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Costs, benefits and interlinkages between adaptation and mitigation

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15.1 Introduction

The thirteenth Conference of the Parties to the United Nations Framework Convention on Climate Change in 2007 decided that developing countries should be compensated for adaptation costs to climate change through the Adaptation Fund (first draft decision of the third session of the conference of the parties serving as the meeting of the parties to the Kyoto Protocol). This shows that adaptation to climate change has become important in international climate negotiations. Today, adaptation is widely recognized as an equally important and complementary response to climate change mitigation (for example, Commission of the European Communities 2007; IPCC 2007a; Agrawala and Fankhauser 2008).

Still, relatively little information is available to support more integrated climate policies that focus on both mitigation and adaptation (Klein *et al*. 2005). In particular, in integrated assessment models that aim at supporting climate policy by analysing their economic and environmental consequences and formulating efficient responses, explicit consideration of adaptation is still in its infancy (Tol 2005; Wilbanks 2005; Agrawala *et al*. 2008).

This chapter tries to fill the gap in integrated assessment models by integrating adaptation and residual damage functions from AD-RICE (de Bruin *et al*. 2009) with the FAIR model (den Elzen and van Vuuren 2007; Hof *et al*. 2008). This version of the FAIR model (from now on called AD-FAIR) enables an analysis of the interactions between mitigation, emissions trading, adaptation and residual damages (that is, damages not avoided by adaptation measures) on a global as well as regional scale. Furthermore, adaptation is modelled explicitly as a policy variable, providing insights in the economic consequences of adaptation. This information is vital for effective adaptation governance.

Because this study aims at introducing a novel approach of modelling adaptation in the FAIR model and at showing what results can be obtained from this approach,

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little attention has been given to analyse uncertainty (see Hof *et al*. 2008, for an extensive assessment of the uncertainties in cost–benefit analyses of climate change policies).

15.2 Methodology

15.2.1 Background on modelling adaptation in integrated assessment models

Adaptation aims to reduce the vulnerability of natural and human systems against actual or expected climate change effects (IPCC 2001). This implies that in order to model adaptation, first the impacts (or damages) of climate change have to be taken into consideration. Damage estimates of climate change involve scientific uncertainties (for example, impact of climate change on the number of storms or change in mortality) as well as value judgements (for example, how to monetize non-market damages and how to deal with uncertainty; see Azar 1998; Dietz *et al*. 2007; Weitzman 2007). Despite these large uncertainties and value judgements, several studies have estimated the damages related to climate change, and incorporated these estimates in integrated assessment models. The most notable examples are FUND (Tol 2002a, b) and DICE/RICE (Nordhaus 1994, 2008; Nordhaus and Boyer 2000). Both estimated the impacts and associated damages of climate change by identifying the most important sectors vulnerable to climate change. DICE/RICE includes the sectors agriculture, sea-level rise, other market sectors (forestry, energy systems, water systems, construction, fisheries and outdoor recreation), health, non-market amenity impacts, human settlements and ecosystems, and catastrophic events. In the DICE/RICE assessment, potential catastrophic events are by far the most important factor in total damages: for a 2.5 °C temperature increase compared to 1900, catastrophic events make up more than half of total estimated damages at the global scale (Nordhaus and Boyer 2000: 91). FUND identifies similar, but fewer, sectors than Nordhaus, omitting most of the other market sectors identified by Nordhaus and, more importantly, catastrophic events. Damages from increasing occurrence of extreme weather events are included neither in the FUND nor DICE/RICE model. Furthermore, both authors warn that their damage estimates are highly speculative. For example, Tol (2002a: 65) argues that 'a lot needs to be done before one can place any confidence in the estimates'.

In addition to uncertainty, another limitation in the FUND and DICE/RICE damage curves is that adaptation is not explicitly taken into account as a policy variable. Instead, optimal adaptation is assumed in the construction of these curves – and the curves consist of the aggregated costs of remaining damages and adaptation costs. There have been few attempts to model adaptation as a decision variable in integrated assessment models, with Hope *et al*. (1993) among the first. However, they seem to be over-optimistic about the amount of damages that can be avoided by adaptation according to current existing empirical literature on this issue (de Bruin *et al*. 2009). In the recent AD-RICE model, de Bruin *et al*. (2009) used a more transparent method to model adaptation as a decision variable in the RICE integrated assessment model. As this is the most recent and best-documented attempt to explicitly model adaptation in an integrated assessment model, we have integrated the adaptation and residual damage curves from AD-RICE with the FAIR model.

15.2.2 Modelling climate–economy interactions

As the backbone of our study, we use the FAIR 2.1 model which includes 17 regions, described in detail in previous publications (den Elzen and Lucas 2005; den Elzen and van Vuuren 2007). Here, we will only provide a short description of the FAIR model.[1] FAIR uses a flexible set of assumptions and integrates information from detailed energy, climate and socio-economic models. It describes the interactions between multi-gas emissions, greenhouse gas concentrations and the climate system, as well as the interaction between the climate system and the economy through climate change damages and mitigation costs (including emissions trading), for different international burden sharing regimes. These elements are integrated in order to perform a cost–benefit analysis of climate policies (Hof *et al*. 2008).

Figure 15.1 gives a schematic overview of the AD-FAIR model. Regional climate mitigation targets, emissions trading and mitigation costs depend on the global climate mitigation target and the burden-sharing regime. Adaptation costs and residual damages depend on climate change impacts and the amount of adaptation measures taken to reduce these impacts. Climate impacts depend on global temperature increase, associated with a global emission pathway and parameters in the climate model, such as climate sensitivity. Mitigation, adaptation and residual damages are characterized by different dynamics. Mitigation reduces global temperature increase, and hence potential damages, in the long run. In the short run (that is, the coming 20–30 years) this effect is negligible, as the temperature increase for reduction pathway and baseline are very similar due to inertia in the climate system. Adaptation can reduce residual damages in the short run, but does not reduce climate change and therefore future potential damages. To estimate both the direct and indirect consumption losses of mitigation, adaptation and residual damages, we use a simple economic growth model based on a Cobb–Douglas production function for each region (Hof *et al*. 2008).

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[1] See www.mnp.nl/en/themasites/fair/index.html.

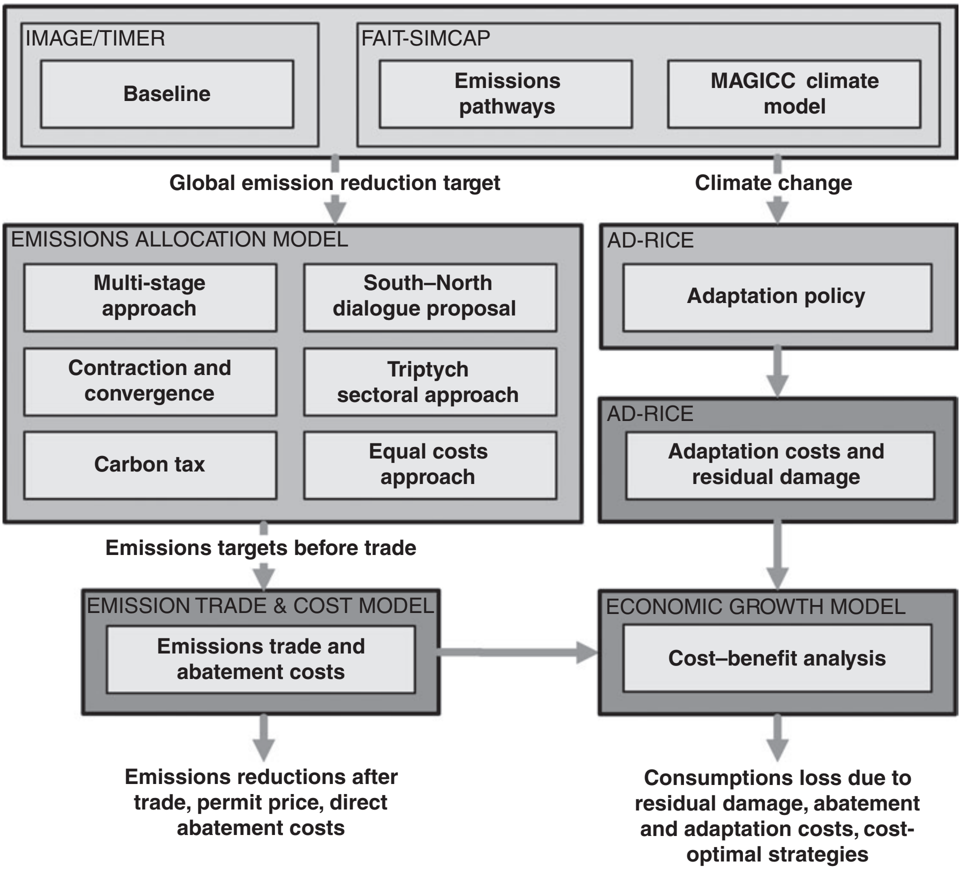

Figure 15.1 Schematic overview of the AD-FAIR model.

15.2.3 Modelling adaptation and residual damages: AD-RICE

The AD-RICE cost and residual damage functions in this chapter are based on the damage functions of the RICE model. These damage functions include both adaptation costs and residual damages. Because the parameterization of these regional damage functions plays a major role in our results, we here give some insight into these damage functions. The parameterization of the RICE damage functions is explained in detail in Nordhaus and Boyer (2000). RICE projects that damages will be small in East Asia, the United States and Japan. This is mainly caused by the assumed low willingness to pay to avoid catastrophic risks in these regions. Damages in the Middle East and South America are projected to be similar to the global average. The other regions – OECD Europe, South East Asia and especially West and East Africa and South Asia – have much higher damages of climate change according to RICE. In Africa, this is mainly due to negative health impacts.

In South Asia, the high risk of catastrophic impacts and the negative effects of climate change on agriculture cause high damages. Health impacts and the risk of catastrophic events are the main reasons for the high damages in South America.

Here we give a short summary of the AD-RICE methodology (see for a more detailed description de Bruin *et al.* 2009). First of all, the regional damage functions of the online available GAMS version of RICE99[2] are separated into a residual damage (*RD*) and adaptation cost (*PC*) component:

$$\frac{D_{r,t}}{Y_{r,t}} = \frac{RD_{r,t}(GD_{r,t}, P_{r,t})}{Y_{r,t}} + \frac{PC_{r,t}(P_{r,t})}{Y_{r,t}}. \qquad (15.1)$$

The sum of residual damages and adaptation costs equals net damages *D*. Both residual damages and adaptation costs in region *r* at time *t* depend on the level of adaptation (*P*). Note that residual damages can be negative as well; in this case, adaptation can increase the benefits of climate change. Gross or potential damages *GD* (damages that would occur without any adaptation activities) take the following form:

$$\frac{GD_{r,t}}{Y_{r,t}} = \alpha_1 \Delta T_t + \alpha_2 \Delta T_t^{\alpha_3} \qquad (15.2)$$

where $\alpha_2 > 0$ and $\alpha_3 > 1$ and ΔT stands for global temperature increase since 1900. Adaptation activities can reduce residual damages or increase climate change benefits:

$$RD_{r,t} = GD_{r,t}(1 - P_{r,t}), \; 0 \leq P_t \leq 1 \text{ if } GD_t > 0; \qquad (15.3)$$

$$RD_{r,t} = GD_{r,t}(1 + P_{r,t}), \; 0 \leq P_t \leq 1 \text{ if } GD_t < 0. \qquad (15.4)$$

The level of adaptation is chosen for every time period. No adaptation ($P = 0$) means that gross damages are not reduced; in this case, residual damages equals gross damages. At the other extreme, with $P = 1$ all gross damages are avoided by adaptation and residual damages equal zero. It is assumed that adaptation costs increase at a growing rate, since cheaper adaptation will be applied first, and more expensive and less effective options later:

$$\frac{PC_{r,t}}{Y_{r,t}} = \gamma_1 P_{r,t}{}^{\gamma_2}, \text{ where } \gamma_1 > 0 \text{ and } \gamma_2 > 1. \qquad (15.5)$$

In our scenarios, adaptation efforts are determined by minimizing the regional sum of residual damages plus adaptation costs. In other words, the level of

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[2] Available at www.econ.yale.edu/~nordhaus/homepage/dicemodels.htm.

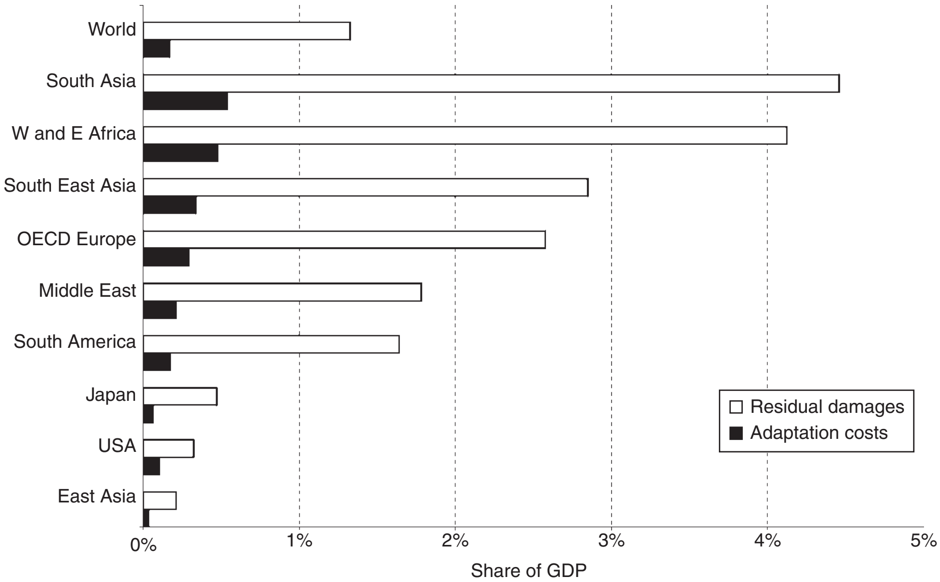

Figure 15.2 Regional distribution of residual damages and adaptation costs as percentage of GDP with a 2.5 °C increase in global temperature according to AD-RICE.

adaptation is chosen so that the marginal costs of adaptation equal the marginal benefits of reducing residual damages.

Figure 15.2 shows the result of the above methodology on separating the damages of RICE into adaptation costs and residual damages for a 2.5 °C global warming. As in de Bruin *et al.* (2009), adaptation costs are much smaller than residual damages in the case of optimal adaptation. This is due to the shape of the adaptation cost curves: up to a certain point adaptation is relatively easy and therefore cheap, but after this point adaptation costs rise sharply. So it would in principle be possible to adapt more, but at such high costs that the benefits of more adaptation (that is, the avoided residual damages) would be lower than the cost of more adaptation.

Because the results strongly depend on the regional damage estimates of RICE, Figure 15.3 shows how the regional damage projections of RICE compare to those of FUND 2.8[3] for a global warming of 2.5 °C. It is clear that there are some significant differences in damage estimates. The most apparent difference is that FUND projects lower climate change damages than RICE for all regions. As mentioned above, an explanation could be that FUND, unlike RICE, does not include catastrophic events and many of the other market sectors that are included

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[3] The FUND code can be downloaded at www.fnu.zmaw.de/FUND.5679.0.html.

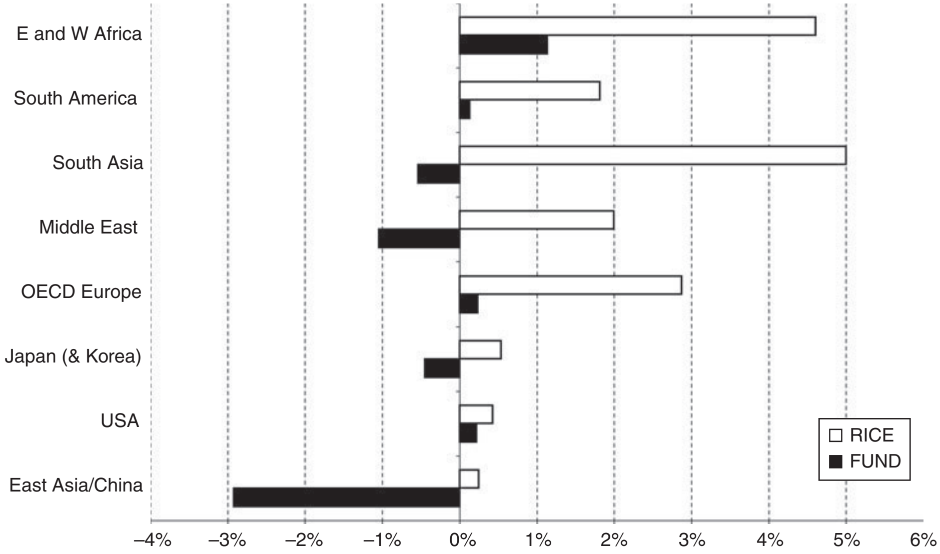

Figure 15.3 Regional damage estimates of a 2.5°C increase in global temperature according to FUND 2.8 compared to RICE.

in the damage estimates of RICE. Not only does FUND generally project lower damages, there are some regional differences in the estimates as well. For example, RICE projects negative impacts for the Middle East at a global warming of 2.5 °C, whereas FUND projects slightly positive impacts. The main reason for this is more optimistic projections for agriculture in the Middle East by FUND (Tol 2002b: 138). One similarity of FUND and RICE is that both project the lowest damages for East Asia and high damages for East and West Africa. In sum, however, this comparison shows how uncertain the damage estimates are and hence how careful our results have to be interpreted.

15.2.4 Calibration of the AD-FAIR model

As baseline for this study, we use the medium IPCC SRES baseline emissions scenario IMAGE&/TIMER SRES B2 (Nakicenovic *et al.* 2000; van Vuuren *et al.* 2007), extrapolated to the year 2250 as described in Hof *et al.* (2008). The B2 baseline describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with moderate population growth and intermediate levels of economic development. Overall, these scenarios are a reasonable description of possible future developments (van Vuuren and O'Neill 2006). Population estimates are taken from the medium long-term UN population projections. Estimates of mitigation costs are based on a wide set of marginal abatement cost curves, differentiated over time as described in detail in den Elzen *et al.* (2007).

Table 15.1 *Calibration of the AD-RICE adaptation cost function and gross damage function applied to the 16 FAIR regions*

	Gross damage function parameters (15.2)			Adaptation cost function parameters (15.5)	
	α_1	α_2	α_3	γ_1	γ_2
Canada	0.0	0.0	1.01	0.0	2.094 287
USA	−0.001 037	0.000 383	4.057 580	0.015 816	10.205 560
Central America	0.0	0.005 709	1.852 274	0.331 922	5.058 278
South America	0.0	0.005 874	1.489 249	0.216 088	3.965 002
Northern Africa	0.0	0.005 709	1.852 274	0.331 922	5.058 278
Western Africa	0.0	0.021 521	1.205 976	0.750 540	5.121 911
Eastern Africa	0.0	0.021 521	1.205 976	0.750 540	5.121 911
Southern Africa	0.0	0.005 709	1.852 274	0.331 922	5.058 278
OECD Europe	−0.000 193	0.004 630	2.294 257	0.340 520	4.243 043
Eastern Europe	NA	NA	NA	NA	NA
Former USSR	NA	NA	NA	NA	NA
Middle East	0.0	0.006 966	1.532 830	0.315 328	5.190 274
South Asia	0.0	0.015 117	1.701 511	0.782 582	5.282 538
East Asia	−0.002 222	0.000 638	2.973 172	0.022 482	6.294 820
South East Asia	0.0	0.010 905	1.554 867	0.502 242	5.178 300
Oceania	0.0	0.0	1.01	0.0	2.094 287
Japan	−0.002 791	0.001 187	2.650 637	0.030 792	3.259 174

The MAGICC 4.1 model (Wigley and Raper 2001, 2002; Wigley 2003) is used to calculate the temperature implications of the emission pathways. The climate sensitivity is set at the best estimate according to the IPCC Fourth Assessment Report (IPCC 2007b) of 3 °C, meaning that a doubling of pre-industrial carbon dioxide concentrations will lead to a global average surface warming of 3 °C.

Calibration of the gross damage function (15.2) and adaptation cost curve (15.5) is done using the optimal control scenario of RICE, in such a way that it best replicates the results of the original RICE model. Table 15.1 provides the results of the calibration on the parameter values (see de Bruin *et al*. 2009 for the derivation of these parameters).

In the economic growth model, the savings rates per region in 2005 are taken from the World Development Indicators database (World Bank 2008) and are assumed to converge linearly to 21 per cent in 2100 in every region and stay constant afterwards. The initial capital stock in every region is based on the growth study datasets of the International Institute for Applied Systems Analysis (Miketa 2004); depreciation is set at 5 per cent annually.

Finally, we adopted the United Kingdom Green Book discounting method (United Kingdom Treasury 2003) for computing the discounted income losses due to mitigation costs, adaptation costs and residual damages over the time period

2005–2250 (Hof *et al.* 2008 discusses the implications of different discounting methods.).

15.2.5 Mitigation strategies

Several climate mitigation targets are analysed. These are taken from den Elzen and van Vuuren (2007) and cover a range of multi-gas emission reduction pathways corresponding with carbon dioxide-equivalent concentrations peaking between 500 and 800 ppm. With a climate sensitivity of 3°C, this implies that the global temperature increase of these emission reduction pathways ranges from 2 °C for the 500 ppm carbon dioxide-equivalent concentration peak to 4 °C for 800 ppm. Global emissions in the most stringent climate mitigation target that we analysed (concentrations peaking at 500 ppm carbon dioxide-equivalent) need to peak in 2015 at 28 per cent above 1990 level, after which emissions are reduced strongly to 53 per cent of 1990 level in 2050. In the 800 ppm pathway, emissions peak in 2040 at 66 per cent above 1990 level, after which emissions decline more gradually to 21 per cent above the 1990 level in 2100.

Emission burdens are allocated across regions using either the ‘contraction and convergence’ regime with convergence year 2050 (Contraction and Convergence 2050: Meyer 2000) or the ‘multi-stage’ regime (den Elzen *et al.* 2006; Gupta 1998). The ‘contraction and convergence’ regime is most often used in quantitative analysis because of its simplicity and straightforwardness (Hof *et al.*, this volume, Chapter 4). In this regime, emission burdens are allocated so that per capita emissions converge from their current values to a global average by 2050. In the ‘multi-stage’ regime, an increasing number of countries accept commitments over time based on per capita income and per capita carbon dioxide-equivalent emissions. First, countries accept emission intensity targets and as they become more developed, absolute reduction targets are set. The participation threshold levels are differentiated according to the stabilization level as described in den Elzen *et al.* (2008).

15.3 Analysis

This section looks at how adaptation costs relate to mitigation costs and residual damages. First of all, this serves as a check whether adaptation costs as projected by AD-FAIR are in line with the most recent estimates in literature. Furthermore, this section will provide insight in the size and development of the climate change cost components (that is, adaptation costs, mitigation costs and residual damages) over time and the effect of these costs on regional incomes for different mitigation strategies.

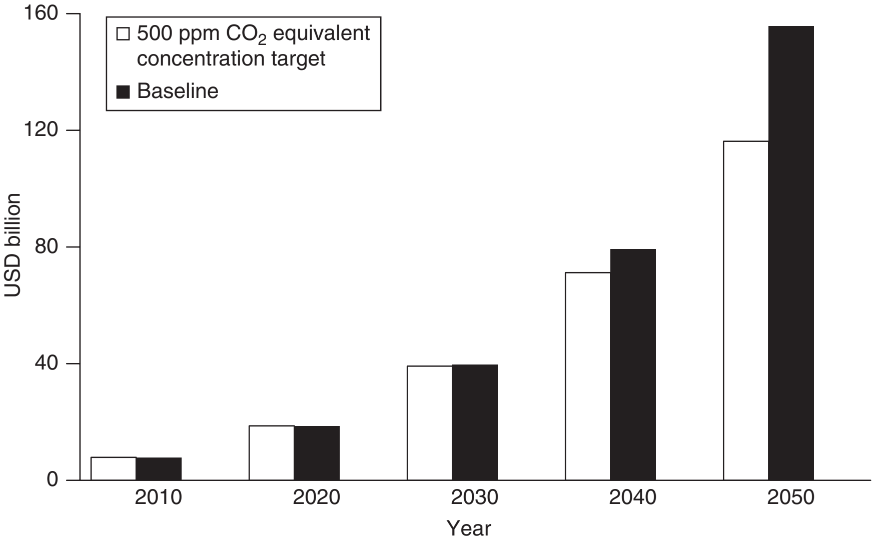

Figure 15.4 Projected adaptation costs from 2010 until 2050 with a concentration peak target of 500 ppm carbon dioxide-equivalent and a baseline scenario without any mitigation efforts.

15.3.1 Global climate change costs

Figure 15.4 shows the adaptation costs in the next decades in a scenario without any mitigation efforts compared to a scenario with a strong climate policy, based on the AD-RICE adaptation cost curves and assuming optimal adaptation. The underlying assumptions are listed in Section 15.2. In 2020, adaptation costs are estimated to amount to USD 18 billion in both scenarios (we use constant 2005 US dollar prices throughout this chapter). Adaptation costs will steadily increase over time, due to increased global warming and hence higher potential damages. Adaptation costs without any mitigation efforts are up to USD 40 billion in 2030, rising to USD 155 billion in 2050. With a strong climate policy that keeps the concentration level below 500 ppm carbon dioxide-equivalent, adaptation costs in 2050 are projected at USD 115 billion. These estimates are of the same order of magnitude as estimates of adaptation costs by the World Bank (2006) and UNFCCC (2007). The World Bank arrives at an order of magnitude of USD 10 to 40 billion per year for developing countries only. The climate convention secretariat estimates the investment and financial flows needed for adaptation to be USD tens of billions per year for the coming decades and potentially more than USD 100 billion per year in the longer run.

Figure 15.4 also shows that adaptation costs for a strong mitigation scenario and a scenario without any mitigation efforts are similar in the short term, and only start to diverge in the longer run (from 2040 onwards). The reason for this is that climate projections for scenarios with and without climate policy only start to diverge after

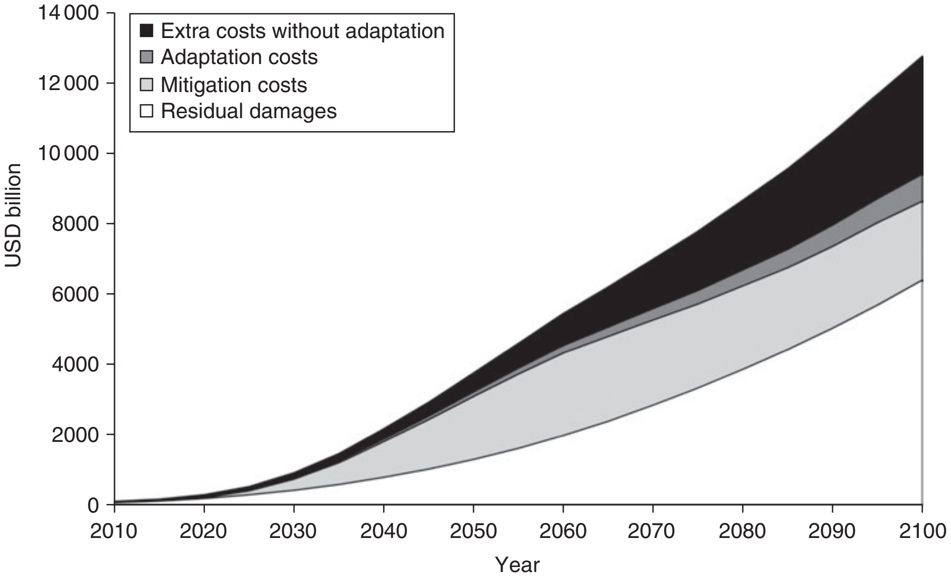

Figure 15.5 Global mitigation costs, adaptation costs, residual damages and extra costs if no adaptation is undertaken, with a concentration target of 550 ppm carbon dioxide-equivalent and a 'Contraction and Convergence 2050' regime.

2040 as a result of inertia in the climate system, combined with reduced sulphur emissions in the scenario with climate policy, which increases temperatures.

Figure 15.5 shows how the projected global adaptation costs compare with the other costs of climate change, that is, mitigation costs and residual damages, assuming an emission pathway leading to a concentration level peak of 550 ppm carbon dioxide-equivalent. Even with such a stringent climate mitigation target and optimal adaptation, residual damages are still the largest component of total climate change costs during most of the century. Especially in the second half of this century, residual damages are projected to increase sharply, reaching USD 6.5 trillion at the end of the century. However, residual damages will reach more than USD 11 trillion if no mitigation takes place, showing that mitigation does reduce damages substantially in the long run. Mitigation costs for a concentration peaking target at 550 ppm carbon dioxide-equivalent rise sharply from 2020 onwards, stabilizing at about USD 2.3 trillion in the second half of the century.

Figure 15.5 also shows the effect of not adapting optimally to climate change. There are many examples of suboptimal adaptation, due to many different reasons. Perhaps the most important of these is that there might not be enough information available about future climate change to adapt optimally to it. But even when this information is available, politicians might still underestimate the risks of climate change. Even though the share of adaptation costs in the total climate change costs is relatively small, adaptation plays a major role by reducing potential damages. The extra costs if no adaptation measures are taken (defined as the increase in residual damages minus the decrease of adaptation costs) are projected to amount to USD 30 billion globally in 2010 and increase sharply to USD 3.4 trillion in 2100. Investment in adaptation is therefore very effective: residual damages are on average reduced by about five dollars for every dollar invested in adaptation.

The above analysis could suggest that there is a trade-off between adaptation and mitigation, since both reduce residual damages. In order to analyse whether there is indeed a trade-off, we compare four different scenarios with each other. In the first scenario called ‘reference’ there are no mitigation nor adaptation measures; the second scenario consists of optimal adaptation, but no mitigation; the third consists of our most stringent mitigation path (leading to a concentration peak of 500 ppm carbon dioxide-equivalents); and in the final one both the most stringent mitigation measures and optimal adaptation are implemented.

Figure 15.6 shows the discounted climate change costs (with a fixed discount rate of 2.5 per cent) over the next two centuries for these four different scenarios. It shows that the mitigation-only and the adaptation-only scenarios both reduce the discounted costs substantially and to about the same degree compared to the reference case. The main difference seems to be that mitigation is more expensive,

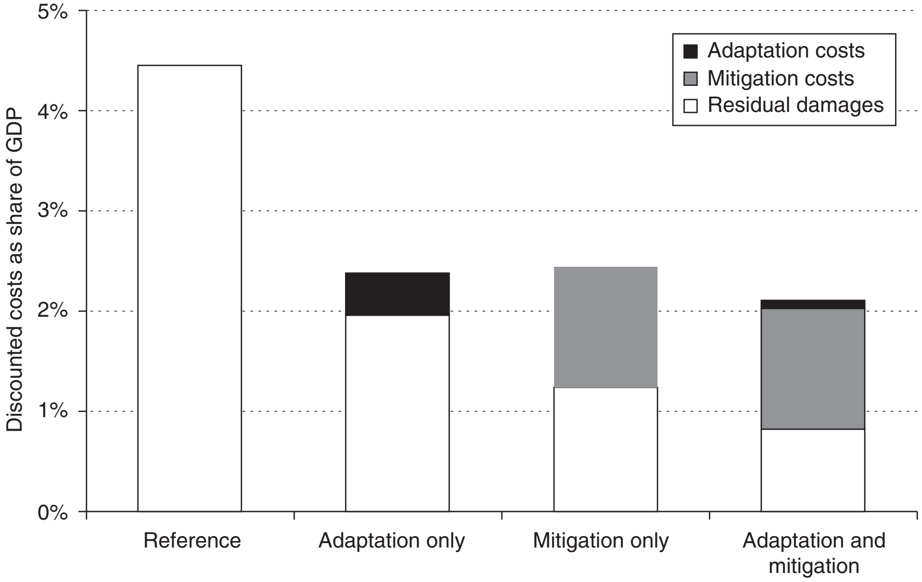

Figure 15.6 Global discounted climate change costs for four scenarios. Global discounted climate change costs for four scenarios: no mitigation and no adaptation (reference), no mitigation and optimal adaptation, no adaptation and stringent mitigation, and both optimal adaptation and stringent mitigation.

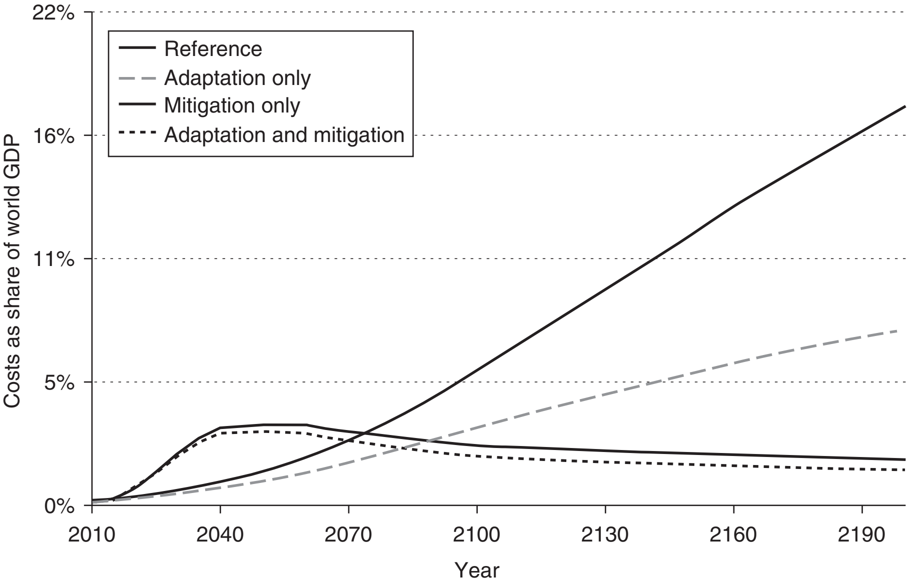

Figure 15.7 Global climate change costs over time for four scenarios. Global climate change costs over time for four scenarios: no mitigation and no adaptation (reference), no mitigation and optimal adaptation, no adaptation and stringent mitigation, and both optimal adaptation and stringent mitigation.

but reduces damages to a higher degree. Implementing both adaptation and mitigation, however, reduces costs even further. This indicates that adaptation and mitigation complement each other and cannot be regarded as substitutes. This becomes even clearer when looking at the total undiscounted costs over time (Figure 15.7): even though the adaptation-only and mitigation-only cases lead to similar discounted costs, the dynamics differ completely. For the adaptation-only case the costs are lower during most of this century, but steadily increase afterwards because climate change is not mitigated. In 2200, total climate change costs of the adaptation-only case are four times the mitigation-only case.

15.3.2 Regional climate change costs

Figure 15.8 shows the regional distribution of all climate change cost components in 2030 for a mitigation path leading to a peak concentration level of 550 ppm carbon dioxide-equivalent. Obviously, higher concentration targets imply lower mitigation costs, but higher adaptation costs and damages.

Residual damages are especially large in all lower income regions except East Asia, as is to be expected from the RICE damage functions. Interestingly, East Asia is even projected to benefit from modest climate change: climate change damages

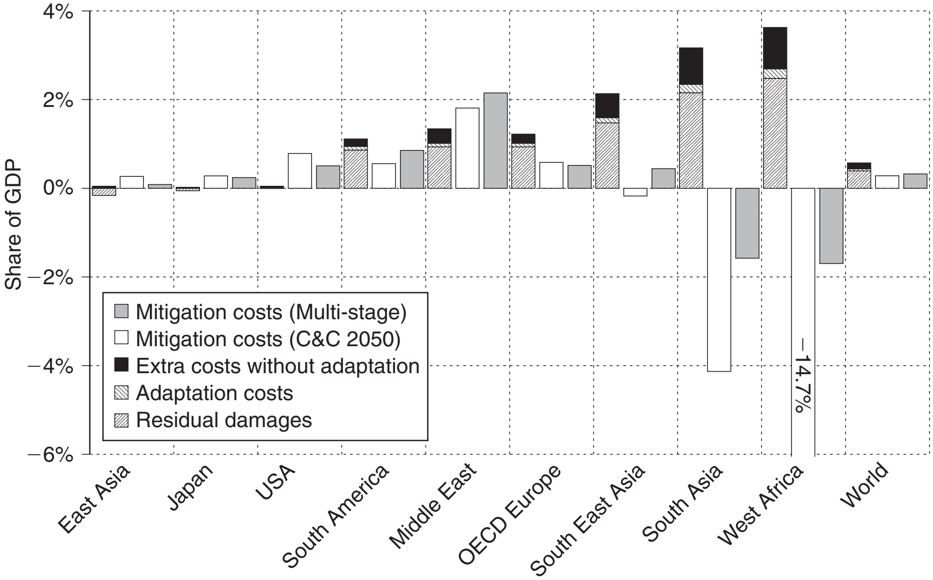

Figure 15.8 Climate costs components in 2030 as share of GDP with concentrations peaking at 550 ppm carbon dioxide-equivalent for selected regions assuming either a ‘Contraction and Convergence 2050’ (C&C 2050) or a ‘multi-stage’ regime.

are (slightly) negative in 2030 because of positive impacts on agriculture and non-market amenity value (such as climate-related time use) for small increases in temperature.

The regional differences in the distribution of mitigation costs are very large, both for a ‘contraction and convergence 2050’ burden-sharing regime and a ‘multi-stage’ regime. In regions less affected by climate change damages (United States, Japan and East Asia), the largest share of total climate change costs consists of mitigation costs in 2030 for both burden-sharing regimes. Mitigation costs in West Africa and South Asia are projected to be negative in the short to medium run, meaning that these regions will benefit from selling emission permits. The benefits from selling emission permits in these regions can even offset residual damages and adaptation costs with a ‘Contraction and Convergence 2050’ burden-sharing regime. In a ‘multi-stage’ regime, however, residual damages and adaptation costs far outweigh the revenues of selling emission permits in both South Asia and West Africa.

Globally, adaptation costs only amount to a small fraction of GDP. The regional differences are large, however. Adaptation costs as share of GDP are especially high in West Africa (about six times the world average in 2030), explained by the high potential damages in this region. Relative adaptation costs are also high in South Asia (about five times the world average in 2030) and South East Asia (about 3.5 times the world average). In absolute terms, about 60 per cent of total global adaptation costs are carried by low- and middle-income regions. Almost all of the remaining adaptation costs are carried by Europe, while the United States and Japan only account for a fraction of total adaptation costs. The low costs of adaptation in the United States, Japan and East Asia are largely explained by the projected low climate change damages of RICE.

The total climate change costs (the sum of adaptation, residual damage and mitigation costs) relative to GDP are the highest in the Middle East, followed by South East Asia in 2030 for both burden-sharing regimes. South America and West Africa will also face relatively high climate change costs in a ‘multi-stage’ regime, while OECD Europe will face high climate change costs in a ‘Contraction and Convergence 2050’ regime. In most low- and middle-income regions adaptation is very important - total climate change costs increase by almost 1 per cent of GDP for West Africa and South Asia in 2030 and by 0.5 per cent of GDP for South East Asia if no adaptation takes place. The reason is that in most low- and middle-income regions, potential damages are relatively high, increasing the need for adaptation.

15.3.3 Regional discounted income losses of climate change

The discounted climate change income losses as percentage of discounted income (from now on simply called discounted income loss) over a range of climate mitigation targets provide us with useful information. First, a climate mitigation target can be identified for which the discounted income loss is minimized, providing an indication of the optimal climate mitigation target. However, this strongly depends on the chosen assumptions as the discount rate and damage estimates, as shown earlier by Hof *et al*. (2008). With our assumptions and for a ‘multi-stage’ burden-sharing regime, the global and regional discounted income loss for different concentration peak levels is shown in Figure 15.9. Global discounted income loss is minimized at a concentration peak target of around 540 ppm carbon dioxide-equivalent, resulting in a discounted income loss of 2.3 per cent.

The regional differences in the climate mitigation target for which discounted income loss is minimized are large. The United States minimizes discounted income loss at a concentration peak higher than the evaluated range of 500 to 800 ppm carbon dioxide-equivalent, due to their low damage estimates. The minimum for East Asia is at around 600 ppm carbon dioxide-equivalent, OECD Europe at about the same level as the global average, and South Asia and East Africa minimize their discounted income loss at a concentration peak level below our analysed range of 500 to 800 ppm carbon dioxide-equivalent, as residual damages in these regions increase rapidly for less stringent climate mitigation targets. These results indicate that it could be difficult for the world to agree to one single climate mitigation target

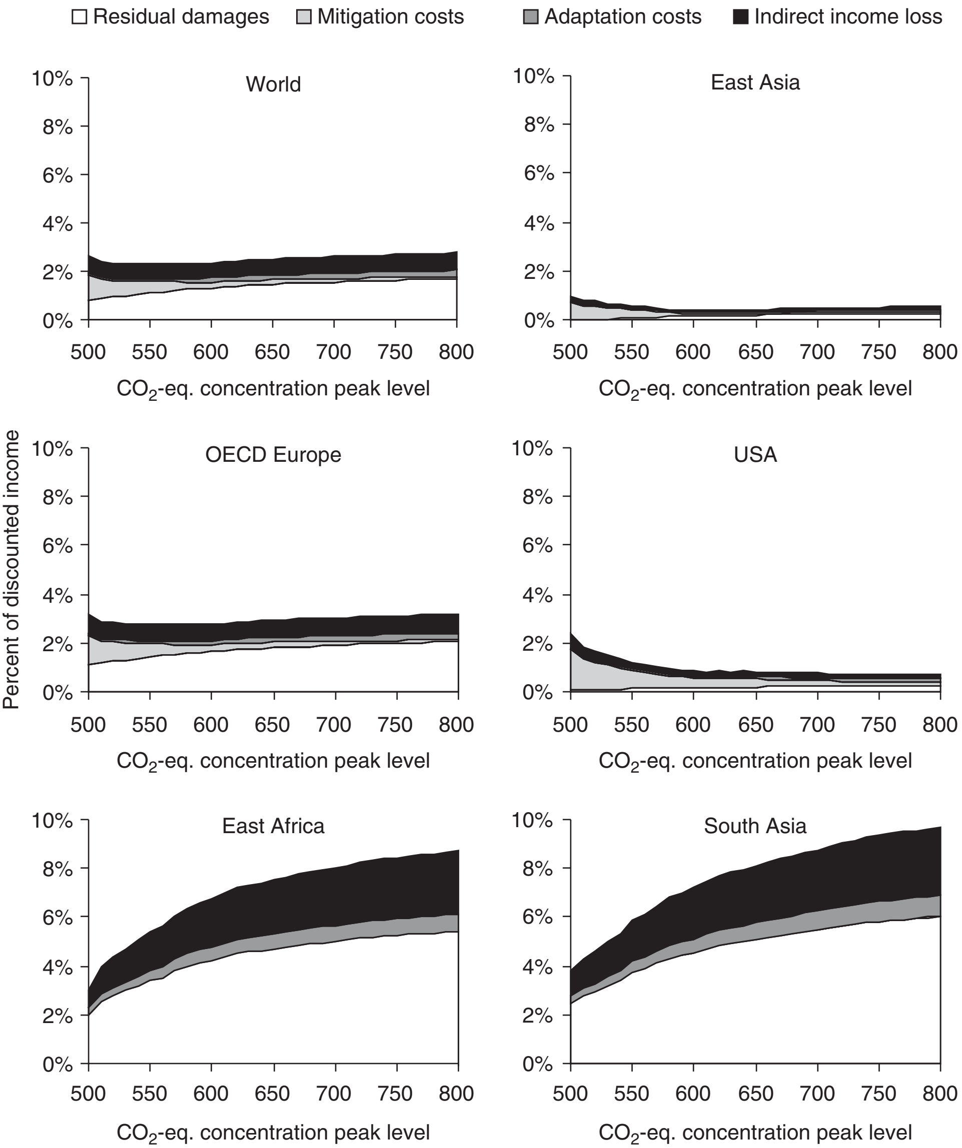

Figure 15.9 Discounted income loss in selected regions due to different climate change costs components for a range of concentration peak levels (in ppm) and a 'multi-stage' burden sharing regime, as percentage of discounted income. Mitigation costs in East Africa and South Asia are slightly negative and included in the residual damage estimates.

(a result which is well known from the game-theoretic literature on international agreements: see Barrett 1994; Finus *et al*. 2006).

Second, the variation in discounted income loss between different climate mitigation targets tells us something about the costs of not reaching the climate mitigation target with lowest costs. For the global economy, these costs are relatively small: for all concentration peak levels between 500 and 800 ppm carbon dioxide-equivalent, discounted income losses lie in the relatively narrow range of 2.3 per cent to 2.8 per cent. For Europe and East Asia, differences in discounted income loss are relatively small as well. For the United States, discounted income loss for concentration peak levels below 600 ppm carbon dioxide-equivalent are projected to increase quite strongly due to rapidly increasing mitigation costs, although the relatively low damages (as estimated by the RICE model) imply that total costs in the United States remain below the world average even for a 500 ppm carbon dioxide-equivalent concentration target. In East Africa and South Asia, the discounted income loss is much higher than the world average, due to higher projected residual damages. Moreover, income losses also increase strongly for higher concentration targets as the impacts of climate change become more severe. This indicates that adaptation is especially important in high-impact regions, which are mostly developing regions.

Finally, it is worth noting that the slope of the residual damage curve in Figure 15.9 for all regions decreases with increasing concentration levels. This may sound counterintuitive, since damages increase exponentially with temperature increase, and higher concentrations imply higher temperatures. The explanation lies in the timing of mitigation. If we want to achieve a very stringent mitigation target, very early emission reductions are required. This means that residual damages will be lowered relatively early as well. On the other hand, if we want to achieve a less stringent concentration target, emissions in the short run can stay the same and should be reduced only in the longer run. Therefore, residual damages are only lowered in the long run as well. Because of discounting, the further residual damages occur in the future, the smaller the impact on the present value of these damages. This explains why the residual damage curve in Figure 15.9 is concave.

15.4 Conclusions

In this study, we used an integrated assessment model to analyse the interactions between adaptation costs, mitigation costs and emissions trading, and residual damages. Our analysis is subject to a number of qualifications and caveats, the most important being the large uncertainties of the damage estimates by the RICE model of Nordhaus and Boyer (2000), on which we base our method for modelling adaptation. Therefore, the results should be interpreted with sufficient care. However, we can still draw a number of conclusions.

First, we have shown that adaptation and mitigation are not substitutes of each other. Adaptation and mitigation have completely different dynamics. Adaptation can effectively reduce climate change damages in the shorter run, but is much less effective in the long run since it does not reduce climate change itself. Mitigation is very effective in reducing climate change damages in the long run. Implementing both adaptation and mitigation gives the best results according to our model.

Second, even though the costs of adaptation are small compared to residual damages and mitigation costs, adaptation is important in the context of reducing potential damages, especially in lower-income regions. Keeping in mind that our results depend on very uncertain estimates of damage and adaptation costs, we project that with optimal adaptation efforts more than a quarter of the potential damages are avoided by adaptation in the long run. Relatively small investments in adaptation could avoid substantial amounts of damages, especially in lower income regions where potential damages are projected to be higher.

Third, the total amount of adaptation in a region depends only in the longer term on the climate mitigation target. Without any mitigation, climate change will be stronger, increasing the need for adaptation. Regardless of the mitigation strategy, adaptation costs will increase strongly over time, as climate will change even if emissions are cut back drastically. Our model projections show that global adaptation costs will increase from USD 6 billion in 2010 to USD 125 billion in 2050.

Fourth, climate change costs differ substantially between regions. For regions such as East Africa and South Asia, income losses are much higher than the global average and rise steeply for higher concentration targets as well. This indicates that both adaptation and mitigation are important especially for these developing regions.

To sum up: adaptation will increase sharply over time even if strong mitigation measures are taken, and adaptation is especially important in developing regions. This indicates that the chances that developing countries join a climate mitigation regime could be higher if adaptation, and especially adaptation funding, is incorporated in such a regime.

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