. It does not cost much

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

Table 9: Adaptation estimates for the RICE regions in the health sector when adaptation level is set at the expected level for a 2.5°C increase in temperature

Source: own calculations based on Nordhaus and Boyer (2000), WHO (2008) and Murray and Lopez (1996)

to adapt ones activities. We, therefore, assume very low adaptation costs, i.e. 10% of total net damages. The estimates are given in Table 10. As this form of adaptation consists of the changing of ones leisure habits and does need a beforehand investment we categorise it as flow.

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

The difficulty of adapting to such impacts is a central criterion for inclusion in this sector. We assume that some the damages of a catastrophic event can be prevented through knowledge of the forthcoming disaster (early warning systems, scientific research etc.). Though early warning systems have been found to be very effective for extreme events (e.g. Adams et al. 2003), they will not likely be very effective for such catastrophes as considered here. We conservatively assume that in the optimum some 10% of damages can be reduced through stock adaptation (i.e. through anticipatory adaptation). We also assume that good adaptation strategies after a disaster (i.e. reactive) can further decrease damages by 10%. Most damages will be in the category of residual damages, so we assume that they comprise 90% of total net damages. Table 11 gives our estimates regarding adaptation costs and benefits and damages.

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

Table 10: Adaptation estimates for the RICE regions in the non market time use sector for a 2.5 °C increase in temperature

Source: own calculations based on Nordhaus and Boyer (2000), WHO (2008) and Murray and Lopez (1996)

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

Table 11: Adaptation estimates for the RICE regions in the catastrophic events sector for a 2.5 °C increase in temperature

Source: own calculations based on Nordhaus and Boyer (2000), WHO (2008) and Murray and Lopez (1996)

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

RICE acknowledges the difficulty of adaptation for coastal cities, islands, and natural ecosystems. Ecosystems cannot easily adapt to the changing climate and will often disappear, thus the adaptation potential is rather low (0.2), as are the associated adaptation costs (10% of net damages). Ecosystems form a smaller part of the total than do human settlements. Human settlements, such as the example given by Nordhaus and Boyer (2000), namely Venice, can adapt at high costs. Here the adaptation costs will be high, we assume 90% of net damages, and the adaptation level will also be high namely 0.8 but will be lower in developing regions, namely, 0.4. Adaptation here is of the stock form as vulnerable settlements are protected before climate change impacts occur. The corresponding aggregated estimates of ecosystems and human settlements are given in Table 12.

**Total Impacts** Table 13 presents the overview of impacts per category for the different regions, summarizing the information from this section. Not only are the levels of total impacts different across regions, but the relative importance of the various categories differs widely across regions. This also implies differences in adaptation options and costs for the regions.

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

Table 12: Adaptation estimates for the RICE regions in the settlements sector for a 2.5 °C increase in temperature

Source: own calculations based on Nordhaus and Boyer (2000), WHO (2008) and Murray and Lopez (1996)

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

Table 13: Damage categories and estimates as fraction of GDP at a 2.5 °C temperature increase from 1900 levels

Source: Nordhaus and Boyer (2000)

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