**DIW** Berlin

Deutsches Institut
für Wirtschaftsforschung

**DIW Berlin: Politikberatung kompakt**

13

# Costs of Inaction and Costs of Action in Climate Protection – Assessment of Costs of Inaction or Delayed Action of Climate Protection and Climate Change

Claudia Kemfert
Katja Schumacher

## Final Report

Project FKZ 904 41 362
for the Federal Ministry
for the Environment

Berlin, 2005

## DIW Berlin: Politikberatung kompakt 13

Claudia Kemfert*
Katja Schumacher*

# Costs of Inaction and Costs of Action in Climate Protection

## Assessment of Costs of Inaction or Delayed Action of Climate Protection and Climate Change

Final Report

Project FKZ 904 41 362 for the Federal Ministry for the Environment

Berlin, 30. November 2005

* DIW Berlin, Abteilung Energie, Verkehr, Umwelt. ckemfert@diw.de; kschumacher@diw.de
(German Institute for Economic Research, Dept. Energy, Transport, Environment)

IMPRESSUM

DIW Berlin
German Institute for Economic Research
Königin-Luise-Str. 5
14195 Berlin
Tel.  +49 (30) 897 89-0
Fax  +49 (30) 897 89-200
www.diw.de

ISBN 3-938762-02-0
ISSN 1614-6912

# Table of Contents

# Tables and Figures

# 1 Summary

The ultimate objective of the climate convention and of related instruments like the Kyoto protocol is to reduce greenhouse gas emissions to a level that avoids dangerous climate change. In order to considerably reduce risks of climate change, the European Union already decided a climate protection target: to prevent global surface temperature to increase more than 2°C (Celsius) compared to pre industrial levels. The number and intensity of extreme weather events, such as flooding caused by heavy precipitation, heat waves and big storms has considerably increased in the past. With a temperature increase of over 2°C the probability of even more frequent heavy climate events could rise substantially. Big re-insurance companies, such as the MunichRe, figured out that extreme weather events have risen by a factor 3.1 since 1960. This has led to drastic growth in both economic and insured losses. For example, the flooding in Europe in the year 2003 caused losses of 9.3 billion Euros only in Germany.

This study aims at calculating the costs of inaction, i.e. when no climate policy takes place, contrasted with the costs of action, i.e. the costs of climate policy. We intend to shed some light on what might happen if concrete climate policy started today or started at a later point of time. In particular, we are interested in the costs of inaction, and thus the potential economic damages from climate change. For this, we apply a world economic model that includes damage functions and economic interrelations from climate impacts. We assess the potential impacts of climate change and provide some sensitivity analyses with respect to the assumptions on the reaction of the climate system.

The main difficulties with such quantitative impact studies lie in the monetary valuation of damages from climate change and in regional as well as in temporal differences of action and impact. Mitigation costs and ancillary benefits as well as adaptation costs and benefits typically accrue in the same region. However, this is not true for mitigation benefits: local or regional emissions reduction efforts result in globally and temporally dispersed benefits. Benefits of avoided climate change impacts amass much later than the costs of mitigation (OECD 2004). Impact assessment studies most often only evaluate responses to changes in mean climate and not those associated with abrupt changes or extreme events. Furthermore, monetising damages of goods like biodiversity or health is very problematic as the uncertainties are very large and inherent value judgements cannot objectively be made.

This paper assesses and compares the costs and benefits of climate protection, i.e. the „costs of inaction“, which include climate damages, adaptation costs on the one hand with the “costs of action”, i.e. mitigation costs on the other hand. We apply a scenario approach with which we compare different emissions stabilisation scenarios to a reference case. The assessment of the “costs of inaction” is based on a globally very aggregated and simplified damage approach, which crucially depends on the parameter values taken into account.

The scenarios aim at avoiding a global surface temperature increase of more than 2°Celsius (C) compared to pre-industrial levels. Especially we assess a reference scenario where no climate protection or emission mitigation actions take place and two mitigation scenarios: scenario one “early Action” (ScenA) intends not to overshoot the 2°C limit, scenario two “delayed Action” (ScenB) starts with drastic emission reduction effects at a later time period (2030).

It turns out that only with early emission reduction warming beyond the limit of 2°C can be avoided. Even drastic emissions reduction efforts starting at a later point of time (2030) will not be sufficient to stay within the 2°C limit. Damages from climate change are lower if the limit is met. The costs of action are substantial. However, the avoided damage costs are even higher than the costs of action. This is particularly the case when emission reduction efforts are postponed to later time periods. Both policy scenarios provide benefits in terms of avoided damages. ScenA leads to higher positive effects than ScenB in terms of gross world product (GWP) because the avoided damages are higher and overcompensate the mitigation costs.

## 2 Introduction

The number and intensity of extreme weather events, such as flooding caused by heavy precipitation, heat waves and big storms has considerably increased in the past. With a temperature increase of over 2°C the probability of even more frequent heavy climate events could rise substantially. Big re-insurance companies, such as the MunichRe, figured out that extreme weather events have risen by a factor 3.1 since 1960. This has led to drastic growth in both economic and insured losses. For example, the flooding in Europe in the year 2003 caused losses of 9.3 billion Euros only in Germany.

The ultimate objective of the climate convention (Art. 2) and related instruments like the Kyoto protocol is to reduce greenhouse gas emissions to a level that avoid dangerous climate change. In order to reduce risks of climate change considerably, the European Union already decided a climate protection target: to avoid global surface temperature increase of more than 2°C compared to pre-industrial levels. The temperature target has been repeatedly reiterated by the Environmental Council since 1996, and, in March 2005, also by the Heads of Government of the EU. However, even an increase of the global temperature by 2 C compared to the pre- industrial level leads to substantial climate impacts, such as on ecosystems and water scarcity. In order to stay within the temperature limit of 2°C with high likelihood, a stabilisation of greenhouse gas concentrations of 400 ppm would be necessary (Hare and Meinshausen 2004). Greenhouse gas emissions need to be reduced drastically, globally by at least 50% up to 2050.

After the Russian ratification of the Kyoto protocol, the Kyoto protocol entered into force on 16 February 2005. This also means that in 2005 international negotiations for further emissions reduction targets need to begin. The German government is aiming for an EU greenhouse gas emission reduction target of 30% by 2020 compared to 1990 emissions level and similarly ambitious targets for other industrialised countries. Germany would then be prepared to accept an emissions reductions target of 40% by 2020.

The European spring council (March 2005) reaffirmed that the overall global annual mean surface temperature should not exceed 2°C above pre-industrial levels. Furthermore, the Council notes that there is increasing scientific evidence that the benefits of limiting overall global annual mean surface temperature increase to 2°C above pre industrial level outweigh the costs of abatement policies. The Council encourages considering mid- to long-term strategies and targets (2020: 15-30 %) and therefore asked the Commission to continue to work on a cost benefit analysis of emissions reductions strategies. The costs of climate protection need to be compared with avoided damages, avoided adaptation costs and ancillary benefits (as for example avoided air pollution). There are only a few quantitative assessment studies that evaluate the cost of inaction, i.e. the costs of climate change (e.g. Tol et al. 2004, Nordhaus and Boyer 2000, Fankhauser 1994, Hope 2004. For an overview see for example Pittini and Rahman 2004 and Schellnhuber et al. 2004). The main difficulties with such quantitative impact studies lie both in regional as well as timely differences. Mitigation costs, adaptation costs and benefits and ancillary benefits typically accrue in the same region. However, this is not true for mitigation benefits: local or regional emissions reduction efforts result in globally and timely dispersed benefits. Benefits of avoided climate change impacts amass much later than the costs of mitigation (OECD 2004). Impact assessment studies most often only evaluate responses to changes in mean climate and not those associated with abrupt changes or extreme events. Furthermore, quantitative impacts are difficult to assess, as both the evaluation of non-market impacts as well as the aggregation of regional impacts is very problematic. In particular, monetising damages of goods like biodiversity or health is very problematic as the uncertainties (as for example the chosen discount rate) and impreciseness are extraordinary large. Because of these difficulties cost benefit analyses alone are not an appropriate tool for the assessment and determination of strategies and targets for climate protection.

This paper assesses and compares the costs and benefits of climate protection, by quantifying so called „costs of inaction“, i.e. climate damages and adaptation costs, on the one hand and the “costs of action”, i.e. mitigation costs on the other hand. We compare the benefits of mitigation (that means the avoided damages of climate change, avoided adaptation costs and ancillary benefits), with the costs of action, i.e. the costs of meeting concrete emissions reductions targets to stay within the limit of 2°C global warming above pre-industrial levels. In particular, we assess a reference scenario where no climate protection or emissions mitigation activities take place and compare it with two mitigation scenarios: scenario A (“early action”) intends to avoid average global warming of more than 2°C, scenario B starts with are economically feasible at a later time period (2030) (“delayed action”).

## 3 Overview of Impact – Integrated Assessment- Studies

The majority of studies in climate policy have focussed on the costs of climate policy, i.e. the costs of action. To date, detailed information is available on the regional and global costs of various climate policies. Policy makers want to compare these costs to the benefits that arise due to the climate policies they initiate. Not many studies so far, however, have tackled the challenge of evaluating the costs of inaction or the benefits of climate policies. Many problems occur that make a simple cost benefit analysis challenging. Those problems relate to the dispersion of costs and benefits over time and space, to uncertainties and the synthesis of quantitative and qualitative information. This section thus gives a detailed overview of current research activities in this area. Among the initiatives, the most comprehensive one is the recently published OECD book on 'the benefits of climate change policies' (2004).[1]

The OECD book presents a selection of review papers each focussing on different aspects of the benefits of mitigation policy. The study points out that problems with coherent benefits research arise for two reasons, partly due to lack of research and partly due to lack of synthesis of research into some coherent measure or set of measures for policymakers and the public to understand and weigh the benefits. The goal, thus, is to provide a survey of available information and to set out a framework and priorities for future research work. The overall aim of the OECD initiative is to improve the information on the benefits of climate policies for policymakers. Several interesting studies exist that focus on the quantitative assessment of the costs and benefits of mitigating climate change with the help of integrated assessment models (e.g. Tol et al. 2004, Nordhaus and Boyer 2000, Fankhauser 1994, Hope 2004, etc.). The models differ in their regional, sectoral and time coverage and need to be seen in light of the model structure, assumptions and uncertainties as pointed out below. For a survey and discussion of studies using an integrated assessment approach see also Pittini and Rahman (2004) and Schellnhuber et al. (2004).

## 3.1 Climate change: Why bother?

The Intergovernmental Panel on Climate Change (IPCC) in its Third Assessment Report sets out five reasons for concern relating to I) the risks to unique and threatened systems, II) the risks from extreme climate events, III) the distribution of impacts, IV) to aggregate impacts and V) to risks from future large-scale discontinuities, and assessed the links between those concerns (or impacts) and global mean temperature change in 2100 (see Figure 1). These can then be linked again to different emissions pathways or concentration levels as for example provided by the IPCC's Special Report on Emissions Scenarios (SRES). (IPCC 2000) and stabilisation scenarios based on these SRES scenarios. It shows that even a $CO_2$-concentration of 450ppm which is well known to be associated with high costs is likely to lead to an increase in global mean temperature above 2°C compared to 1990 (0.6°C have to be added to get the warming above pre-industrial levels) (see also Hare and Meinshausen, 2004) and to substantial impacts related to the reasons of concern I and II and also some for III and IV. The

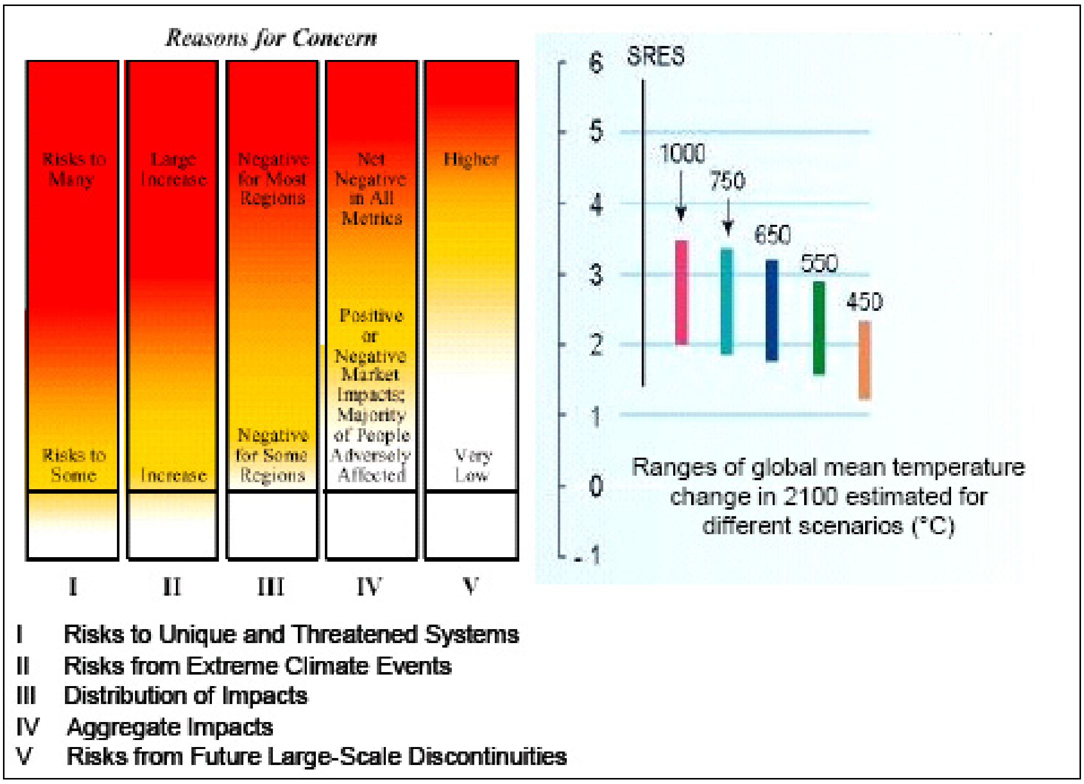
---

[1] That is the benefits of avoiding climatic change and reducing the likelihood of any resulting net adverse impact.

IPCC assessment clearly reveals the high and multidimensional uncertainties that exist regarding any impact analysis.

Impacts of climate change occur not only due to a change in mean climate (warmer mean temperature, melting of glaciers and pole caps), but also in due to changes in climate variability and frequency and severity of extreme events (such as the magnitude and quantity of droughts, storms and floods) and due to irreversible abrupt non-linear changes. It would mean that the system - due to external forces - is pushed from one equilibrium to the other, thus crossing a threshold that can lead to unpredictable and/or irreversible changes. Examples for such events are a change in the thermohaline circulation in the North Atlantic Ocean or the die-back of the Amazon forest, leading to a release of the stored carbon thus enhancing global warming.

Figure 1 Relating global mean temperature change to reasons for concern



**Source: IPCC (2001), Synthesis Report.**

Impact studies so far most often focus on changes in mean climate only. However, a number of studies, among others by Schneider and Lane (2004), Narain and Fisher (2000), Baranzini et al. (2003), suggest that accounting for variability in climate and abrupt non-linear change is likely to shift the 'optimal' level of abatement. Moreover, Schneider and Lane (2004) argue that a reduction of the likelihood of high consequence events could be among the main benefits of early and stringent GHG mitigation.

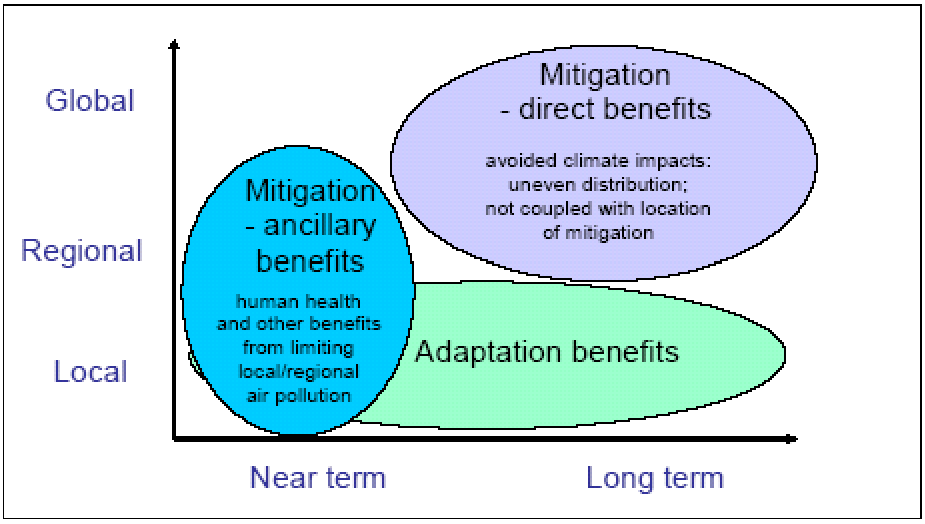
## 3.2 Benefits – What? Where? When?

For the assessment of global mitigation policy benefits it is important to note the various dimensions of benefits. Firstly, a common understanding is needed what kind of benefits may occur. There are direct benefits of mitigation in the form of avoided damages in, for, example agricultural production, coastal and water resources, terrestrial ecosystems productivity, biodiversity etc. In addition, there are adaptation benefits, in form of avoided adaptation costs, and indirect or ancillary benefits. Ancillary benefits of GHG mitigation exist in the form of a reduction of harmful air pollutants such as sulphur dioxide ($SO_2$), nitrogen dioxide ($NO_x$), volatile organic compounds (VOC) and primary particulate matter ($PM_{10}$). (Schellnhuber et al. 2004) Carbon sequestration technologies often also remove other pollutants from the waste gas stream. A policy that reduces the use of fossil fuels has beneficial effects in terms of mitigating both climate change and regional scale/large scale air pollution. In addition, considerable costs of fossil fuel transports including damage costs from accidents such as oil spills would be mitigated., Climate policy may also lead to a diversification of energy sources, which would decrease the economic and societal sensitivity to disruption of supply.

The other dimensions of benefits relate to the distribution over space and time. Mitigation efforts undertaken now or at any point in time will lead to benefits that partly arise at a much later point of time. This requires a normative judgement of the value of future generations when comparing the costs and benefits in present time values. For economic analyses an appropriate discount rate needs to be chosen. Apart from the distribution of costs and benefits over time, the long-term horizon of climate change presents another major research challenge. Greenhouse gases, in particular carbon, stay in the atmosphere for very long time periods, thus contributing to climate change on a long-term scale. Thus emissions mitigated today produce benefits that reach far into and beyond the 21st century. Any such long-term analysis suffers from very high uncertainties.

Similarly to the time dimension or intergenerational aspects, intragenerational or regional equity of the distribution of costs and benefits plays a major role. Mitigation costs and ancillary benefits typically occur in the same location (or region) where mitigation efforts are taken. Similarly, adaptation costs and benefits accrue in the very same location. However, mitigation costs and direct benefits from mitigation are not immediately linked. Mitigation efforts may take place anywhere in the world and reduce global GHG concentrations. The benefits from the reduction in terms of avoided climate change impacts, however, may show at a very different location from where mitigation originated. The challenge for policy makers thus is to weigh the benefits of climate policy on a global scale rather than a regional one. In this context, equity issues become of importance as the vast majority of GHG emissions stem from industrialized countries while the impacts of climate change are expected to hit less developed countries the hardest. Figure 2 provides an overview of how those different dimensions of mitigation and adaptation policy benefits are linked.

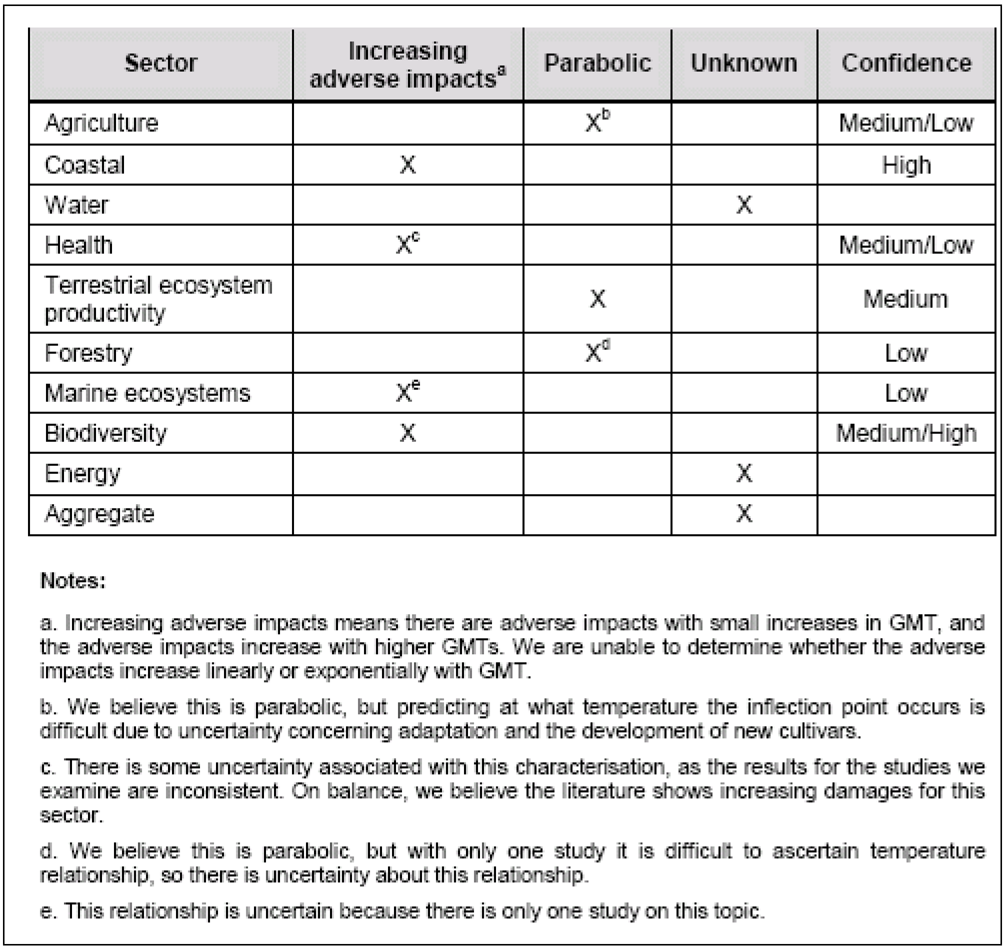
Figure 2 Mitigation and adaptation policy benefits over space and time



**Source: Morlot and Agrawala (2004)**

Another distributional aspect relates to the sectoral allocation of climate change mitigation benefits. As the IPCC's five reasons of concern show some sectors or systems will be affected harder at lower temperature increases than others. Hitz and Smith (2004) survey the existing literature on global impact from climate change by sector. The sectors cover agricultural production, coastal resources, water resources, human health, energy, terrestrial ecosystems productivity, forestry, biodiversity, and marine ecosystems productivity. The survey reveals that some sectors, such as coastal resources, health, marine ecosystems, and biodiversity exhibit increasing adverse impacts. Increasing adverse impacts means there are still adverse impacts with very small increases in global mean temperature. These adverse impacts increase with higher global mean temperatures. The authors (Hitz and Smith 2004) were unable, however, to determine whether the adverse impacts increase linearly or exponentially with global mean temperature. Other sectors, such as agriculture, terrestrial ecosystems productivity and forestry exhibit parabolic relationships between temperature increase and impact. This means that a small increase in temperature may exhibit positive impacts while the impact turns adverse for larger increases in temperature. At which temperature increase the inflection point occurs differs by sector as well as by region and is difficult to determine due to uncertainties concerning adaptation (agriculture) and the lack of studies especially for the lower range of temperature change to compare with (forestry). For the other sectors, the authors could not establish a consistent pattern between temperature and impact from the existing data. An overview of their findings together with their assessment of a level of confidence for the deciphered relationships is given in Table 1.

Table 1 Summary of sectoral damage relationships with increasing temperature



| Sector | Increasing adverse impacts[a] | Parabolic | Unknown | Confidence |
|---|---|---|---|---|
| Agriculture | | X[b] | | Medium/Low |
| Coastal | X | | | High |
| Water | | | X | |
| Health | X[c] | | | Medium/Low |
| Terrestrial ecosystem productivity | | X | | Medium |
| Forestry | | X[d] | | Low |
| Marine ecosystems | X[e] | | | Low |
| Biodiversity | X | | | Medium/High |
| Energy | | | X | |
| Aggregate | | | X | |

**Notes:**

a. Increasing adverse impacts means there are adverse impacts with small increases in GMT, and the adverse impacts increase with higher GMTs. We are unable to determine whether the adverse impacts increase linearly or exponentially with GMT.

b. We believe this is parabolic, but predicting at what temperature the inflection point occurs is difficult due to uncertainty concerning adaptation and the development of new cultivars.

c. There is some uncertainty associated with this characterisation, as the results for the studies we examine are inconsistent. On balance, we believe the literature shows increasing damages for this sector.

d. We believe this is parabolic, but with only one study it is difficult to ascertain temperature relationship, so there is uncertainty about this relationship.

e. This relationship is uncertain because there is only one study on this topic.

**Source: Hitz and Smith (2004)**

Though positive impacts appear at lower levels of temperature change in some sectors and regions, research suggests negative impacts as global mean temperatures increase beyond certain levels. Across all sectors one consistent pattern among all studies is an increasingly adverse impact beyond an approximate increase in global mean temperature of 3 to 4°C. At lower levels of temperature increase, however, a number of studies show negative impacts for some sectors. These conclusions need to be seen in light of the existing uncertainties, including a lack of impact studies for the lower temperature range and problems of estimating existing impact studies, which prevent them from identifying a precise critical temperature beyond which damages are adverse and increasing. Hitz and Smith (2004) do not attempt to aggregate impacts across sectors. This is because the results vary widely within studies, from scenario to scenario and between studies. The studies do not analyse the same scenarios or use the same baselines and are most often based on different units. Also, there are important linkages between sectors (such as agriculture and water resources), which cannot be accounted for in individual sector studies. Many studies do not take into consideration extreme events or the possibility of abrupt non-linear disruption. Also, the assumptions on the speed and nature of economic and technological development differ by study and influence how vulnerable systems will react to climate change. In addition to these concerns, all of the above mentioned aspects and uncertainties apply (regional and timely impacts, long term aspects, kind of benefits etc.).

## 3.3 From sectoral to global, from physical to economical: Aggregation and monetization of impacts

As climate change is a global problem and the costs of climate policies (costs of action) can relatively easy and meaningfully be expressed in economic units (e.g. price per ton of carbon), policymakers seek to compare these costs with the associated global benefits of climate policies (costs of inaction). However, while it is difficult to aggregate impacts across sectors, giving impacts an economic value is seen to be even more challenging. In addition to all the uncertainties mentioned, an economic valuation of climate change impacts inevitably implies value judgements with respect to which non-market impacts[2] to include and how to value them, with respect to predicting how relative and absolute impacts will develop into the future

---

[2] Non-market impacts are impacts for which a market price does not exist, such as biodiversity, ecosystems, health, tourism, recreation.

and with respect to aggregating the costs of climate change across regions and countries (equity weighting) and aggregating across generations (discount rate).

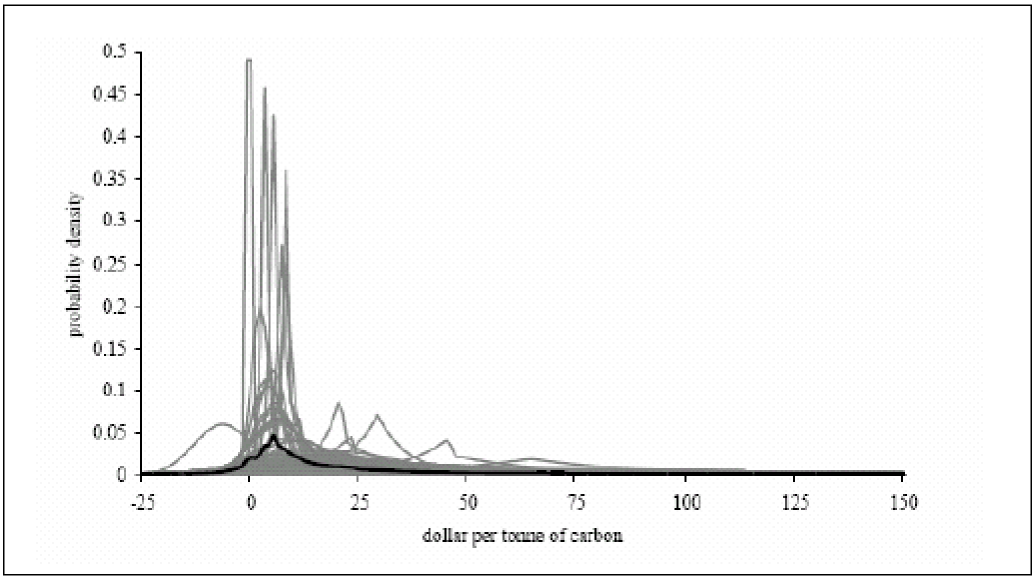
Pittini and Rahman (2004) provide an overview of findings with respect to marginal costs of climate change impacts (i.e. the social cost of carbon). The estimates mainly result from analyses with integrated assessment models (IAM). IAMs combine scientific and economic aspects of climate change into a single dynamic modelling framework. They produce estimates for the social costs of carbon either as shadow prices of carbon in comparing marginal abatement costs to marginal damage costs or as average incremental costs of a small perturbation in emissions from a business as usual baseline. Pittini and Rahman point out that results from IAMs are driven by inherent value judgements, which renders it difficult to compare carbon price estimates. In addition, the IAMs surveyed differ in their regional aggregation, in their complexity of climate and/or economic components, in their level of including non-market impacts, and in the assumptions on their business as usual baseline. Tol (2004) stresses that IAMs - in order to assess absolute damage costs - need to establish the future size of the population and the economic, natural, social and human capital stocks at risk. With a timeframe as long as global warming damages, no prediction of future developments can be done with any confidence. Scenarios are thus used to describe possible futures. They do not claim to describe the most likely future. Because of the use of these scenarios, global warming damage assessments have a contingent nature: they are contingent upon the assumptions embedded in socioeconomic scenarios, whether explicit or not In addition, Pittini and Rahman point out that there are severe limitations in the coverage of some key climate change issues, such as the impacts of low-probability high-risk impacts, extreme weather event, social contingent impacts and impacts in the areas of biodiversity, ecosystems. Thus, the social costs of carbon presented in the following need to be seen in light of the shortcomings. They will not represent any true value of the marginal damage costs until these issues are better understood and supplementary probabilistic sensitivity analyses are undertaken and incorporated into the estimates to account for uncertainties.

Findings from several review studies provide a range of a possible carbon damage costs. In particular, Pittini and Rahman (2004) refer to estimates from the following studies:

- Pearce et al. (1996) review existing studies for the IPCC 2nd assessment report and report a range of **5-125 US$/tC** (tons of carbon) in 1990 prices (or 6-160 US$/tC in 2000 prices) relating to carbon emissions from 1991-2000. For the period 2001-2010, the estimates range from **7-154 US$/tC** 1990 prices (and 9-197 US$/tC in 2000 prices). Social cost estimate increase over time, as marginal damage costs tend to increase with higher greenhouse gas concentrations.

- 8 major studies are reviewed by Clarkson and Deyes (2002) and reveal an estimated range of **50-200 US$/tC** for the global damage costs of carbon emissions. In real terms these number should be increased by approximately 1.5 US$/tC per year because the costs of climate change are likely to increase over time.
- 24 estimates from 12 studies are reviewed in Pearce (2003) and lead to a range of **6-39 US$/tC** for the social price of carbon.
- Tol (2003b) conducts a meta-analysis of 88 estimates from 22 published studies for the marginal social costs of carbon dioxide. He finds a very wide and right skewed distribution of costs (see Figure 3), with a mean at **104 US$/tC**. Weighing these estimates, Tol concludes that the marginal costs may not exceed **50 US$/tC** and are likely to be even lower than that. The weights are based on Tol's normative value judgement. They are applied to reflect different quality levels of the estimates and to account for the fact that there are groups of results in the database that originate from the same modelling exercise and thus incorporate an inherent bias. Thus, the results need to be seen in light of the method and normative assumptions chosen by Tol.

Figure 3 Meta-analysis of 88 estimates of the marginal social costs of carbon



***Source*: Tol (2003b).**

**Note:**

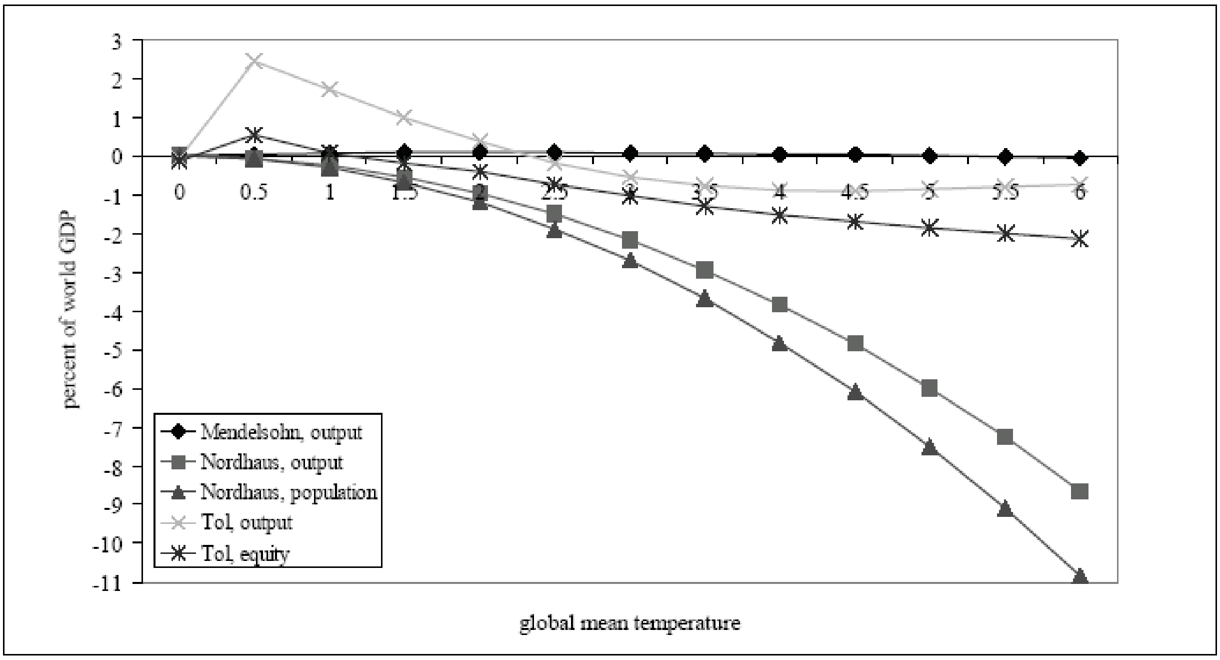
Tol (2003b) collects 88 estimates of marginal social cost of carbon dioxide figures, from 22 studies. As Tol notes, one would expect the reported estimates to vary considerably, with high to low end marginal social cost estimates ranging from USD 1666/tC through to USD 7/tC. The probability density function in grey highlights the full range of the 88 estimates. The combined probability density function appears in black.

The range of impacts of changes in global mean temperature (up to 6°C) on global GDP is illustrated in Figure 4.[3] Four scenarios from three studies with different approaches to aggregating costs show a broad range of possible damage costs. It needs to be pointed out that any such quantitative assessment and its interpretation needs to seen in light of the underlying problems and caveats as discussed above (such as differing model structures, approaches, and assumptions taken as well as differing time horizon, regions, sectors, and kind of damages covered). They do, however, serve as an illustration of the range of results from such efforts. Depending on the weighting factor used for aggregating costs across sectors and regions, some studies imply initial aggregate benefits from small changes in mean temperature while others show substantial damages even at low level of temperature changes. However, all four scenarios consistently show increasing damages (in terms of GDP losses) for higher magnitudes of climate change.

---

[3] The global GDP loss for a specific time period or point in time can be deduced for each GHG concentration scenario in multiplying the social costs of carbon (in $/tC) with the amount of global emissions (C) and comparing the resulting global total costs with global GDP to yield the percentage global loss.

Figure 4 Impact of climate change as a function of the change in global mean temperature



***Source*: Tol et al. 2004.**

**Note:**

Mendelsohn et al. (1997) aggregate impacts across different regions weighted by regional output. Nordhaus and Boyer (2000) aggregate either weighted by regional output or weighted by regional population. Tol (2002) aggregates either by regional output or by equity, that is, by the ratio of world per capita income to regional per capita income.

## 3.4 Conclusions: What to draw from the existing and where to go from here?

Despite these challenges, the OECD study (2004) points out some general patterns that can be detected in the literature

1. Some sectors, such as agriculture, may experience net positive impacts globally of a small amount of climate change
2. Some sectors show adverse impacts even for low levels of global warming (such as biodiversity, health, marine ecosystems)
3. No research indicates any positive impact from climate change as temperatures increase beyond certain levels.
4. Marginal adverse impacts emerges across all sectors for a temperature increase beyond 3-4°C in global mean temperature

5. Number of studies indicates that the economically 'optimal' level of mitigation is increased when accounting for the risks of irreversible, abrupt climate change. Thus, calling for more investment in abatement in the near-term.

A broad conclusion is that sound summary estimates of benefits in a single (monetary) measure to compare with aggregate costs may not be adequate on their own to inform policy decisions. Cost benefit methods alone may be inadequate and should be complemented with risk-based methods (such as probabilistic approaches). The OECD study calls for a presentation of benefits in two different forms: monetised estimates and physical impact estimates. They point out that a coherent set of indicators and research strategy is needed. Such a strategy would involve the following steps: Firstly, global physical variables for impacts should be researched and identified. Thereafter, regional physical variables should be tackled. These should be followed by an economic valuation leading to a set of regional monetary variables. Finally, an attempt of monetised aggregate benefits assessment can be undertaken. A modest and preliminary research goal thereby should be to have consistent and comparable regional information so that impacts associated with levels of global mitigation can be assessed.

# 4 Climate Change – Extreme Weather Events

The number and intensity of extreme weather events, such as flooding caused by heavy precipitation, heat waves and big storms has increased considerably. Table 2 illustrates extreme climate events, the probability of occurrence and potential impacts. Not only the number of extreme climate events is expected to increase but also the intensity, especially of extreme precipitation events. Some regions (particularly poor regions) will and already have been more strongly affected than other regions. It is expected that in the region of North America more storms, hurricanes and tornados with extreme wind intensities will occur. In Asia floods are more likely to happen. In Europe, however, not only extreme heat waves or floods are more likely but also storms, such as tornados (MunichRe 2002).

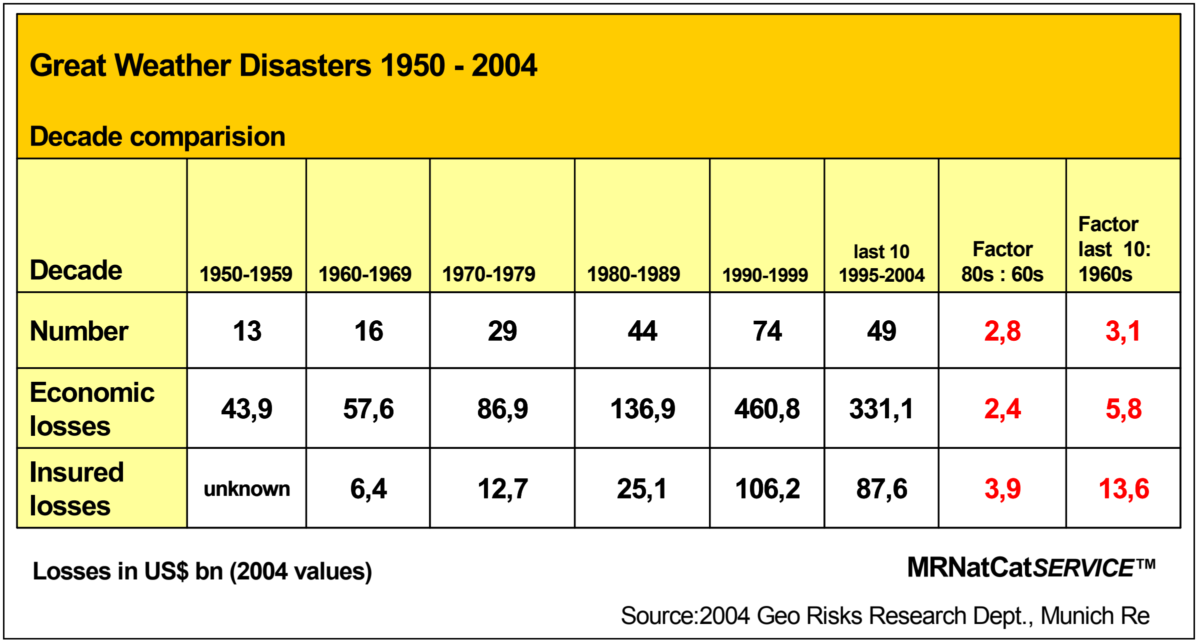
Table 2 Projected Changes during the 21st century in extreme climate phenomena and their likelihood

| Extreme Climate Event | Probability | Impacts |
|---|---|---|
| Higher max. Temperature. More Hot Days and Heat Waves over nearly all land areas | Very likely | Increased Incidence of Deaths and serious diseases in older age groups and urban poor.<br>Increase of Heat Stress in livestock and wildlife<br>Shift of Tourist Areas<br>Încrease of risks of damages to a number of crops<br>Reduction of Energie Supply Reliability<br>Increase of Energy Demand for Cooling |
| Higher minimum Temperatures, fewer cold days, frost days and cold waves over nearly all land areas | Very Likely | Decreased cold- related human Morbidity and Mortality<br>Decreased Risks of Damages to a number of Crops, and increased Risks to Others<br>Extrended Range and Activity of some pest and Disease Vectors<br>Reduced Heating Energy Demand |
| More Intense Precipitation Events | Very Likely | Increased Flood, Landslide, Avalanche and Mudslide Damage<br>Increased Soil Erosion<br>Increased Flood Runoff could Increase Recharge of some Floodplain Aquifiers<br>Increased Pressure on Government and Private Flood Insurance Systems |
| Increased Summer Drying over most Mid-Latitude Contiental Interiors and associated Risks of Drought | Likely | Decreased Crop Yields<br>Increased Damage to Building Foundations caused by groud Shrinkage<br>Decreased Water Resource Quantity and Quality<br>Increased Risk of Forest Fire |
| Increase in Tropical Cyclone Peak Wind Intensities, mean and peak precipitation intensities | Likely | Increased Risk to Human Life, Risk of Infection Disease Epidemics and many other Risks.<br>Anstieg der Risiken für Krankheiten und Epidemien<br>Increased Coastal Erosions and Damage to Coastal Buildings and Infrastructure.<br>Increased Damage to Coastal Ecosystems such as Coral Reefs and Mongroves. |
| Intensified Droughts and Floods associated with El Nino events in many different Regions | Likely | Decreased Agricultural and Rangeland Productivity in Grought- and Flood Prone Regions.<br>Decreased Hydro- Power Potentials in Drought prone Regions |
| Increased Asian Monsoon Precipitation Variability | Likely | Increase in Flood and Drought Magnitude and Damages in Temperature and Tropical Asia |
| Increased Intensity of mid- latitude storms | Low | Increased Risk to Human Life and Health<br>Increased Property and Infrastructure Losses<br>Increased Damage to Coastal Ecosystems |

Source: IPCC (2001).

Table 3 shows the number of extreme weather events and their economic and insured losses from 1950 until today. As the table shows, the number of extreme weather events went up drastically. From the 1960s to the 1980s the number of such events went up by a factor of 2.8. Moreover, within the last ten years the number of extreme events was as much as 3.1 times higher than in the 1960s. This led to drastic increases for both economic and insured losses (Table 3 and Figure 5).

Table 3 Great weather disasters 1950- 2004



**Great Weather Disasters 1950 - 2004**

**Decade comparision**

| Decade | 1950-1959 | 1960-1969 | 1970-1979 | 1980-1989 | 1990-1999 | last 10 1995-2004 | Factor 80s : 60s | Factor last 10: 1960s |
|---|---|---|---|---|---|---|---|---|
| Number | 13 | 16 | 29 | 44 | 74 | 49 | 2,8 | 3,1 |
| Economic losses | 43,9 | 57,6 | 86,9 | 136,9 | 460,8 | 331,1 | 2,4 | 5,8 |
| Insured losses | unknown | 6,4 | 12,7 | 25,1 | 106,2 | 87,6 | 3,9 | 13,6 |

**Losses in US$ bn (2004 values)**

**MRNatCat*SERVICE*™**

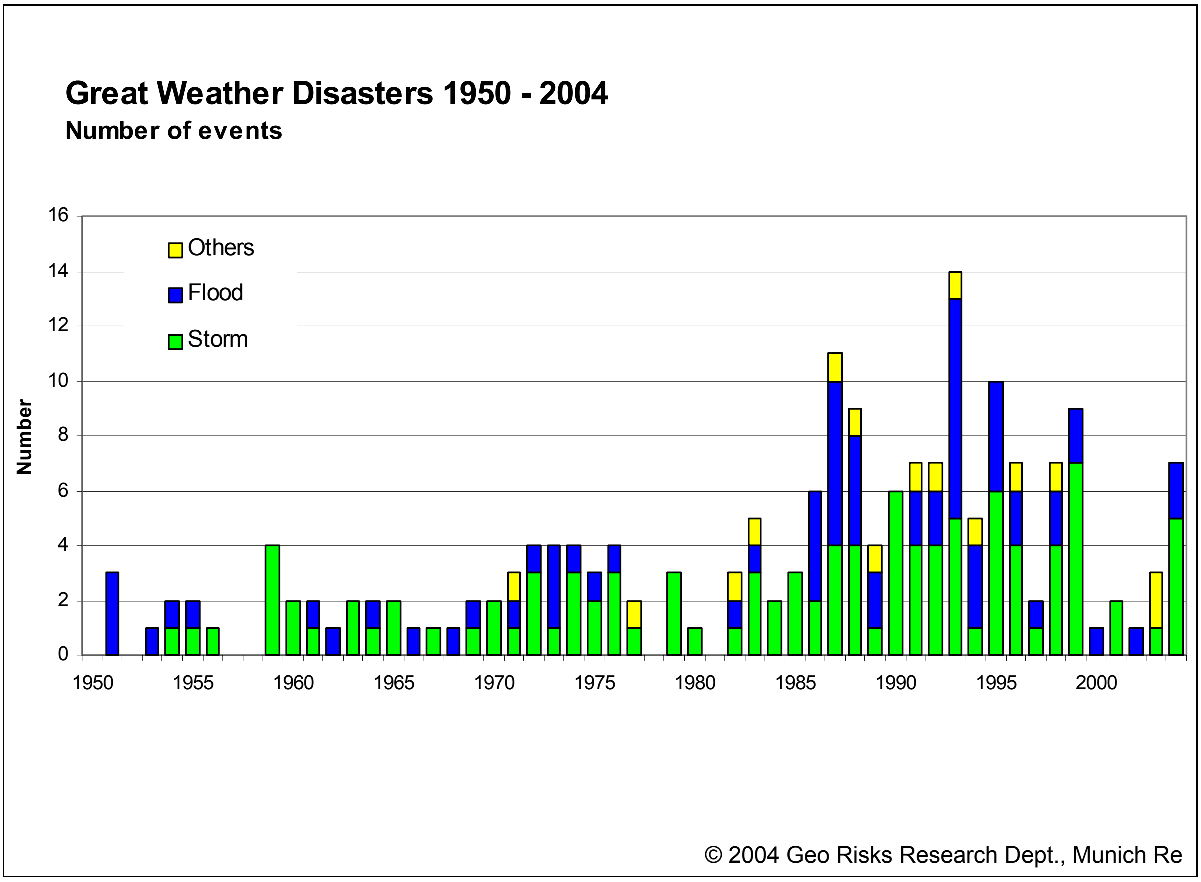
Source:2004 Geo Risks Research Dept., Munich Re

Extreme heat phenomena and precipitation events also happened in Europe (including Germany): in the summer of 2002 Middle and Eastern Europe were infested by a flood catastrophe, caused by heavy rainfalls. This extreme weather event affected the Eastern and Southern part of Germany, the South West of the Czech Republic and Austria and Hungary caused by the strong flooding of the main rivers, Danube, Elbe, Moldau, Inn and Salzach. The flood hit Germany, Austria and the Czech Republic the hardest. Economic damages amounted to up to 9.2 billion Euros in Germany only.[4]

---

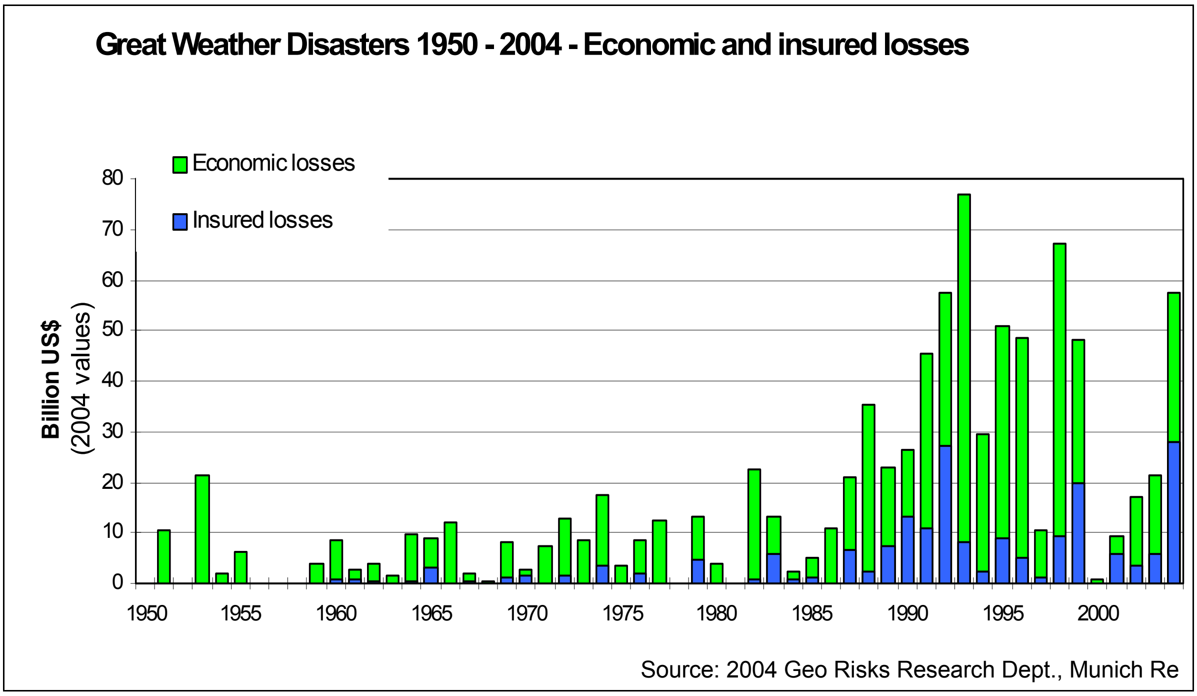
[4] One of the largest re-insurance companies, the Munich Re assessed the damages associated with the flood, see Münchner Rück: Jahresrückblick Naturkatastrophen 2002, München 2002.

Figure 5 Great weather disasters 1950-2004



© 2004 Geo Risks Research Dept., Munich Re

Figure 6 Economic and insured losses of great weather disasters 1950-2004



Source: 2004 Geo Risks Research Dept., Munich Re

In the summer of 2003, only one year after the big flood, Europe suffered from an extreme heat wave. The economic damages included increased diseases (such as cardiovascular problems or, for example, malaria that can occur also in the European country area) and an increased number of heat related deaths. Especially in France, the mortality rate of elderly people increased considerably in this period. Furthermore, damages of crop gains, disruption of energy supply and an increase of forest fires, especially in Southern Europe, took place.[5] In total, economic damages related to the European heat wave can be assessed at 10 to 17 billion Euros.[6]

## 5 Costs of Action versus Costs of Inaction of Climate Protection – A Quantitative Assessment

We assess the costs of action, i.e. the costs of emissions reduction, and the costs of inaction, i.e. the impacts of human induced climate change, with the help of a quantitative modelling tool (WIAGEM - World Integrated Assessment General Equilibrium Model). We compare three scenarios: The reference scenario, which does not include any climate protection measures. Scenario A (ScenA, “early action”) limits the increase in global surface temperature to 2°C, while Scenario B (ScenB, ”delayed action”) defers the introduction of emissions reductions to a later point of time (2030). Here, we assume that concrete emissions mitigation policies that intend to reach specific emissions reduction targets start after 2030. No climate policy takes place before 2030.

Our analysis is performed using the multi-regional WIAGEM model. WIAGEM is an integrated economy-energy-climate model that incorporates economic, energy and climatic modules in an integrated assessment approach (Kemfert 2002a and 2002b). To evaluate market and non–market costs and benefits of climate change, WIAGEM combines an economic model - with special focus on the international energy market - with a climate model that accounts for temperature changes and sea level variations. The design of the model focuses on multilateral trade flows. The representation of economic activities is based on an intertemporal general equilibrium approach and contains the international markets for oil, coal and gas.

---

[5] High water temperatures of rivers due to high outside temperatures cause risks of inadequate cooling of nuclear reactors. In 2003, this initiated a shut down of nuclear power plants in Germany and France.

[6] Tony Blair assessed the economic damages at about 13.5 billion US$ and 26.000 fatalities, see speech of the British Prime Minister on the occasion of the 10th anniversary of the “Price of Wales Business & the Environment Programme”, London 14. September 2004.

The climatic model is based on general interrelations between energy and non-energy related emissions, temperature changes and sea level variations, all inducing substantial market and non-market damage cost economic impacts. WIAGEM accounts for all six greenhouse gases (GHG) that potentially influence global temperature, sea level variation and the assessed probable impacts in terms of costs and benefits of climate change. Additionally, the model includes net changes in GHG emissions from sources and removals by sinks resulting from land use change and forestry activities.

Market and non-market damages are evaluated according to the damage costs approaches of Tol (2002, 2003 and 2004) who calculates different damages of regional climate change. To assess impacts by climate change, we follow Tol's approach (2003) to cover impacts on forestry, agriculture, water resources and ecosystem changes as an approximation of a linear relationship between temperature changes, per capita income or GDP and adaptation costs due to climate change. This means, increased emissions lead to an increase of the global surface temperature which causes global economic impacts. Regional economic imapcts depend on the countries economic performance and population development, i.e. per capita income. Tol (2003) estimates climate change impacts covering a variety of climate change impacts. Along with sectoral impacts on agriculture, forestry, water resources and energy consumption, he covers impacts on ecosystems and mortality due to vector borne diseases and cardiovascular and respiratory disorders. In addition to the damage cost assessments of Tol, we implement adaptation costs and additional costs to the economy lowering other investments (crowding out effect).

We include the same regional damage functions in our model. However, the damage functions are disaggregated according to the specific sort of damage (impacts on forestry, water, mortality). We assume that there is a functional relationship between overall temperature change and regional economic income (see Annex). The model results differ substantially from the findings of Tol (2004). This is because of two main reasons. First; we apply a fundamentally different global economic approach than Tol (2002) applies in his cost assessment study. We use a global general equilibrium approach that covers interregional and intersectoral trade effects, he uses a much simpler approach that neglects the interregional trade effects. The model applies a recursive dynamic approach so that we cover feedback effects from damages or other shocks. This means, in each time period (the model covers 5 year time intervals), impacts occur due to temperature change and regional per capita productivity change . This affects the dynamic impacts in the model: if impacts of climate change occur countries face higher expenditures. These expenditures cannot be spent as initially planned (thus crowding out investment). The main difference in the modelling framework here in comparison to Tol is that we apply a recursive dynamic approach where countries face impacts of climate change. Second, we include a detailed climate model that assesses the temperature changes from emission profiles (Kemfert 2002). Both reasons cause the fact that the dynamic feedback effects from the climate and the economic system yield much higher damage costs as earlier studies. In addition to the pure economic income effects we cover economc shocks due to adaptation. Countries spend a certain amount on adaptation when climate change occurs.[7] These expenditures are crowding out investments that cannot be spent as previously intended in a growth model. Adaptation (or protection costs) in WIAGEM mean costs that occur to adapt to damages. They do not prevent future damages. Future damage costs are only reduced in the following way: with less climate change by, for example reduced emissions, countries spend less protection costs. Ancillary benefits are related to the level of emissions. A reduction in emissions implies higher ancillary benefits. We find that these effects cause reactions on economic development.

Figure 7 graphically illustrates the modelling structure and the interaction of economic activities, energy consumption, climate and ecological impacts in WIAGEM. Uncertainty about the correct determination of the model, data and key parameters distorts the understanding of the social, economic and ecologic impacts of climate change. Uncertainties could justify postponing significant mitigation efforts. However, uncertainty also includes the risk of significant climate changes that induce considerable impacts. The uncertainty about data quality is reduced because the model is based on a detailed economic database representing a well-known and scientifically accepted economic database. Model and parameter uncertainties are covered by choosing an innovative modelling approach and by including parameter sensitivity analysis.

WIAGEM is a multi-sector, multi-region dynamic intertemporal integrated assessment model. The model covers a time horizon of 100 years and solves in five-year time increments.[8] The basic idea behind this modelling approach is the evaluation of market and non-market impacts

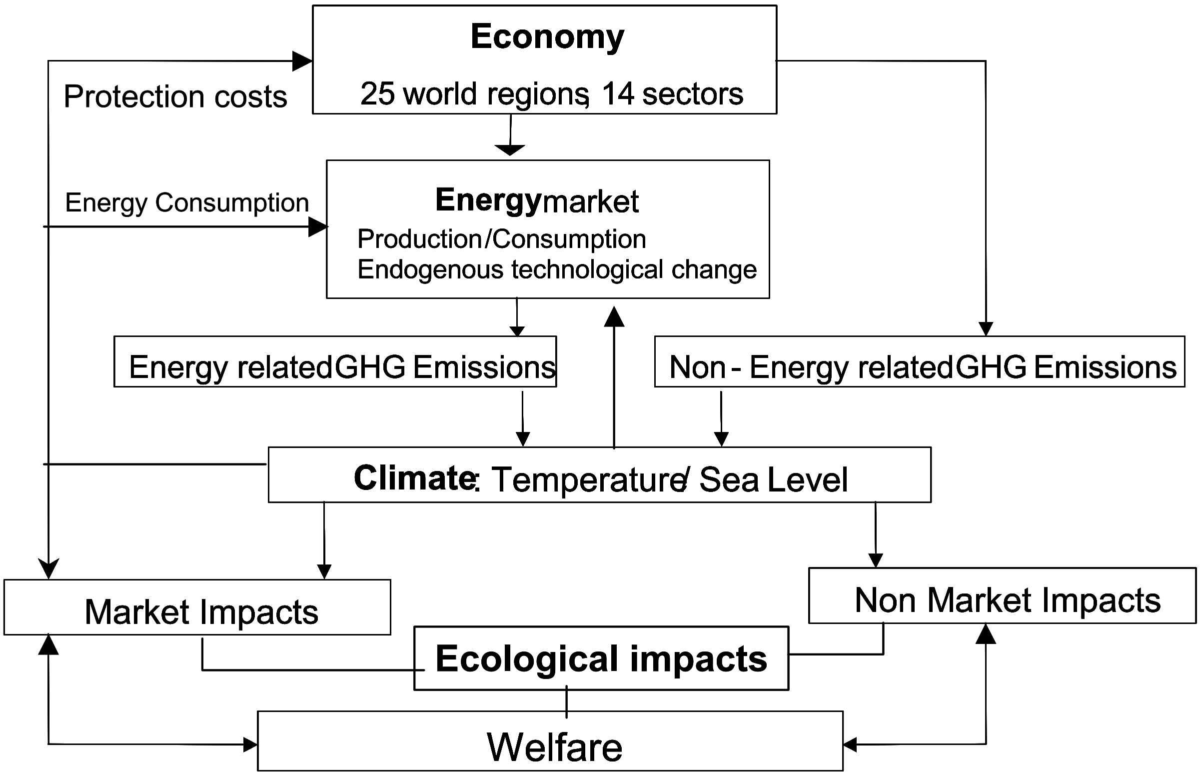
---

[7] If climate change is reduced (by for example reduced emissions), countries spend less percentage of investments for adaptation.

[8] See Kemfert (2002b) for a detailed model description.

induced by climate change. The economy is represented by 25 world regions, which are further aggregated into 11 trading regions for this study (see Table 4).

Figure 7 Modelling structure in WIAGEM



The economy of each region is disaggregated into 14 sectors, including five energy sectors: coal, natural gas, crude oil, petroleum and coal products, and electricity. Goods are produced for the domestic and export markets. The output of the non-energy sectors is aggregated into a non-energy macro good. WIAGEM covers a production function that allows for (imperfect) substitution between the input goods, labour, energy (i.e. coal, oil and gas) and capital (so called constant elasticity of substitution CES production function). The substitution elasticities are crucial parameters of the model: if we allow for a very good substitution option between the individual energy inputs, mitigation costs may be reduced as countries simply substitute coal with gas. Vice versa, if we allow for low substitution options, countries face higher mitigation costs, as it is more difficult to substitute for example coal with gas.

The same functional form (CES) is assumed for the household's utilities: they can choose between current consumption or savings, under the constraint of individual incomes. Also here the substitution elasticity is a crucial parameter, as with high savings and low current consumption economic growth can be lower. The basic assumptions for the elasticity values are shown in Table 5.

Table 4 Definitions of countries and regions in WIAGEM

| | Regions |
|---|---|
| ASIA | India and other Asia (Republic of Korea, Indonesia, Malaysia, Philippines, Singapore, Thailand, China, Hong Kong, Taiwan) |
| CHN | China |
| CNA | Canada, New Zealand and Australia |
| EU15 | European Union |
| JPN | Japan |
| LSA | Latin America (Mexico, Argentina, Brazil, Chile, Rest of Latin America) |
| MIDE | Middle East and North Africa |
| REC | Russia, Eastern and Central European Countries |
| ROW | Other Countries |
| SSA | Sub Saharan Africa |
| USA | United States of America |

WIAGEM covers the option to increase low carbon technologies which lowers mitigation costs. Countries invest in R&D expenditures that brings low carbon technologies with reduced costs. Even those countries can benefit by technological changes that do not increase their expenditures in R&D by so called spillover effects: if, for example, Europe invents a new low carbon technology, it will be exported also to other countries (e.g. China).

Table 5 Key parameter of model WIAGEM

| Type of elasticity | Value |
|---|---|
| Armington elasticity of substitution | 1 |
| Armington elasticity of transformation | 2 |
| Elasticity of fossil fuel supply | 1 (coal), 4 (gas, oil) |
| World interest rate | 2 |
| Elasticity of substitution between non-energy and energy composite in production and final demand | 0.25-0.5 (Annex B),<br>0.20-0.4 (non-Annex B) |
| Interfuel elasticity of substitution | 0.5 (final demand)<br>2 (industry) |

In addition to the non-energy macro good, oil, coal and natural gas are traded internationally. The global oil market is characterized by imperfect competition to reflect the ability of the OPEC regions to use their market power to influence market prices. Coal is traded in a competitive global market, while natural gas is traded in competitive regional markets with prices determined by global or regional supply and demand.

Energy-related greenhouse gas emissions occur as a result of energy consumption and production activities. WIAGEM includes all six greenhouse gases covered under the Kyoto Protocol: carbon dioxide ($CO_2$), methane ($CH_4$), nitrous dioxide ($N_2O$), and the fluorinated gases HFC, PFC and $SF_6$. Thereof the first three are considered to have the greatest impact on climate change over the 100-year period covered by the model. Key assumptions about the gases are shown in Table 6. WIAGEM also covers non-energy related emissions, we assume a constant growth rate over time, see Table 6.

Table 6 Summary key assumptions greenhouse gases[9]

| Trace Gas | $CO_2$ | CH4 | $N_2$0 |
|---|---|---|---|
| Atmospheric Concentration | | | |
| Pre- Industrial (ppmv) | 278 | 0.789 | 0.275 |
| 1992 (ppmv) | 353 | 1.72 | 0.310 |
| Energy related Emissions | | | |
| 1992 (billion tons) | 6.0 | 0.08 | 0.0001 |
| Growth rate, post 1992 | | | |
| Non-energy related Emissions | | | |
| 1992 (billion tons) | 0.2 | 0.454 | 0.0139 |
| Growth rate, post 1992 | 0 | 0.8 | 0.2 |

Impacts of climate change cover market and non-market damages; the former comprise all sectoral damages, production impacts, loss of welfare etc., while the latter contain ecological effects such as biodiversity losses, migration, and natural disasters. To assess impacts by climate change, we follow Tol's approach (2002) to cover impacts on forestry, agriculture, water resources and ecosystem changes as an approximation of a linear relationship between global temperature changes, per capita income or GDP and adaptation costs due to climate change. We estimate climate change vulnerability covering a comprehensive evaluation of diverse climate change impacts. Along with sectoral impacts on *agriculture, forestry, water resources and energy consumption*, he covers impacts on ecosystems and mortality due to vector borne diseases and cardiovascular and respiratory disorders (see Appendix I for more

---

[9] Source: IPCC (1990) and IPCC (1992)

details). We assume that there is a functional relationship between global temperature change, regional population change and economic income change that affects the impacts on ecosystems, forestry, health and water. We furthermore assume that energy consumption, here space heating and cooling, depends on the economic income, energy productivity and overall temperature change (see Annex for detailed mathematical description and parameters): That means, with increasing global temperature impacts of climate change increase, depending on the regional economic performance of a country (per capita income) and the population development. We assume a linear relationship between temperature change and climate change impact on forestry and water. Energy consumption for heating and cooling depends on the temperature development, population and income change, and technological progress within the energy sector. The loss of ecosystems depends on the per-capita income change and population change. We furthermore assume a non-linear relationship between health[10] (mortality) and regional temperature change and income. The main shortcoming of this approach (from Tol covered in this study) is the assumption of a global surface temperature that leads to regional impacts, and not a regional temperature development. Only for the impact assessment of health and mortality we account for regional temperature weights.

We apply the same functional relationships as Tol (2004) who assesses economic impacts of climate change on ecosystems, forestry, water and health. He applies damage functions that relate on the global temperature change (not regional temperature change) and the per capita economic performance of a region. However, as we apply a fundamentally different economic model, our model results show that damage assessments are much higher than earlier studies. Most of the previous Integrated Assessment studies (Nordhaus 1991, Cline 1992) assume one damage function for the global assessment of damages. Tol (2002) firstly assessed regional damages in relation with global surface temperature and regional per capita performance. We apply the same functional relationship for the sectors ecosystem, forestry, water and mortality (parameters see Appendix). However, we cover detailed and disaggregated dynamic economic and climate feedback effects.  Two main reasons lead to different damage effects than previous studies: First, we cover a detailed CGE model that incorporates interregional and intersectoral trade effects and dynamic investment decisions. Second, most integrated assessment models so far include one aggregate damage function for the world and do not disaggre-

---

[10] Although there exist more recent studies that estimate an economic growth reduction of malaria disease alone by 1% per year, we still stick to the chosen relationship with less drastic impact assumptions, see Malaney et al (2004)

gate regional impacts. In this model approach, we assume that regional impacts of climate change are caused by the overall (global) temperature changes, income changes of a country and regional population. We then sum up all impacts. However, regional differences in climate change are not accounted for.

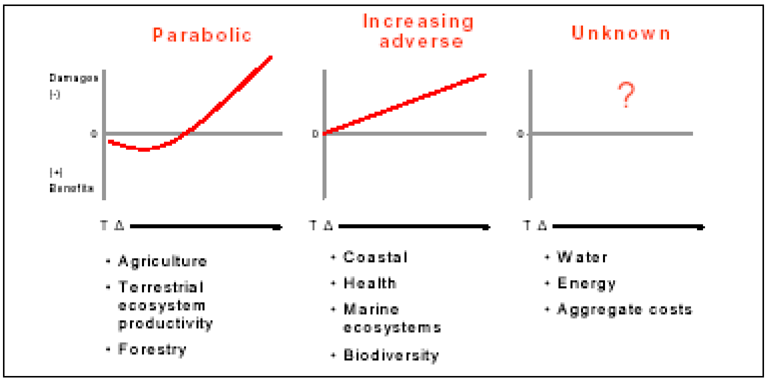
# 6 Model Results

This chapter presents our model results on the costs and benefits of climate policy. The first section highlights previous estimates from comparable studies. Our results are then presented in light of those estimates.

## 6.1 Results from Comparable Studies

Quantitative modelling studies crucially depend on the assumptions about economic development, the incorporation of dynamic interrelations, the aggregation level, time and the climate threshold. Furthermore, the assumptions about damages of climate change significantly affect the quantitative impact assessment.

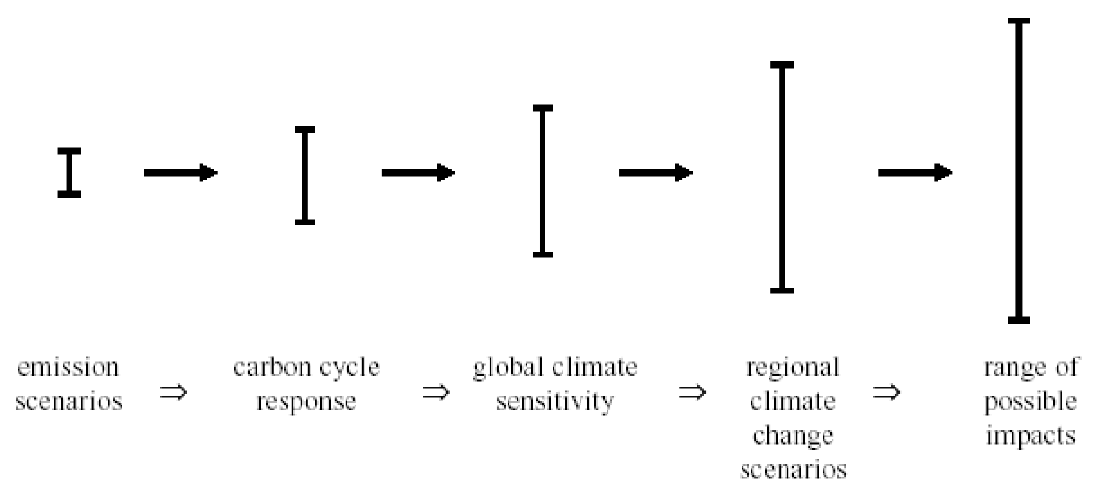
Figure 8 Damage functions



**Source: Morlot and Agrawala (2004), Chapter 1 OECD study**

Within the terrestrial ecosystem productivity area, a parabolic damage function is seen to be most realistic, as especially in the short term time horizon benefits from climate change might be most likely (Morlot and Agrawala, 2004). Most studies assume a linear relationship between temperature change in time and impacts on health, biodiversities, marine ecosystems and coasts. Still highly uncertain are impacts on water and energy. As some model studies only incorporate few aspects, a comparison of impact assessment studies becomes very challenging.

Figure 9 Range of major uncertainties in impact assessments

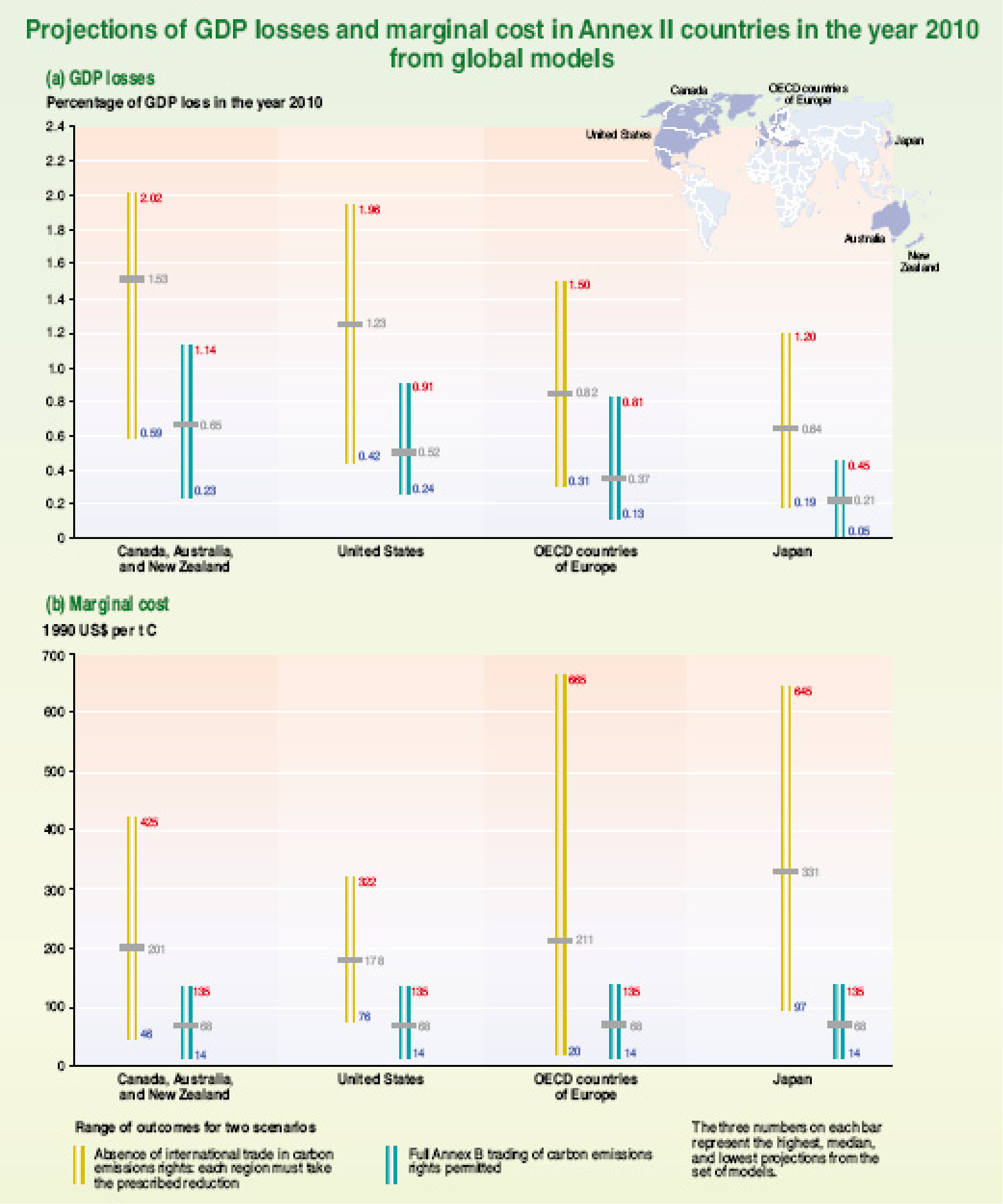


**Source: OECD (2003)**

The range of uncertainties related to impact assessment studies is very high. Market and non-market impacts estimates vary widely between individual studies (OECD 2004).

In this study, we incorporate both market and non-market impacts. Market impacts are reflected in a very detailed way as we apply a disaggregated CGE model that cover the main economic regions of the world that are linked via bilateral trade flows. Non-market impacts are included by a very aggregated functional relationship, that certainly crucially depends on the key assumptions and parameters. Also, impacts from damages are covered based on sectoral and regional damage functions that depend on global temperature and regional economic income and population changes. As regional climate change is not taken into account, and damage functions are very aggregated and stylised, this is still a very rough global estimate of impacts.

Figure 10 Global Mitigation Costs as GDP losses and marginal costs of different global models



**Source: IPCC (2001) and Weyant (1999)**

Global mitigation costs assessments differ widely, as model constructions, assumptions and parameterization diverge substantially. IPCC (2001) summarised abatement costs as percentage of GDP of different regions. An emissions trading system reduces costs considerably.

## 6.2 Model Calculations

This section presents our model calculations. We compare the benefits and costs of climate protection, that is, on the one hand the avoided climate damages and adaptation costs as well as the ancillary benefits, on the other hand i.e. the costs of emissions mitigation related to avoiding global mean warming by more than 2°C. Especially, we assess a reference scenario where no climate protection or emission mitigation actions take place and two mitigation scenarios: Scenario one “early Action” (ScenA) aim at avoiding a global surface temperature increase of more than 2°C compared to pre-industrial levels, while scenario two “delayed action” (ScenB) starts with drastic emission reduction policies at a later time period (2030) resulting in much higher levels of emissions and temperature increase throughout the entire time horizon of 100 years. Furthermore, we assume in ScenA and ScenB a climate sensitivity of 2.8°C (see Appendix I). In an additional sensitivity analysis, we compare the results with those for a high climate sensitivity (HCS-4.2°C) and a low climate sensitivity (LCS-1.5°C).

Table 7 Scenario description

| **Scenario Description** | **Emission Mitigation Start** | **Climate sensitivity** |
|---|---|---|
| Scenario A (ScenA) | Now | middle (2.8°C) |
| Scenario B (ScenB) | 2030 | middle (2.8°C) |
| Scenario B with faster technological change (Scen-B-ITC) | 2030 | middle (2.8°C) |
| Scenario A- high climate sensitivity (ScenA-HCS) | Now | high (4.2°C) |
| Scenario A- low climate sensitivity (ScenA-LCS) | 2030 | low (1.5°C) |
| Scenario B- high climate sensitivity (ScenB-HCS) | 2030 | high (4.2°C) |
| Scenario B- low climate sensitivity (ScenB-LCS) | 2030 | low (1.5°C) |

Figure 11 Greenhouse gas concentrations of different scenarios (in ppm $CO_2$)

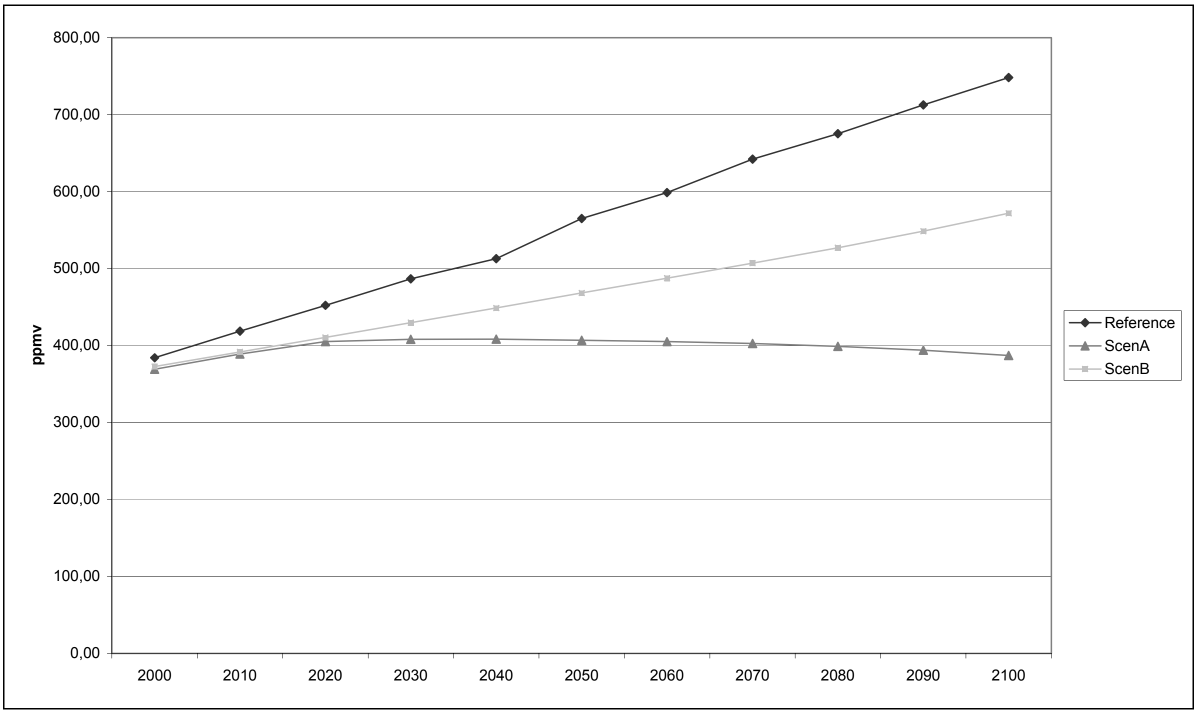
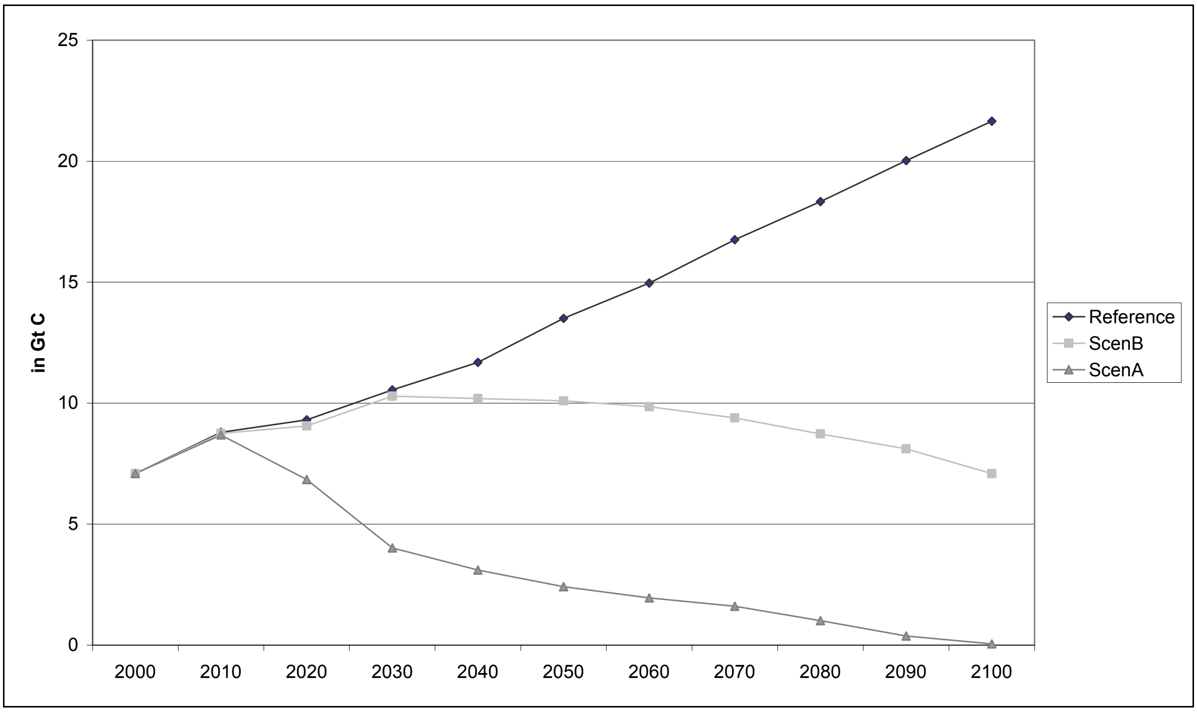


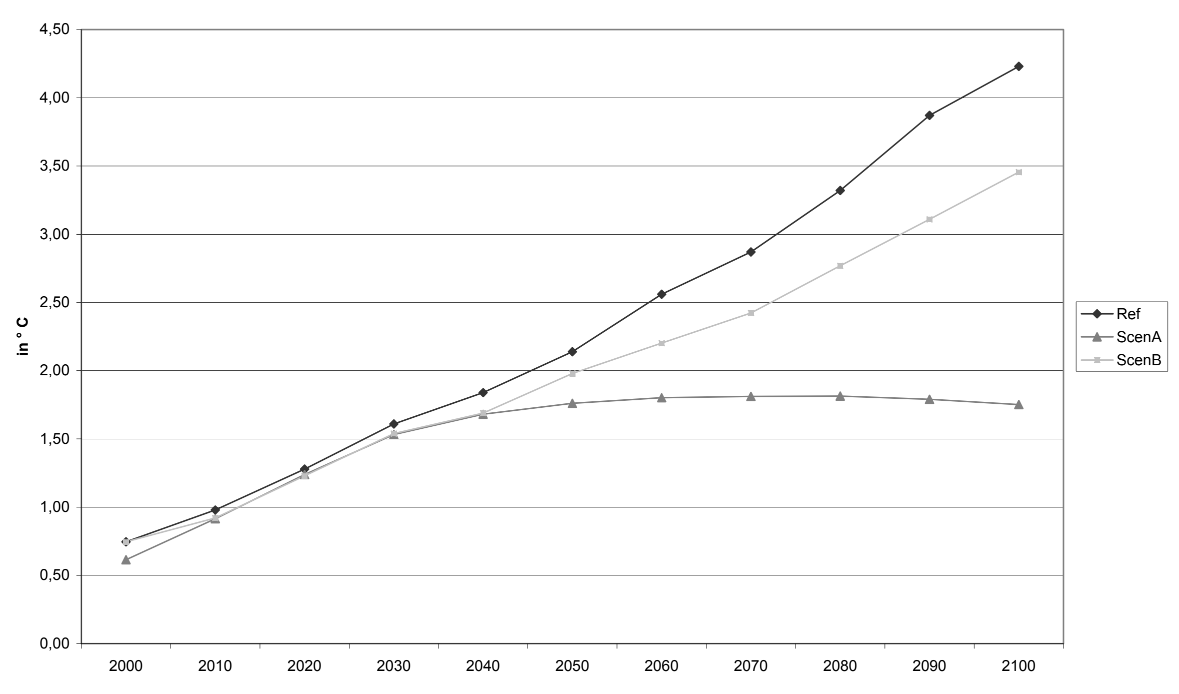
Figure 12 Carbon dioxide emissions development in Gt C



In ScenA, we assume that a temperature limit of 2°C is met (assuming a climate sensitivity of 2.8°C). This implies that emissions need to be reduced considerably in comparison to the reference scenario. In the reference scenario, emissions reach a concentration of about 750 ppm ($CO_2$ equiv.), which is transformed into a temperature increase of 4.3 °C in 2100 (Figure 11 and Figure 13). In order to avoid a temperature increase of more than 2°C, emission concentration need to be reduced by about 45 percent to a level of slightly over 400 ppm in 2100 ($CO_2$). Assuming lower climate sensitivity, a higher emissions concentration (slightly less than 600 ppm) is possible in accordance with the 2°C target). Reversely, with higher climate sensitivity more severe emissions cuts are necessary to reach the 2°C target. The $CO_2$ concentration would need to come down to less than 400 ppm compared to 750 ppm in the baseline.

It turns out that in ScenB avoiding global warming of more than 2°C cannot be fulfilled at all as climate protection in form of concrete emission reduction starts too late (2030). In order to avoid a temperature increase of more than 2°C, we have to incorporate induced technological developments. This means that we implement a scenario where we explicitly allow technological innovations, i.e. energy efficient and cheap technologies. In the other scenarios, we also include technological innovations (exogenous and endogenous) but not in that large extend. But even with the inclusion of induced technological development, warming exceeds the temperature limit of 2°C if climate policy starts in 2030. Even with the assumption of low climate sensitivity in ScenB, the temperature target of 2°C cannot be met.

Figure 13 Temperature development of different scenarios (in °C)[11]



We report the total costs as the sum of mitigation costs (as a result of a climate policy) and the damage costs (Figure 14). The damage costs, or costs of inaction, refer to the damages that occur as a result of the temperature increase (Figure 13) and the corresponding emissions concentration (that is, including ancillary costs e.g. due to air-pollution). It shall be noted that even the target of limiting the temperature increase to 2°C above pre-industrial levels (ScenA) will still result in damage costs i.e. in costs related to damages that occur at a temperature increase of 2°C. In the reference scenario where no mitigation action is taken costs solely relate to damage costs.

Total costs, i.e. the sum of mitigation costs and damages costs[12], are substantially lower in ScenA than in ScenB. Because climate policies start early, mitigation costs are initially higher in ScenA than in ScenB. Interestingly, however, despite a much later start of climate mitigation policies in ScenB, the costs of action are almost identical in terms of percentage GDP losses in the two time periods 2050 and 2100. This is because, in ScenB, more drastic meas-

---

[11] In scenario A, the temperature target is 2°C in 2100, some decline below 2°C is because of terminal conditions of the model in 2100.

[12] Mitigation costs assess all economic costs to reach the emissions targets, i.e. production declines or substitution costs towards another technology. We compute these costs as shadow costs of emissions reduction measured in percentage of GDP. Damage costs cover all impacts due to climate change.

ures need to take place after 2030, which overcompensate reduced mitigation costs in the time before 2030. As in ScenB emission mitigation starts late and the temperature target of 2°C cannot be reached by 2100, damages are much higher than in ScenA, especially in later time periods (2100). This results in higher total costs for ScenB.

Figure 14 Total costs as sum of costs of action (mitigation costs) and damage costs in 2050 and in 2100

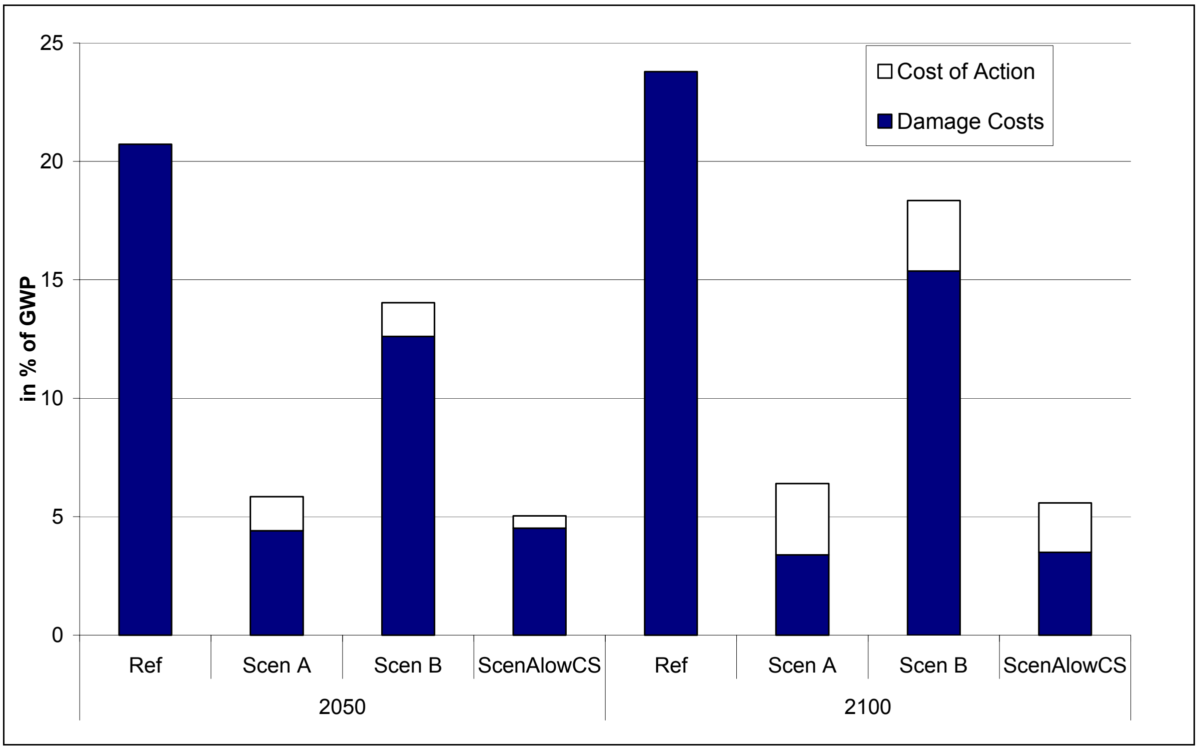
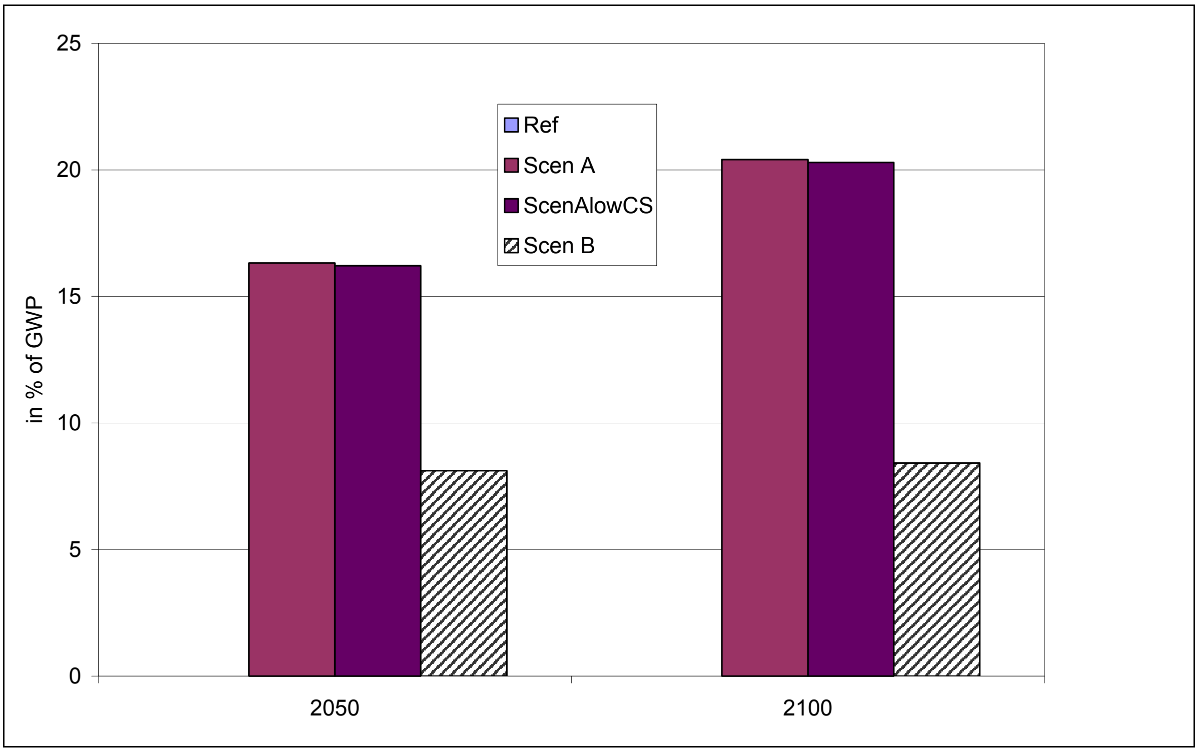


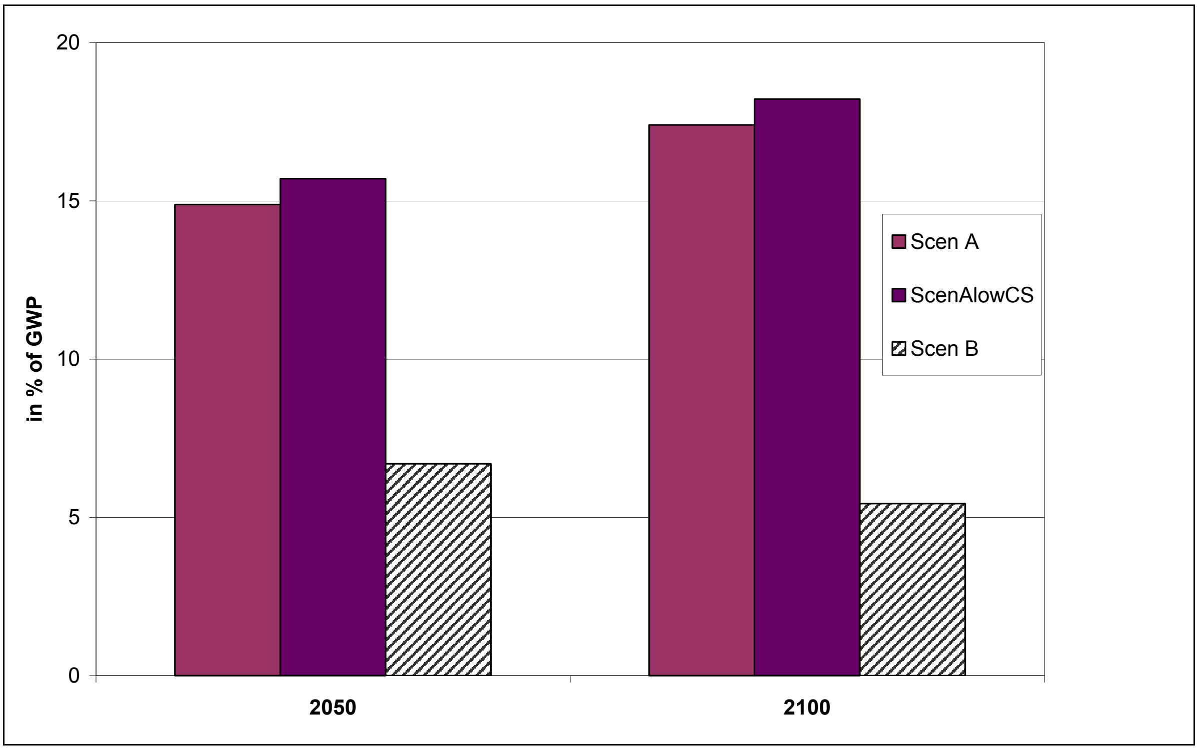
Figure 15 shows the damages avoided in ScenA and ScenB compared to the reference scenario. Both ScenA and ScenB result in lower emissions concentration and temperature increase than the reference scenario. Thus, both policy scenarios provide benefits in terms of avoided damages. As the temperature target of 2°C is met in ScenA and the corresponding emissions concentration is substantially lower, the avoided damages are much higher in ScenA than in ScenB.

Figure 15 Avoided damages compared to the reference scenario



The net effects compared to the reference scenario, i.e. the difference of avoided damages (compared to the reference case) and mitigation costs are shown in terms of percentage changes of gross world product (GWP) in Figure 16. We see the net gain the policy scenarios induce compared to the reference scenario. ScenA leads to higher positive effects in terms of gross world product (GWP) than ScenB, compared to the reference scenario because the avoided damages are higher and mitigation costs are almost identical.

Figure 16 Net effects compared to reference case as difference of avoided damages and mitigation costs



If we assume a lower climate sensitivity (ScenA lowCS), a higher greenhouse gas concentration, and thus higher emissions, would be possible in order to meet the 2°C temperature target. This would lead to lower mitigation costs and, thus, lower total costs. At the same time, avoided damages would be slightly lower than in ScenA as the same temperature target is reached at a higher corresponding level of greenhouse gas emissions and thus damages are higher with the lower climate sensitivity.[13] The net effect, i.e. the difference between avoided damages and mitigation costs, would be higher than for higher climate sensitivity, as the reduction in mitigation costs overcompensates the slight reduction of benefits (i.e. avoided damages).

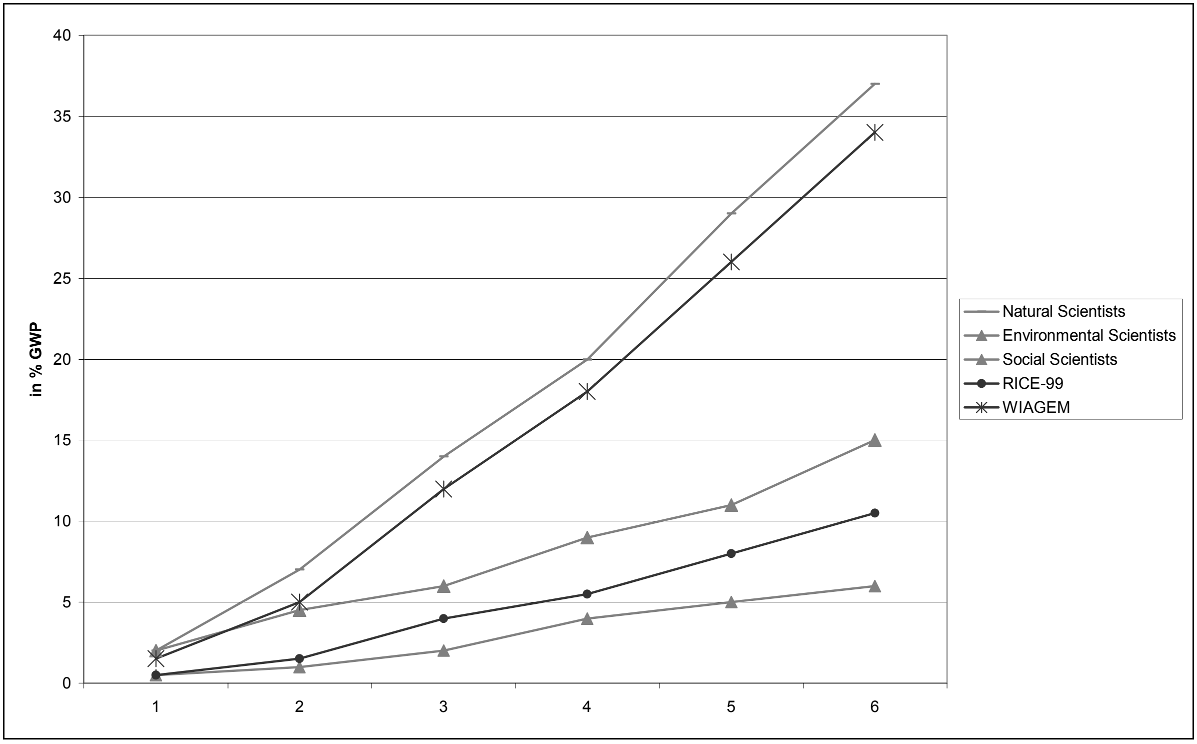
Global damages in the reference case reach 20 to 23 percentage of global GWP in 2050 and 2100, respectively. In the spectrum of previous results (Figure 17) these results lie within the area of environmental and natural scientists. In comparison to previous studies (i.e. IPCC 2001 and Weyant 1999), we estimate higher damages than other economic studies. In this

---

[13] Higher damages occur because ancillary benefits are lower. Ancillary benefits are related to the emissions level and not to the change in temperature. Thus, with a lower climate sensitivity and correspondingly higher emissions ancillary benefits decrease even though temperature related damages remain the same.

study we cover a full economic CGE model linked with a climate model that is able to assess dynamic impacts (economic growth, trade) but also monetise damages of climate change. The costs of action (mitigation costs) estimations lie well within the range of earlier studies (Weyant 1999).

Figure 17 Damage assessments of different science perspectives[14]



**Source: OECD (2003) with own additions**

Our damage assessment differs substantially from previous findings Nordhaus (1991), Cline (1992) or Tol (2002, 2004). This is because of two main reasons. First; we apply a fundamentally different global economic approach than Tol (2002) applies in his cost assessment study. We use a global general equilibrium approach that covers interregional and intersectoral trade effects, he uses much simpler approach that neglects the interregional trade effects. The model applies a recursive dynamic approach so that we cover feedback effects from damges or other shocks. Second, we include a much more detailed climate model that assesses the temperature changes from emissions development (Kemfert 2002). We find that the dynamic feedback effects from the climate and the economic system cause much higher

---

[14] RICE-99 is an Integrated Assessment model that combines a simplified economy-growth model with a climate model and assumes a global damage function for the world developed by William Nordhaus. The model has been modified over time, RICE-99 refers to the version of 1999 (Nordhaus und Boyer 2000)

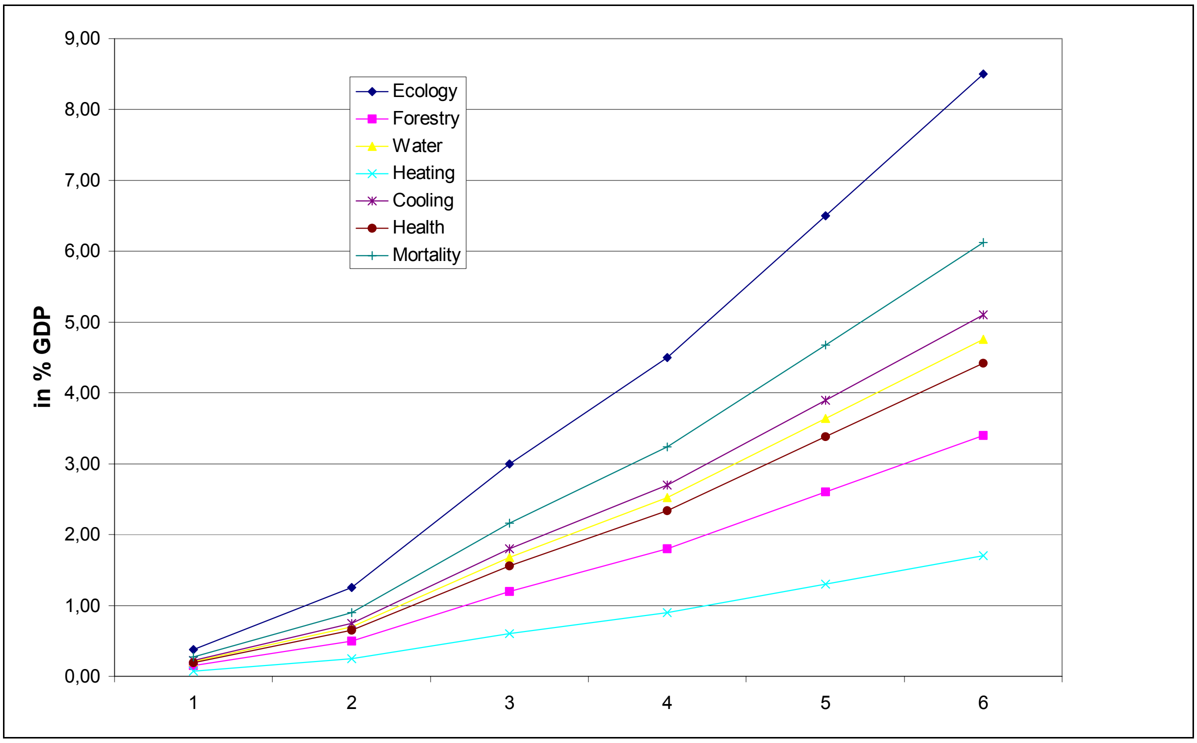
damage costs as earlier studies. In addition to the pure economic income effects we cover economc shocks due to adaptation. Countries spend a certain amount on adaptation when climate change occurs.[15] These expenditures are crowding out investments that cannot be spent as previously intended in a growth model. We find that these effects have an additional major impacts on economic development.

In contrast to Nordhaus and Cline we apply regionally different damages function that are based, however, on the global temperature change. Damages occur basically because of three main issues: First, the global temperature change which is caused by energy related and non-energy related emissions, second, the regional population change and third the economic performance, the economic income change of a region. So, not only regions with a high economic performance but also with high population growth are affected by climate change if the global temperature changes. In comparison to other studies, higher economic damages have three reasons: the dynamic modelling approach with interregional and intersectoral feedback effects, the detailed climate system that is affected by the emissions coming from the economic performances and sectoral disaggregation of damage functions instead of adding one damage function into the model. The total effects differ from many economic studies but not from earlier studies of natural scientists. Figure 18 illustrates the individual damages in percentage of GDP: ecological impacts have the highest impact as well as health and mortality. In this study, this is especially the case because of the relationship between income changes and population (health) and temperature and population (mortality). With increasing temperature energy demand for cooling increases.

---

[15] If climate change is reduced (by for example reduced emissions), countries spend less percentage of investments for adaptation.

Figure 18 Damage functions in % of GDP with increasing temperature[16]



Tol (2002) finds total world damages within the range of 6-9 % of world GDP (sum of all regions). These damages differ widely between regions. The regional disparities of damages occur because of population development and economic performances. Our model approach takes the same assumptions about the relationship between global surface temperature, population development and economic performances. However, as we cover dynamic feedback effects the total impacts are higher, here in the range up to 20 % of global GDP. For example, high-developed nations such as Europe, USA and Japan heavily depend on international trade[17]. If these nations have to divert expenditures to climate impacts and adaptation, these investments are not available to be spent in other sectors. As the model covers the dynamic growth effects and trade effects, economic losses are higher. Especially fast growing nations such as China have to accept welfare losses if climate change occurs.

---

[16] We cover impacts on agriculture implicitly in the ecosystem changes

[17] Trade in goods account for more than 35 % of GDP (PPP)

# 7 Conclusion

We conclude with the following two statements:

1. Only with early emission reduction warming beyond the limit of 2°C can be avoided. Even drastic emissions reduction efforts starting at a later point of time (2030) will not be sufficient to stay within the 2°C limit.
2. Damages from climate change are lower if the 2°C temperature limit is met. The costs of action are substantial. However, the avoided damage costs are even higher than the costs of action.

# References

Baranzini, A., M. Chesney, and J. Morisset (2003). The impact of possible climate catastrophes on global warming policy. Energy Policy 31: 691-701.

Bruckner, T., G. Hooss, H.-M. Fuessel and K. Hasselmann (2003). Climate system modelling in the framework of the tolerable windows approach: The ICLIPS climate model. Climatic Change 56: 119-137.

Clarkson, R. and K. Deyes (2002). Estimating the social cost of carbon emission. Government Economic Service Working Paper 140. London.

Cline, W.R (1992). The Economics of Global Warming, Washington D.C.

Fankhauser, S. 1994. The social costs of greenhouse gas emissions: An expected value approach. In: Energy Journal 15(2):157-184.

Hare, Bill and Malte Meinshausen (2004). How much warming are we committed to and how much can be avioded? PIK report No 93, October 2004.

Harvey, L.D.D., J. Gregory, M. Hoffert, A. Jain, M. Lal, R. Leemans, S.C.B. Raper, Wigley, T.M.L. and J.R. de Wolde (1997). An Introduction to Simple Climate Models Used in the IPCC Second Assessment Report. IPCC Techinical Paper II. Geneva, Switzerland.

Hasselmann, K., S. Hasselmann, R. Giering, V. Ocaña and H. v. Storch (1996). Sensitivity study of optimal $CO_2$ emission paths using a simplified structural integrated assessment model (SIAM). Climatic Change 37: 345 - 386.

Hasselmann, K. M. Latif, G. Hooss, C. Azar, C.C. Jaeger, O.M. Johannesson, M. Welp, C. Kemfert and A. Wokaun, in prep.: The challenge of long term climate change. Discussion paper of the European Climate Forum.

Hitz, S. and J. Smith (2004). Estimating global impacts from climate change. In: The Benefits of Climate Change Policies. OECD. Paris.

Hope, C. (2004). The marginal impact of $CO_2$ from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern. Mimeo University of Cambridge, UK.

Hooss, G., R. Voss, K. Hasselmann, E. Maier-Reimer and F. Joos (2001). A nonlinear impulse response model of the coupled carbon cycle-climate system (NICCS). Climate Dynamics 18:189-202.

Hooss, G. (2001). Aggregate models of climate change: development and applications. Max Planck Institute for Meteorology, Examensarbeit 83, Dissertation am Fachbereich Geowissenschaften der Universität Hamburg.

IPCC (Intergovernmental Panel on Climate Change) (1990). First Assessment Report. Cambridge University Press. Cambridge, UK

IPCC (Intergovernmental Panel on Climate Change) (1992). Climate Change 1992 – The Supplementary Report to The IPCC Scientific Assessment Cambridge University Press. Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change) (1996). Climate Change 1995: The Science of Climate Change. Cambridge University Press. Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change) (2000). Special Report on Emissions Scenarios. Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change) (2001). Climate Change 2001: The Scientific basis. Cambridge University Press. Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change) (2001). Climate Change 2001: Synthesis Report: Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge, UK.

Joos, F., M. Bruno, R. Fink, U. Siegenthaler, Th. F. Stocker, C. LeQuere and J.L. Sarmiento (1996). An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. Tellus 48 B: 397 - 417.

Joos, F., C. Prentice, S. Sitch, R. Meyer, G. Hooss, G.-K. Plattner and K. Hasselmann (2001). Global Warming feedbacks on terrestrial carbon uptake under the IPCC emission scenarios. Global Biogeochemical Cycles 15(4): 891-907.

Kemfert, C. (2002a). Global Economic Implications of alternative Climate Policy Strategies, Environmental Science and Policy 5 (5): 367-384.

Kemfert, C. (2002b). An Integrated Assessment Model of Economy-Energy-Climate – The model WIAGEM –-, Integrated Assessment 3 (4): 281-299.

Maier-Reimer, E. and K. Hasselmann (1987). Transport & storage of $CO_2$ in the ocean – an inorganic ocean-circulation carbon cycle model. Climate Dynamics 2: 63 - 90.

Maier-Reimer, E. (1993). The biological pump in the greenhouse. Global & Planetary. Climatic Change 8: 13 - 15.

Malaney, P., Spielman, A. and Sachs, J. (2004). The Malaria Gap. American Journal of Tropical Medicine, 71, pp. 141-146.

Mendelsohn, R. and M. Schlesinger (1997). Climate Response Functions. University of Illinois: Urbana-Champaign.

Meyer, R., F. Joos, G. Esser, M. Heimann, G. Hooss, G. Kohlmaier, W. Sauf, R. Voss and U. Wittenberg (1999). The substitution of high-resolution terrestrial biosphere models and carbon sequestration in response to changing $CO_2$ and climate. Global Biogeochemical cycles 13(3): 785-802.

Morlot, J. C. and S. Agrawala (2004). Overview. In: The Benefits of Climate Change Policies. OECD. Paris.

Münchner Rück (2002). Jahresrückblick Naturkatastrophen 2002. München.

Narain, Urvashi and Anthony Fisher (2000). Irreversibility, Uncertainty and Catastrophic Global Warming, Gianinni Foundation Working Paper 843, Berkeley: University of California, Department of Agriculture and Resources Economics, Berkeley.

Nordhaus, W. and J. Boyer (2000). Roll the Dice Again: Economic Modeling of Climate Change. Cambridge, MA: MIT Press.

Nordhaus, W., Boyer, J. (2000). Warming the World: Economic Models of Global Warming. MIT Press, Washington

Nordhaus and D William (1991). To Slow of not to Slow: The Economics of the Greenhouse Effect. In: The Economic Journal, vol 1001, 1991, S. 920-937.

OECD (2003). Estimating the Benefits of Climate Change Policy, ENV/EPOC/GSP. OECD. Paris .

OECD (2004). The Benefits of Climate Change Policies. OECD. Paris.

Osborn, T.J. and T.M.L. Wigley (1994). A Simple Model for Estimating Methane Concentrations and Lifetime Variations. Climate Dynamics 9: 181-193.

Pearce, D. W. (2003a). The Social Cost of Carbon and its Policy Implications. Oxford Review of Economic Policy 19(3): 362-384.

Pearce, D. W., W. R. Cline, A. Achanta, S. Frankhauser, S., R. Pachauri, R., R. Tol and P. Vellinga (1996). The Social Costs of climate change: Greenhouse damage and the Benefits of control. In:

Intergovernmental Panel on Climate Change 1995. Climate Change 1995: Economis and Social Dimensions of Climate Change. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Pearce, D. W. (2003). The Social Costs Of Carbon And Its Policy Implications. Oxford Review of Economic Policiy 19 (3). London.

Pittini, M. and M. Rahman (2004). The social cost of carbon: Key issues arising from a UK review. In: The Benefits of Climate Change Policies. OECD. Paris.

Schneider, S.H., J. Lane (2004). Abrupt non-linear climate change and climate policy. In: The Benefits of Climate Change Policies. OECD. Paris.

Schnellnhuber, J., R. Warren, A. Haxeltine and L. Naylor (2004). Integrated Assessment of Benefits of Climate Policy. In: The Benefits of Climate Change Policies. OECD. Paris.

Tol, R.S.J. (2001). New Estimates of the Damage Costs of Climate Change, Part I: Benchmark Estimates. Environmental and Resource Economics.

Tol, R. S. J. (2002). Estimates of the Damage Costs of Climate Change, Part II: Dynamic estimates. Environmental and Resource Economics 21: 135-160.

Tol, R. S. J. (2003a). The Marginal Costs of Carbon Dioxide Emissions: an Assessment of the Uncertainties. Working Paper FNU-19. Hamburg University. Hamburg.

Tol, R. S. J. (2003b). The Marginal Costs of Carbon Dioxide Emissions. Paper presented at the Defra International Seminar on the Social Cost of Carbon. London.

Tol, R., T. Downing, O. Kuik and J. Smith (2004). Distributional aspects of climate change impacts. Global Environmental Change: Special Edition on the Benefits of Climate Policy Part A, 14(3): 259-272.

Weyant, John P. and Hill, Jennifer N. (1999). The Costs of the Kyoto Protocol: A multi-model Evulution - Introduction and Overview. The Energy Journal - A Special Issue: The Costs of the Kyoto Protocol: A Multi-Model Evaluation: vii-xliv.

Wigley, T.M.L. (1988). Future CFC concentrations under the Montreal Protocol and their Greenhouse-effect Implications. Nature 335: 333-335.

Wigley, .M.L. and S.C.B. Raper (1992). Implications for Climate and Sea Level Rise of Revised IPCC Emissions Scenarios. Nature 357: 293-357.

Wigley, T.M.L. (1994). MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change): User's Guide and Scientific Reference Manual. National Centre for Atmospheric Research, Boulder, CO.

Wigley, T.M.L., S.C.B. Raper and M. Salmon (1996). Source Code of the MAGICC Model (as used in MiniCam, Version 2.0). Climate Research unit. University of East Anglia, Norwich, U.K.

## Appendix I: Detailed Description of WIAGEM

By coupling the economic and climate impact part of WIAGEM with the detailed climate module ICM, we consider the relationship between man-made emissions and atmospheric concentrations and their resulting impact on temperature and sea level. We cover classes of atmospheric greenhouse gas stocks with different atmospheric lifetimes (modelled by the impulse response function) and reduced forms of the carbon cycle model developed by Maier-Reimer and Hasselmann (1987) and applied by Hooss (2001). Energy and non-energy related emissions of $CO_2$, $CH_4$ and $N_2O$ as well as those of halocarbons and $SF_6$ alter the concentrations of these substances which in turn influence radioactive forcing.

As a result, the multi-gas climate model ICM was obtained that takes into account all important greenhouse gases (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, tropospheric and stratospheric ozone, and stratospheric water vapour) and aerosols by modelling their dynamic atmospheric behaviour as well as the radiative forcing originating from changes in the concentration of the respective substances.

ICM is driven by time-dependent paths of the anthropogenic emissions of $CO_2$, $CH_4$, $N_2O$, halocarbons, $SF_6$ and $SO_2$. In WIAGEM total anthropogenic emissions are determined by:

$$TOTEM_{r,t} = E_{r,t} + NonE_{r,t} - S_{r,t}$$

with TOTEM indicating the total anthropogenic emissions per region and time period, $E_{r,t}$ as regional emissions per time period. Non-energy related emissions are countered for each greenhouse gas, regional and time period. Sinks ($S_{r,t}$) reduce total emissions.[18]

The atmospheric concentration of greenhouse gases may be altered due to direct emissions, exchange with reservoirs (e.g., ocean, biosphere, pedosphere) and chemical reactions (destruction or formation). The biogeochemical submodules of ICM take into account these different processes in a greenhouse gas-specific manner. In general, the modules are reduced-form models of complex two- or three-dimensional greenhouse gas cycles or atmospheric chemistry models and are calibrated with respect to historical concentration records.

The carbon cycle module (see Appendix I) developed at the Max-Planck Institute for Meteorology in Hamburg consists of (a) a differential impulse-response representation of the 3 di-

---

[18] This means also that the emissions reductions targets are reduced.

mensional Hamburg Model of the Ocean Carbon Cycle (HAMOCC), extended into the non-linear high-$CO_2$ domain by explicit treatment of the chemistry governing the $CO_2$ uptake through the ocean surface, and (b) a simple non-linear impulse response model of the terrestrial biosphere's $CO_2$ fertilization. Applying an inverse calibration technique, the quantitatively unknown $CO_2$-fertilization factor has been adjusted in order to give a balanced 1980s mean budget as advised by the IPCC inter- model comparison exercise.

Various components of the MAGICC model (Wigley, 1988; Wigley and Raper, 1992; Wigley, 1994; Osborn and Wigley, 1994; Wigley *et al.*, 1996, Harvey *et al.*, 1997) were adopted in order to simulate the atmospheric chemistry of major non-$CO_2$ greenhouse gases.

Changes in the concentration of non-$CO_2$ greenhouse gases ($CH_4$, $N_2O$, halocarbons, and $SF_6$) are calculated by a simple one-box model approach according to

$$\frac{dC(t)}{dt} = \frac{1}{b}\sum_r TOTEM_r - \frac{1}{\tau}(C - C_{pre-industral})$$

where $b$ is a concentration-to-mass conversion factor and $\tau$ is the lifetime of the greenhouse gas. For $N_2O$, halocarbons and $SF_6$, the lifetime is assumed to be constant (IPCC, 1996; Harvey *et al.*, 1997). $CH_4$ is removed from the atmosphere by soil uptake and chemical reactions with OH. The lifetime of $CH_4$ takes into account both processes and as the OH concentration itself is influenced by $CH_4$, the lifetime attributed to chemical processes is modelled to be dependent on the $CH_4$ concentration according to Osborn and Wigley, 1994).

The atmospheric concentration of different greenhouse gases has the following impact on radiative forcing (IPCC, 1990):

$$\Delta F_{CO2} = 6.3\ln\left(\frac{CO2}{CO2_0}\right)$$

$$\Delta F_{CH4} = 0.036\,(CH4^{0.5} - CH4_0^{0.5}) - f(CH4, N2O) + f(CH4_0, N2O_0)$$

$$\Delta F_{N2O} = 0.14(N2O^{0.5} - N2O_0^{0.5}) - f(CH4_0, N2O) + f(CH4_0, N2O_0)$$

with ΔF measured in $Wm^{-2}$, concentrations for $CH_4$ and $N_2O$ given in ppbv and the subscript 0 used to indicate pre-industrial concentrations. . The $CH_4$-$N_2O$ interaction term (expressed in $Wm^{-2}$) is determined by:

$$f(CH4, N2O) = 0.47 \ln\left[1 + 2.01 \cdot 10^{-5} \cdot (CH4 \cdot N2O)^{0.75} + 5.31 \cdot 10^{-15} \cdot CH4 \cdot (CH4 \cdot N2O)^{1.52}\right]$$

where $CH_4$ and $N_2O$ have to be replaced by actual $CH_4$ and $N_2O$ concentrations or alternatively by their respective pre-industrial levels as expressed in equations 3 and 4.

Total radiative forcing F can be approximated (IPCC, 2001, p. 355) by adding each greenhouse gas radiative forcing effect. In addition to the components just described, the radiative forcing description in ICM takes into account the contributions from $SF_6$, tropospheric ozone and stratospheric water vapour (both dependent on $CH_4$ concentrations), aerosols, and halocarbons including indirect effects according to stratospheric ozone depletion.

The time evolution of the global annual mean surface air temperature is calculated according to the impulse response function approach used in NICCS. A detailed description of this component can be found in Hooss (2001), Hooss *et al.* (2001), Bruckner *et al.* (2003), Joos *et al.* (2001), and Meyer *et al.* (1999). In order to include the radiative forcing of non $CO_2$-greenhouse gases, the carbon dioxide concentration used in NICCS is to be replaced by the equivalent carbon dioxide concentration (measured in ppm) defined by IPCC (1996a, p.320):

$$C_{Equiv} = 278\,ppm \cdot Exp\left(\frac{\Delta F}{6.3\frac{W}{m^2}}\right)$$

Aggregated impacts of climate change are evaluated by:

We follow the approach of Tol (2001) for economic impact assessment of ecosystem changes:

$$E_{t,r} = a\frac{y_{t,r}}{y_{1990,r}}P_{t,r}\frac{y_{t,r}/y_b}{1+y_{t,r}/y_b} \qquad (3.9)$$

with E as the value of the loss of ecosystems and y the per capita income and P as population size. α and $y_b$ are parameter (α =0.5, $y_b$ =\$20.000).

Impact assessment of vector borne diseases are determined by:

$$m_{r,t} = \alpha_r T_t^{\beta} \left(\frac{y_c - y_{t,r}}{y_c - y_{base,r}}\right)^{\gamma} \qquad (3.10)$$

$$\perp y_{t,r} \geq y_c$$

with m representing mortality, and α, γ and $y_c$ denoting parameter (α= 1 (0.5-1.5), γ= 1 (0.5-1.5), $y_c$= \$3100 (2100-4100).

Furthermore, mortality due to changes in global warming are measured:

$$\Delta M = \alpha + \beta T_B \qquad (3.11)$$

where $\Delta M$ denotes the change in mortality due to a one degree increase in global warming, $T_b$ as current temperature and α and β are parameter.

Furthermore, we take into account Tol´s approach to determine demand for space heating (SH) and space cooling energy (SC):

$$SH_{t,r} = a_r T_t^{\beta} \left(\frac{y_{t,r}}{y_{t,1990}}\right)^{\varepsilon} \left(\frac{P_{t,r}}{P_{t,1990}}\right) \prod_{s=1990}^{t} EP_{s,r} \qquad (3.12)$$

$$SC_{t,r} = a_r T_t^{\beta} \left(\frac{y_{t,r}}{y_{t,1990}}\right)^{\varepsilon} \left(\frac{P_{t,r}}{P_{t,1990}}\right) \prod_{s=1990}^{t} EP_{s,r} \qquad (3.13)$$

Total damages are assessed by the following relation:

$$\Delta DAM_t^r = \alpha_t^r \cdot (\Delta PT_t^{\beta} \cdot \frac{y_t^r}{y_0^r}) + PC_t^r \qquad (3.14)$$

ICM estimates the climatic changes due to greenhouse gas emissions and the impact modules estimates the corresponding impacts. Market and non-market damages associated with these impacts, are assessed by coupling the climate module of ICM with WIAGEM. We express impacts as changes to regional and global welfare and GDP.

Mathematically the carbon cycle model containing all differential equations can be described as follows:

$$\mathrm{c}_1 \quad = \quad D(\mathrm{c}_1)\cdot \left\{ e - \frac{n_2}{h_s} c_s(c_1) + \frac{n_2}{h_2} c_2 - (b_3 + b_4) B(c_1) + \frac{1}{\tau_{B3}} c_{B3} + \frac{1}{\tau_{B4}} c_{B4} \right\}$$

$$\mathrm{c}_2 \quad = \quad \frac{\eta_2}{h_s} c_s(c_1) - \frac{\eta_2 + \eta_3}{h_2} c_2 + \frac{\eta_3}{h_3} c_3$$

$$\mathrm{c}_3 \quad = \quad \frac{\eta_3}{h_2} c_2 - \frac{\eta_3 + \eta_4}{h_3} c_3 + \frac{\eta_4}{h_4} c_4$$

$$\mathrm{c}_4 \quad = \quad \frac{\eta_4}{h_3} c_3 - \frac{\eta_4}{h_4} c_4$$

$$\mathrm{c}_{\mathrm{Bc}} \quad = \quad A(\mathrm{c}_1)\cdot \mathrm{c}_1$$

$$\mathrm{c}_{\mathrm{B3}} \quad = \quad b_3 \cdot B(\mathrm{c}_1) - \frac{c_{B3}}{\tau_{B3}}$$

$$\mathrm{c}_{\mathrm{B4}} \quad = \quad b_4 \cdot B(\mathrm{c}_1) - \frac{c_{B4}}{\tau_{B4}}$$

with:

*t* Simulation time

| | |
|---|---|
| $x$ | Spatial coordinates |
| $s$ | Season index |
| $e$ | Anthropogenic $CO_2$ emissions |
| $C_{CO_2}$ | Atmospheric $CO_2$ concentration (by volume) |
| $C_{CO_2,\, equiv}$ | Atmospheric equivalent $CO_2$ concentration |
| $C_{CO_2,\, pre}$ | Pre-industrial $CO_2$ concentration |
| $c_a$ | Anthropogenic carbon in the atmosphere (in GtC) |
| $c_s$ | Anthropogenic carbon in the oceanic mixed layer |
| $c_j$ | Anthropogenic carbon in the $j^{th}$ oceanic layer |
| $c_1$ | Anthropogenic carbon in the composite layer |
| $q_j$ | Carbon flux from layer $j - 1$ into layer $j$ |
| $c_B$ | Anthropogenic carbon allocated by the land vegetation |
| $c_{Bi}$ | Anthropogenic carbon in land biosphere reservoir $I$ |
| $c_{Bc}$ | Short-term anthropogenic carbon in land biosphere |
| $B(C_1)$ | Nonlinear auxiliary function (= additional NPP) |
| $A(C_1)$, $D(C_1)$ | Nonlinear auxiliary functions |
| $T$ | Near-surface temperature change (relative to pre-industrial level) |
| $CC$ | Cloud-cover change (relative to pre-industrial level) |
| $P$ | Precipitation change (relative to pre-industrial level) |
| $H$ | Humidity change (relative to pre-industrial level) |
| $SLR$ | Sea-level rise (relative to pre-industrial level) |
| $PC$ | Principal component |
| $EOF$ | Empirical orthogonal function |