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Estimates of the Damage Costs of Climate Change

Part II. Dynamic Estimates

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Abstract. Monetised estimates of the impact of climate change are derived. Impacts are expressed as functions of climate change and 'vulnerability'. Vulnerability is measured by a series of indicators, such as per capita income, population above 65, and economic structure. Impacts are estimated for nine world regions, for the period 2000–2200, for agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems, fatal vector- borne diseases, and fatal cardiovascular and respiratory disorders. Uncertainties are large, often including sign switches. In the short term, the estimated sensitivity of a sector to climate change is found to be the crucial parameter. In the longer term, the change in the vulnerability of the sector is often more important for the total impact. Impacts can be negative or positive, depending on the time, region, and sector one is looking at. Negative impacts tend to dominate in the later years and in the poorer regions.

Key words: adaptation, climate change, impacts

JEL classification: Q00, Q25, Q40

1. Introduction

A sound knowledge of the impact of climate change is a prerequisite for a well-informed greenhouse gas emission reduction policy. Although governments of most OECD countries are now considering, and some already implementing such policies, insights into what may be the consequences of an enhanced greenhouse effect are still far from complete. Watson et al. (1996) review the literature on climate change impacts in general, and Pearce et al. (1996) and Tol et al. (2000) assess the literature on impacts from an economic viewpoint. These reviews reveal that most impact studies take a static approach. That is, the effect of a single, changed climate (usually, $2\times CO_2$, i.e, climate if the atmospheric concentration of carbon dioxide would be doubled) on the current system is investigated. This is a useful starting point, but climate will change gradually and is not likely to stop at $2\times CO_2$. Moreover, populations and economics will grow, and technologies and institutions will evolve. This paper develops a model of climate change impacts that takes account of the dynamics of climate change and the systems affected by it.

The model develop can be used in a cost-benefit analysis of greenhouse gas emission reduction. Cost-benefit analyses have so far failed to influence climate policy. Emission abatement targets have been more ambitious than justifiable by welfare optimisation (Nordhaus and Yang, 1996; Tol, 1999). However, it is becoming increasingly clear that policy targets will be missed, and most likely by a substantial margin. This situation reopens the discussion on the aims and targets of greenhouse gas emission reduction policy.

This model is not the first in its kind. Most integrated assessment models of climate change (cf. Weyant et al., 1996, for a review) include such a model. Tol and Fankhauser (1998) review these models to conclude that dynamics are usually straightforward and assumptions typically *ad hoc*. Worse, assumptions are seldom openly discussed, so that understanding let alone progress are hampered. Earlier papers (Tol, 1994, 1996) attempt to open the discussion. This paper is a further step in that assumptions are better supported by literature and data. In that, the approach of Mendelsohn et al. (1996a, b; cf. Mendelsohn, 1998) is comparable to this work, although their models excludes changing vulnerabilities to climate change. Sensitivity analyses in this paper are more systematic and extensive.

Obviously, this paper does not result in a climate change impact model that is adequate. The accompanying static impact assessment (Tol, 2001) is far from perfect, with many pieces missing and a lot of questionable assumptions. Adding the dynamics implies adding more assumptions, many of which are debatable. Yet, this paper contributes to clarifying the full scope of the enhanced greenhouse effect, and to the research agenda that is needed for a sound understanding of the issue.

Section 2 briefly discusses the methods used for the dynamic impact assessment, focusing on the common elements for the various impact categories. Sections 3 to 10 present methods and assumptions specific to the impacts, and discusses the results. The impact categories considered are agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems, vector-borne diseases, and cardiovascular and respiratory diseases. Section 11 draws these impacts together to derive a picture of the overall vulnerability to climate change. Section 12 concludes.

2. Some Notes on Methodology

The starting point of the analysis is the static impact assessment of Tol (2001). That study draws on the literature on the impact of climate change and monetary valuation. Selection criteria for a primary impact study to be taken up are that it is global (for reasons of consistency) and that the climate scenario is taken from a General Circulation Model (or reasons for realism). Different studies are combined, and results are extrapolated using basic statistical methods (cf. Van den Bergh et al., 1997). These statistical employ regularities in the data that are here used to extrapolate the static findings over different climates and different vulnerabilities to climate change. With regard to the latter, a crucial assumption is that current

variations in vulnerability related to, say, per capita income can be used to estimate the effect of economic growth on vulnerability to climate change.

Impacts are estimated for nine regions, viz. OECD-America, OECD-Europe, OECD-Pacific, Central and Eastern Europe and the former Soviet Union, Middle East, Latin America, South and Southeast Asia, Centrally Planned Asia, and Africa. These regions coincides with the regions of the *FUND* model (Tol, 1997, 1999).

Parameters are estimated from the underlying literature or guessed. Parameter estimates and parameter guesses are presented as their most likely values, accompanied by their 67% confidence interval. If the probability distribution function of the parameter is normal – a standard assumption – the confidence interval spans the mode (expectation, median) plus or minus the standard deviation. Standard deviations are guessed or estimated from the underlying literature. The values of the standard deviations and the shapes of the probability distributions are not crucial as their paper contains no uncertainty analysis; the standard deviations are used for sensitivity analysis only.

Sensitivity analyses are performed on the most important parameters. Parameters are varied, one at the time, between the best guess plus and minus the standard deviation. Because so many of the assumptions are heroic, the sensitivity analyses are perhaps more informative than the central estimates. The sensitivity analyses also seek to inform the questions how comprehensive and complicated a climate change impact model needs to be, and what are the minimum set of relations and indicator that capture most of the dynamics.

3. Agriculture

3.1. MODEL

Tol (1999) presents results for the impact of climate change on agriculture, based on the studies of Darwin et al. (1995), Kane et al. (1992), Reilly et al. (1994), Rosenzweig and Parry (1994), and Tsigas et al. (1996). Each of these studies combines estimates of changes in crop yield or land productivity with a model of national and international trade in agricultural products. Table I reproduces the results for a 1 °C increase in the global mean temperature and a rate of 0.04 °C/year.

The estimate for the level of climate change is based on the underlying results including adaptation. The estimate for the rate of change is based on the difference of the underlying results with and without adaptation. The underlying studies do not contain information about the speed of climate change relative to the speed of adaptation. Common sense suggests that the impact reacts more than linear to the rate of climate change. It is likely that farmers will need a couple of years to adjust their practices to the changed climatic circumstances. The assumed model is:

Table I. Impacts of climate change on agriculture.

Region	Rate of change %GAP/0.04 °C)	Level of change (%GAP/1 °C)	Optimal temperature (Δ °C wrt 1990)
OECD-A	−0.021 (0.031)	0.398 (0.530)	2.29 (1.32)
OECD-E	−0.026 (0.025)	0.838 (0.450)	0.45 (0.50)
OECD-P	−0.016 (0.038)	0.321 (0.648)	2.71 (0.33)
CEE&fSU	−0.028 (0.027)	1.060 (0.452)	2.96 (0.43)
ME	−0.017 (0.011)	0.233 (0.193)	3.08 (0.49)
LA	−0.022 (0.015)	0.221 (0.280)	2.14 (0.26)
S&SEA	−0.022 (0.007)	0.253 (0.132)	2.16 (0.33)
CPA	−0.023 (0.023)	1.239 (0.403)	3.41 (1.01)
AFR	−0.12 (0.006)	0.189 (0.111)	3.00 (0.48)

Source: Tol (2002).

$$a_{t,r}^{r} = a\left(\frac{\Delta T_t}{0.04}\right)^{\beta} + \rho a_{t-1,r}^{r} \tag{1}$$

ar denotes the change in agricultural production due the rate of climate change; t denotes time; r denotes region; ΔT denotes the change in the global mean temperature; α is a parameter, denoting the benchmark change in agricultural production (cf. Table I); β is a parameter, denoting the non-linearity of the reaction to temperature; β = 2 (1.5–2.5); ρ is a parameter, denoting the speed of adaptation; ρ = 10 (5–15).

The model for the impact due to the level of climate change is less speculative, as the underlying literature contains more information to this regard. The change in agriculture product (after adaptation) was regressed on the change in the global mean temperature and the global mean temperature squared. This was only possible for the studies by Darwin et al. (1995), Reilly et al. (1994), and Rosenzweig and Parry (1994), as the studies by Kane et al. (1992) and Tsigas et al. (1996) are for one GCM only. A regression on temperature and temperature squared implies an optimal temperature, which was estimated for each region for the three studies. The weighted average of the three estimates is used here. The results are given in Table I. The assumed model is:

$$a_{t,r}^{l} = \frac{-2A_r^B T_r^{opt}}{1 - 2T_r^{opt}} T_t + \frac{A_r^B}{1 - 2T_r^{opt}} T_t^2 \tag{2}$$

a^l denotes the change in agricultural production due to the level of climate change; t denotes time; r denotes region; T denotes the change in global mean temperature relative to 1990; A^B is a parameter, denoting the benchmark change in agricultural production (cf. Table I); T^{opt} is a parameter, denoting the optimal temperature (cf. Table I).

Equation (2) is problematic if the optimal temperature is less than 0.5, as the optimum then is a minimum (rather than a maximum). Therefore, for $T^{opt} < 0.5$, (2) is replaced by a bilinear form. If $T = T^{opt}$, $a^l = 2A_B$. If $T = 0$, $a^l = 0$. If $T = 1$, $a^l = A_B$. This *ad hoc* solution is of little consequence, as optimal temperature of 0.5^0C or less only occur in OECD-Europe, and only occasionally so.[1]

The share of agricultural production in total income falls with per capita income. The elasticity across the nine regions is −0.31. So,

$$\frac{GAP_{t,r}}{Y_{t,r}} = \frac{GAP_{1990,r}}{Y_{1990,r}} \left(\frac{y_{1990,r}}{y_{t,r}}\right)^{\varepsilon} \tag{3}$$

GAP denotes gross agricultural product; *Y* denotes gross domestic product; *y* denotes gross domestic product per capita; *t* denotes times; *r* denotes regions; ε is a parameter; $\varepsilon = 0.31$ (0.15–0.45).

4. Results

Figure 1 displays a sensitivity analysis around the impacts of climate change with full adaptationj. In all cases, impacts are fairly limited, never exceeding a positive or negative 0.1% of GDP. For most parameter choices, impacts are slightly positive, or negative 0.1% of GDP. For most parameter choices, impacts are slightly positive, but start falling in the 22nd century. In the last decade, the positions of high and low impacts reverse, because the impact on regions with a high sensitivity and a near optimum (e.g., OECD-America, South and Southeast Asia) starts to dominate. If the optimum temperature to grow agriculture products is high, the pattern is the same, but stretched over time. If the optimum temperature is low, negative consequences of climate change emerge sooner.

Figure 2 displays the result of a sensitivity analysis around the impacts of agricultural adaptation to climate change. The estimated impact is more important than the estimated speed of adaptation. However, comparing Figures 1 and 2, the impact with full adaptation is much more important than the impact of adaptation. This reduces the influence of the *ad hoc* assumptions underlying (1).

5. Forestry

5.1. MODEL

The results for the various GCMs scenarios used by Perez-Garcia (1995) suggest that the relationship between the climate change impact on the forestry sector and the global mean temperature is linear.

Following Mendelsohn and Schlesinger (1997), forestry is assumed grow at the same relative pace as does agriculture.

The model is thus:

$$F_{t,r} - a_r \left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\varepsilon} T_t^{\beta} \tag{4}$$

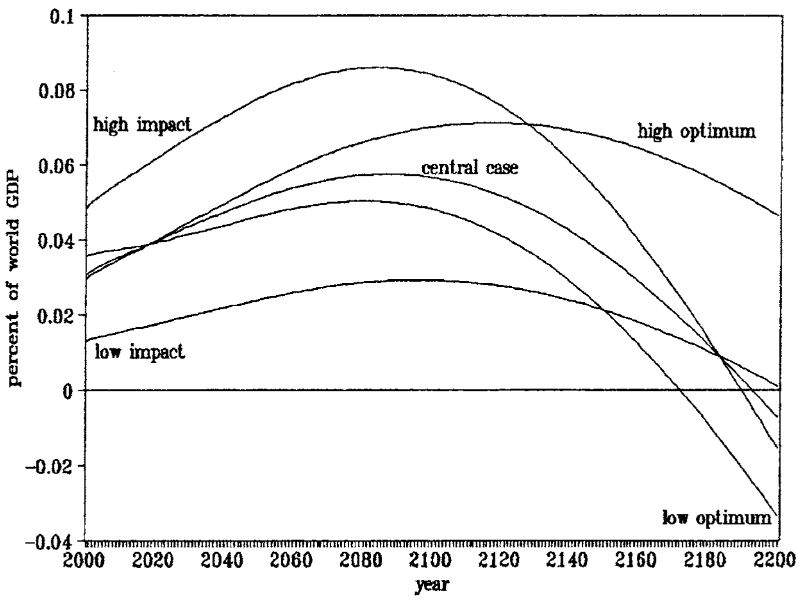

Figure 1. A sensitivity analysis around the impact of climate change on world agriculture with full adaptation. Displayed are the central case, and cases in which the impact with full adaptation is set at its central estimate plus or minus its standard deviation (high and low impact), and in which the optimal temperature is set at its central estimate plus or minus its standard devaiation (high and low optimum).

where F denotes the change in forestry consumer and producers surplus (as a share of total income); t denotes time; r denotes region; y denotes per capita income; T denotes the global mean temperature; α is a parameter; see Table II; $\varepsilon = 0.31$ (0.11–0.51); β is a parameter; $\beta = 1$ (0.5–1.5).

5.2. RESULTS

Figure 3 displays the results. The impact of climate change on forestry is positive but small, primarily because forestry is only a small fraction of the world economy. At the short term, the benchmark estimate is an important of uncertainty, but at the longer term the relative growth rate of the sector takes over.

6. Water Resources

6.1. MODEL

The impact of climate change on water resources is found to be highly uncertain, but potentially very substantial in the static assessment of Tol (1999). Part of the uncertainty is due to the complexities of precipitation, and part of the uncertainty is due to the paucity of global assessments which can be used in for economic

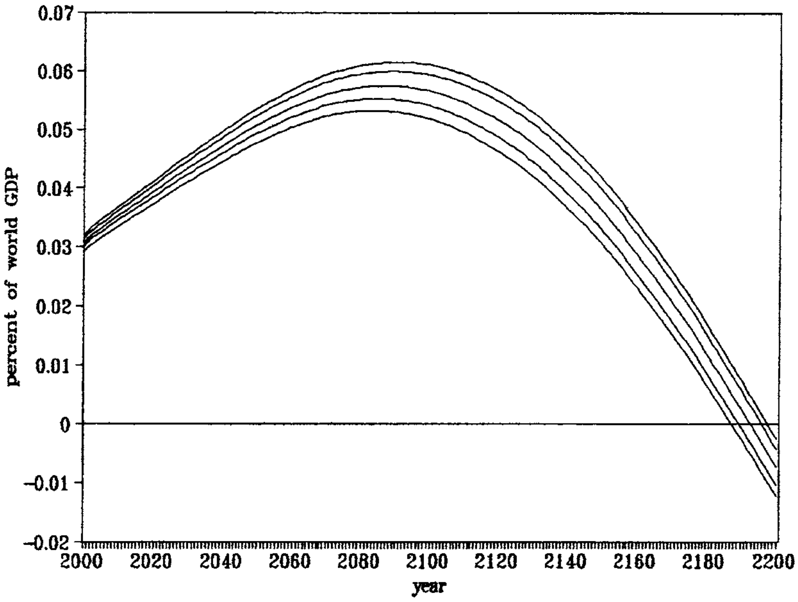

Figure 2. A sensitivity analysis around the adaptation of world agriculture to climate change. The central line depicts total climate change impacts with all parameters set to their central value. In the inner interval, the speed of adaptation is varied between its central estimate plus or minus its standard deviation. In the outer interval, the estimated costs of adaptation are varied between the central estimates plus or minus its standard devaiation.

Table II. Impact of α 1 °C warming on current day forestry, water, heating, and cooling, in million US dollar.

Region	Forestry	Water	Heating	Cooling
OECD-A	218 (24)	−3 (3)	22 (22)	−11 (11)
OCED-E	134 (16)	−2 (2)	13 (13)	−20 (20)
OECD-P	93 (20)	−0 (0)	7 (7)	−1 (1)
CEE&fSU	−136 (17)	−76 (76)	46 (46)	−19 (19)
ME	0 (0)	−1 (1)	8 (8)	−1 (1)
LA	−10 (2)	−1 (1)	3 (3)	−2 (2)
S&SEA	140 (34)	−2 (2)	4 (4)	−4 (4)
CPA	0 (0)	2 (2)	17 (17)	−12 (12)
AFR	0 (0)	−2 (2)	0 (0)	−5 (5)

Source: Tol (2002).

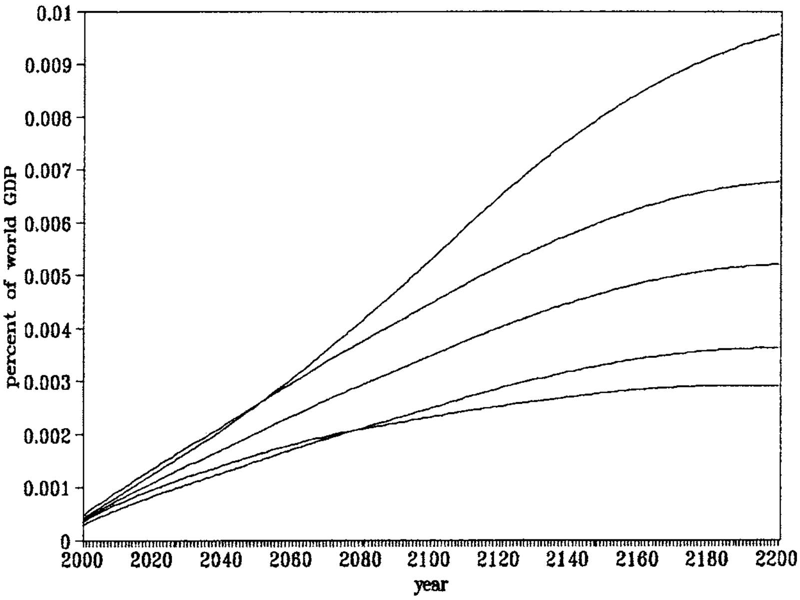

Figure 3. A sensitivity analysis around the costs of climate change to world forestry. The central line depicts the costs if all parameters are set to their central estimates. In the inner interval, impact estimates are varied between the central estimates plus or minus their standard deviations. In the outer interval, the rate at which the forestry sector grows relative to the total income is varied between its central estimates plus or minus its standard deviation.

estimates. Tol (1999) relies on a single study, viz. Downing et al. (1995, 1996), which is incomplete in its reporting.

The model used here is therefore *ad hoc*. The impact of climate change on water resources follows:

$$W_{t,r} - a_r \left(\frac{Y_{r,t}}{Y_{r,1990}} \right)^{\beta} T_t^{\gamma} \tag{5}$$

where W denotes the change in water resources, expressed in billion dollars; t denotes time; r denotes region; Y denotes income; T denotes the global mean temperature; α is a parameter, the benchmark estimate; see Table II; α is a parameter; $\beta = 0.85$ (0.70–1.00), as in Downing et al. (1995, 1996); γ is a parameter; $\gamma = 1$ (0.5–1.5).

6.2. RESULTS

Figure 4 displays a sensitivity analysis around the results. The exact impact depends on a number of factors. The overall pattern, however, is that the impact is substantially negative. In the central case, it gradually tends to −1.0% of world GDP by 2200. Varying the elasticity of water demand to income, this could

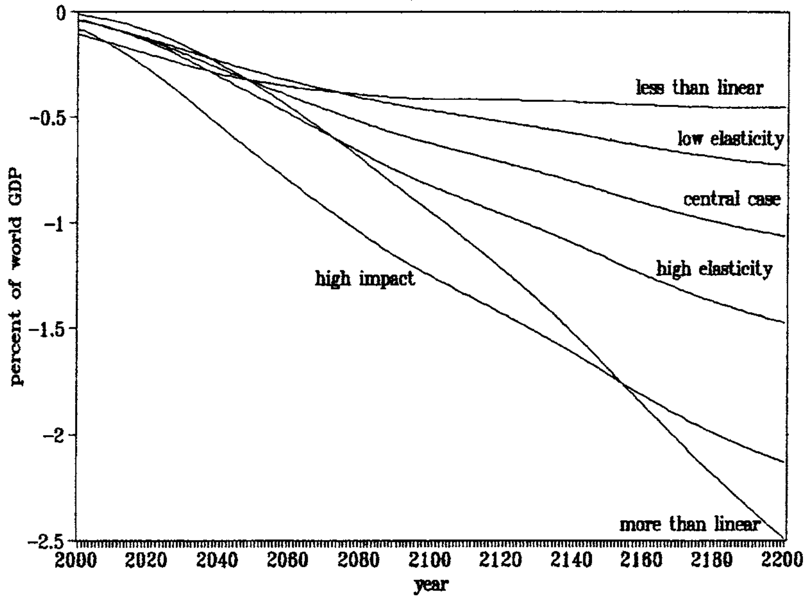

Figure 4. A sensitivity analysis around the impact of climate change on world water resources. Displayed are the central case, in which all parameters are set to their central estimates, cases with high and low growth relative to total economic growth, cases in which water resources react more and less than linearly to climate change, and the case in which the benchmark impact is set at its central estimate plus its standard devaiation.

range between −0.5–1.5% of GDP. The uncertainty about the linearity of water resources' sensitivity to climate change is even more important. In the short run, however, the estimated sensitivity of water resources of climate change is the most important variable.

7. Energy consumption

Tol's (1999) static assessment of the impact of climate change on energy consumption is based on Downing et al. (1995, 1996). The dynamic assessment here draws on the same source.

7.1. MODEL FOR HEATING ENERGY

Downing et al. (1995, 1996) argue that the demand for heating is approximately linear in temperature change. The market for space heating is almost saturated. Downing et al. (1995, 1996) suggest an income elasticity of 0.2, based on UK data. This leads to unrealistic results for the poorer regions (Tol, 1999). Mori and Takahashi (1998) suggest an income elasticity of 0.8, which leads to more realistic

results. Demand obviously increases with the number of people. Technological development reduces the costs of delivering heat. The model is:

$$SH_{t,r} = a_r T_t^{\beta} \left(\frac{y_{t,r}}{y_{t,1990}} \right)^{\varepsilon} \left(\frac{P_{t,r}}{P_{t,1990}} \right) \prod_{s=1990}^{t} AEEI_{s,r} \tag{6}$$

SH denotes the amount of money spent less on spacing heating; *t* denotes time; *r* denotes region; *T* denotes the change in the global mean temperature relative to 1990; γ denotes per capita income; *P* denotes population size; α is a parameter; cf. Table II; β is a parameter; β = 1 (0.5–1.5); ε = 0.8 (0.6–1.0); *AEEI* is a parameter; it is about 1% per year in 1990, converging to 0.2% in 2200; cf. Tol (1997); its standard deviation is set at a quarter of the mean.

7.2. MODEL FOR COOLING ENERGY

Following Downing et al. (1995, 1996), the demand for cooling is roughly linear in temperature change. The market for cooling is substantially less saturated, but Downing et al. (1995, 1996) do not report an estimate of the elasticity, so Mori and Takahashi's (1998) value of 0.8 is used. The model used here is based on elasticities which are constant over time, for want of more detailed information about air conditioning saturation levels. Demand for cooling increases with the number of people. Technological development reduces the costs. The model is:

$$SC_{t,r} = a_r T_t^{\beta} \left(\frac{y_{t,r}}{y_{t,1990}} \right)^{\varepsilon} \left(\frac{P_{t,r}}{P_{t,1990}} \right) \prod_{s=1990}^{t} AEEI_{s,r} \tag{7}$$

SC denotes the amount of money spent additionally on space cooling; *t* denotes time; *r* denotes region; *T* denotes the change in the global mean temperature relative to 1990; *y* denotes per capita income; *P* denotes population size; α is a parameter; cf. Table II, β is a parameter; β = 1 (0.5–1.5); ε is a parameter; ε = 0.8 (0.6–1.0); *AEEI* is a parameter (see above).

7.3. RESULTS

Figure 5 displays the results for heating. Under the best guess assumptions, the money saved from a reduced demand for heating remains below 1.0% of GDP. In the long run, impact starts levelling out due to improved energy efficiency. The income elasticity of heating energy demand adds more to the uncertainty than does the AEEI.

Figure 6 displays the results for cooling. Under the guess assumptions, the additional amount spent on cooling rises to 0.6% of GDP. The patterns and sensitivities are the same for cooling and heating energy demand. Instead of the AEEI, the sensitivity to β of equation (7) is displayed. The linearity of cooling demand in the temperature is important for the intertemporal distribution of the impact, and,

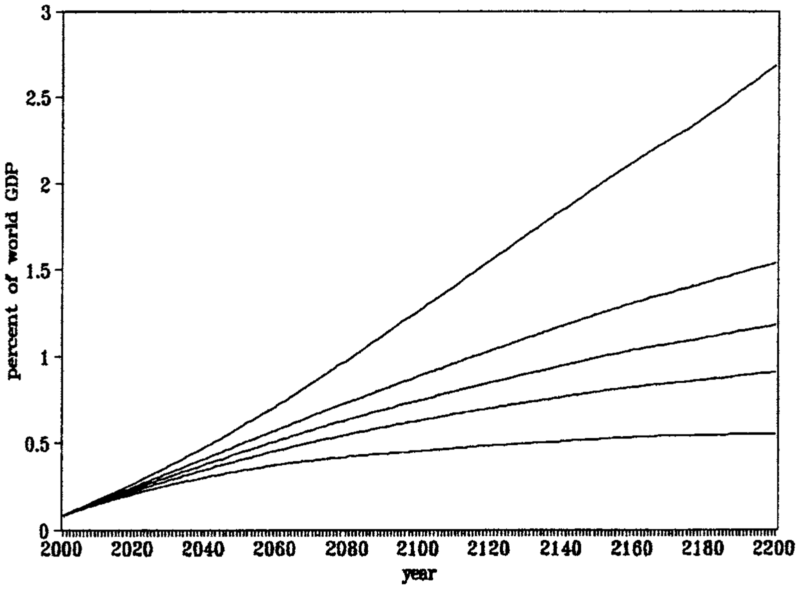

Figure 5. A sensitivity analysis around the impact of climate change on the demand for heating energy. The central line depicts the costs if all parameters are set to their central estimates. In the inner interval, the rate of technological progress is between its central estimate plus or minus its standard deviation. In the outer interval, the rate at which the heating enegy demand grows relative to income is varied between its central estimates plus or minus its standard deviation.

in the long run, a little less important than the income elasticity of cooling energy demand.

8. Sea Level Rise

8.1. MODEL

The impact of sea level rise on coastal systems is outlined in great detail in Tol (1999), drawing on the data of Hoozemans et al. (1993) and Bijlsma et al. (1996). Table III shows the accumulated loss of drylands and wetlands for a one metre rise in sea level. Land loss is assumed to be a linear function of sea level rise. The value of dryland is assumed to be linear in income density ($/km^2), with an average value of $4 million per square kilometre for the OECD. Tol (1999) uses this assumption to extrapolate across regions. It is used here to extrapolate over time. Wetland value is assumed to be logistic in per capita income, with an average value of $5 million per square kilometre for the OECD. These values are based on Fankhauser (1995). If dryland gets lost, the people living there are forced to move. The number of forced migrants follows from the amount of land lost and the average population density in the region. Following Tol (1995), the value of this is set at three times the regional per capita income per migrant.

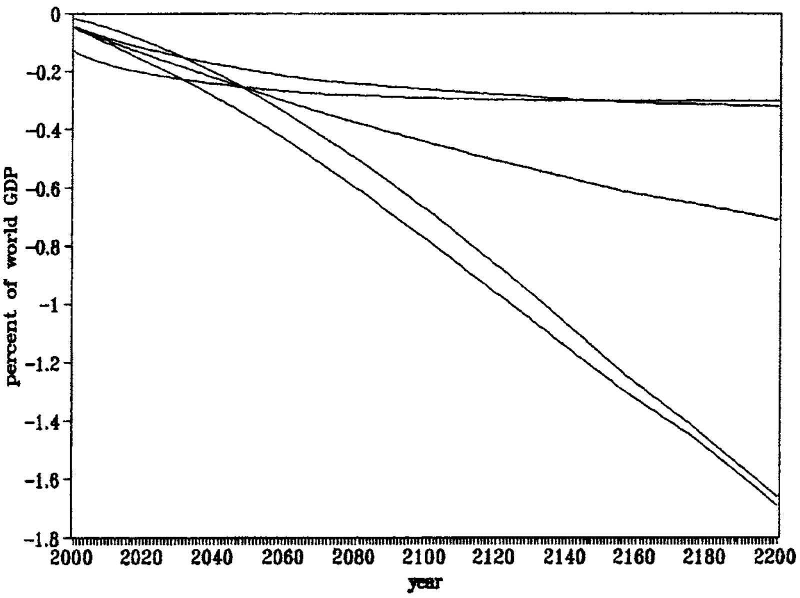

Figure 6. A sensitivity analysis around the impact of climate change on the demand for cooling energy. The central line depicts the costs if all parameters are set to their central estimates. In the inner interval (after 2040), the reaction of cooling energy demand to climate change is varied between more and less then linear. In the outer interval, the rate at which the cooling energy demand grows relative to income is varied between its central estimates plus or minus its standard deviation.

Land loss and migration is reasonably straightforward. However, people will not sit idle while their land get inundated. Instead, they will try to protect what they think is worth protection. Table III dipslays the annual costs of fully protecting all coasts against a one metre sea level rise in a hundred years time (based on Hoozemans et al., 1993). If sea level would rise slower than that (as projected by the IPCC), annual costs are assumed to be proportionally lower. The level of protection, that is, the share of the coastline protected, is assumed to be based on a cost-benefit analysis, following Fankhauser (1994):

$$L = \min\left\{0, 1 - \frac{1}{2}\left(\frac{PC + WL}{DL}\right)\right\} \tag{8}$$

L is the fraction of the coastline to be protected. PC is the net present value of the protection if the whole coast is protected. The GVA reports average costs per year the next century – see Table III. PC is calculated assuming annual costs to be constant. This is based on the following. Firstly, the coastal protection decision makers anticipate a linear sea level rise. Secondly, coastal protection entails large infrastructural works which last for decades. Thirdly, the considered costs are direct investments only, and technologies for coastal protection are mature.

Table III. Impact of a one metre sea level rise.

	Level prot. (%)	Dryland loss (10^3 km^2)	Dryland value (10^6\$/km^2)	Wetland loss (10^3 km^2)	Wetland value (10^6\$/km^2)	Protection costs (10^9\$)	Emigrants (10^6)
OECD-A	0.77	4.8 (2.4)	1.3 (0.6)	12.0 (8.6)	5.4 (2.7)	83 (74)	0.13 (0.07)
OECD-E	0.86	0.7 (0.4)	13.1 (6.6)	4.0 (2.3)	4.3 (2.2)	136 (45)	0.22 (0.10)
OECD-P	0.95	0.3 (0.4)	13.7 (6.7)	1.0 (1.1)	5.9 (2.9)	63 (38)	0.04 (0.02)
CEE&fSU	0.93	1.2 (2.7)	0.9 (0.5)	0.0 (0.0)	2.9 (1.5)	53 (50)	0.03 (0.03)
ME	0.30	0.6 (1.2)	0.5 (0.3)	0.0 (0.0)	1.3 (0.7)	5 (3)	0.05 (0.08)
LA	0.86	7.8 (7.1)	0.3 (0.2)	50.2 (36.4)	0.9 (0.5)	147 (74)	0.71 (1.27)
S&SEA	0.93	9.3 (9.6)	0.5 (0.3)	54.9 (48.0)	0.3 (0.2)	305 (158)	2.30 (1.40)
CPA	0.93	8.4 (15.1)	0.3 (0.2)	15.6 (17.1)	0.2 (0.1)	171 (126)	2.39 (3.06)
AFR	0.89	15.4 (18.4)	0.4 (0.2)	30.8 (14.8)	0.4 (0.02)	92 (35)	2.74 (2.85)

Source: Tol (2002).

WL is the net present value of the wetlands lost due to full coastal protection. Land values are assumed constant, reflecting how much current decision makers care about the non-marketed services and goods that get lost. The amount of wetland lost is assumed to increase linearly over time.

DL denotes the net present value of the dryland lost if no protection takes place. Land values are assumed to rise at the same pace as the economy grows. The amount of dryland lost is assumed to increase linearly over time.

Throughout the analysis, a pure rate of time preference, ρ, of 1% per year is used. The actual discount rate lies thus 1% above the growth rate of the economy, g. The net present costs of protection *PC* thus equal

$$PC = \sum_{t=1}^{\infty} \left(\frac{1}{1+\rho+g} \right)^t PC_a = \frac{1+\rho+g}{\rho+g} PC_a \tag{9}$$

where PC_a is the average annual costs of protection.

The net present costs of wetland loss *WL* follow from

$$WL = \sum_{t=1}^{\infty} t \left(\frac{1}{1+\rho+g} \right)^t WL_0 = \frac{1+\rho+g}{(\rho+g)^2} DL_0 \tag{10}$$

where WL_0 denotes the value of wetland loss in the first year.

The net present costs of dryland loss *DL* are

$$DL = \sum_{t=1}^{\infty} t \left(\frac{1}{1+\rho+g} \right)^t DL_0 = \frac{(1+g)(1+\rho+g}{\rho^2} DL_) \tag{11}$$

where DL_0 is the value of dryland loss in the first year.

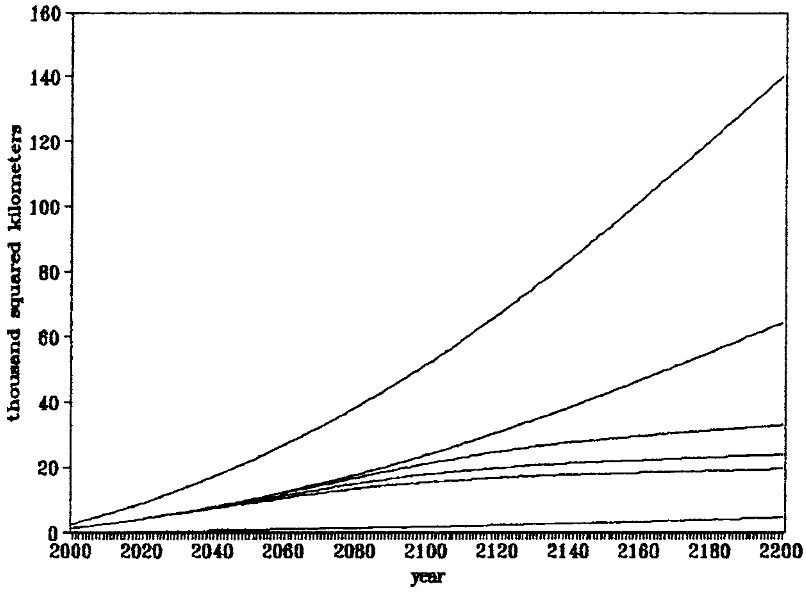

Figure 7. A sensitivity analysis around dryland losses due to sea level rise. Displayed are, from top to bottom, high losses without protection, central losses without protection, central losses with high protection, central losses with central protection, central losses with low protection, and low losses without protection.

8.2. RESULTS

Figure 7 displays a sensitivity analysis around the loss of drylands to sea level rise. The amount of land lost is varied, and the value of drylands is varied so as to influence the level of protection. The sensitivity to sea level rise dominates the influence of land values. The influence of the somewhat speculative model of the adaptive behaviour of coastal zone managers is thus mitigated.

Figure 8 displays a sensitivity analysis around forced migration and its costs. The number of migrants first rises steeply as sea level rise accelerates, then stabilizers, and then gradually falls as more and more land gets protected. In the central case, the number of forced migrants never exceeds 75,000 people per year, a relatively small number. The costs of migration follow a similar pattern, but then against a trend of ever increasing values attached to each migrant.

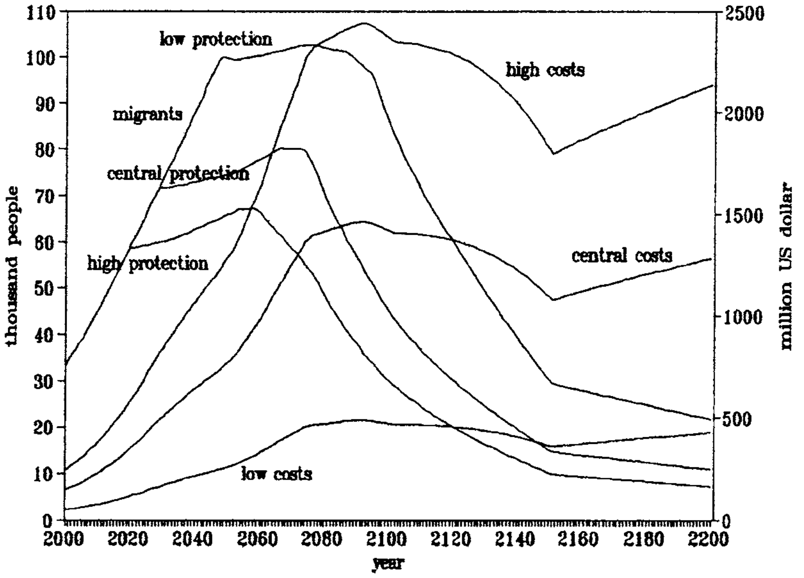

Figure 8. A sensitivity analysis around (the cost of) forced migration due to sea level rise. Depicted are the number of migrants in the case that dryland loss (with protection) is set to its central estimate, plus or minus its standard deviation. Also depicted are high, middle and low estimates of the costs for the case in which dryland loss and the number of migrants are set to their central estimates.

9. Ecosystems

9.1. MODEL

Tol (1999) assesses the impact of climate change on ecosystems, biodiversity, species, landscape *etcetera* based on the "warm-glow" effect. Essentially, the value people are assumed to place on such impacts are independent of any real change in ecosystems *etcetera*. This values is specified as

$$E_{t,r} = a\frac{y_{t,r}}{y_{1990,r}} P_{t,r} \frac{y_{t,r}/y_b}{1 + y_{t,r}/y_b} \tag{12}$$

where E denotes the value of the loss of ecosystems; t denotes times; r denotes region; y denotes per capita income; P denotes population size; α is a parameter such that E equals \$50 per person if per capita income equals the OECD average in 1990; y_b is a parameter; y_b = \$20,000.

9.2. RESULTS

Figure 9 displays some results. In the central case, welfare losses increase from some 0.25% of world GDP to about 0.5%. The estimate is very uncertain, though, particularly with respect to the value attached to species loss. Welfare losses could be less then 0.2% of GDP, but also exceed 1.0%.

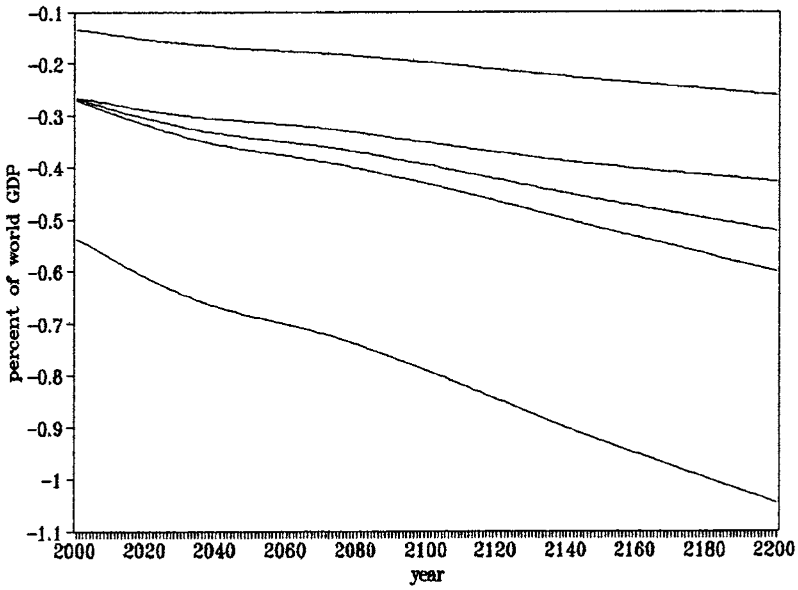

Figure 9. A sensivity analysis around the costs of loss of species, ecosystems, landscapes and so on due to climate change. The central line depicts the case in which all parameters are set to their central value. In the inner interval, the elasticity of valuation to per capita income is varied between its central estimate plus or minus its standard deviation. In the outer interval, the value people attach to ecosystem change is varied between its central value plus or minus its standard deviation.

10. Vector Borne Diseases

10.1. MODEL

Tol (1999) presents estimates of the change in mortality due to vector-borne diseases (viz., malaria, schistosomiasis, dengue fever) as the result of a one degree increase in the global mean temperature. The estimates results from overlaying the model-studies of Martens et al. (1995, 1997), Martin and Lefebvre (1995), and Morita et al. (1994) with mortality figures of the WHO (Murray and Lopez, 1996) for the nine regions identified in this study. Table IV summarizes the findings. Martens et al. (1995, 1997) standardize their results to an increase in the global mean temperature of 1.16 °C. Martin and Lefebvre (1995), and Morita et al. (1994), however, present their results (for malaria only) for various increases in the global mean temperature (2.8 °C to 5.2 °C). Both studies suggest that the relationship between global warming and malaria is linear. This relationship is assumed to apply to schistosomiasis and dengue ever as well.

Vulnerability to vector-borne diseases strongly depends on basic health care and the ability to purchase medicine. These factors are assumed to be linearly related to per capita income. The data of the WHO (WP and Lopez, 1996)) suggest a linear relationship between per capita income and mortality due to malaria, schistosomi-

Table IV. Additional deaths due to vector-borne diseases for a 1 °C global warming.

Region	Malaria	Schistosomiasis	Dengue fever
OECD-A	0 (0)	0 (0)	0 (0)
OECD-E	0 (0)	0 (0)	0 (0)
OECD-P	0 (0)	0 (0)	0 (0)
CEE&fSU	0 (0)	0 (0)	0 (0)
ME	155 (112)	−64 (13)	0 (0)
LA	1,101 (797)	−114 (22)	0 (0)
S&SEA	8,218 (5949)	−116 (3)	6,745 (1,171)
CPA	0 (0)	−128 (25)	393 (68)
AFR	56,527 (40,919)	−503 (99)	343 (60)

Source: Tol (2002).

asis, and dengue fever for the Middle East, Latin America, and South and Southeast Asia. Centrally Planned Asia (too low mortality) and Africa (too high) mortality are outliers. A regression of vector-borne mortality and per capita income suggests that populations with an income above \$3100 per head, with a standard deviation of \$260/head, are not vulnerable to vector-borne diseases. Because of the outliers, the standard deviation is increased to \$1000/head.

The model for vector-borne diseases thus becomes:

$$m_{r,t,d} = a_{r,d} T_t^{\beta} \left(\frac{y_c - y_{t,r}}{y_c - y_{1990,r}} \right)^{\gamma} \quad \textit{if } y_{t,r} \leq y_c \tag{13}$$

while $m_{t,r,d}$ = if $y_{t,r} > y_c$; m denotes mortality; t denotes time; r denotes regions; d denotes disease; α is parameter, the benchmark impact of climate change on vector-borne diseases; cf. Table IV; y denotes per capita income; T denotes the change in the global mean temperature relative to 1990; y_c is a parameter, denoting the per capita income at which vector-borne mortality becomes zero; y_c = \$3100 (2100–4100); β and γ are parameters, denoting the non-linearity of mortality in temperature and income, respectively; α = 1 (0.5–1.5); γ = (0.5–1.5).

Mortality is valued at 200 times the per capita income, with a standard deviation of 100, comparable to the assumptions of Tol (1995).

10.2. RESULTS

Figure 10 displays the additional number of deaths due to malaria, schistosomiasis, and dengue fever. Figure 11 displays the value placed at that. In the central case, the number of additional vector-borne deaths never exceeds 10,000 people per year. The number falls to zero by about 2080, as all regions acquire a sufficient standard of living to afford effective health care. The timing of this obviously varies with

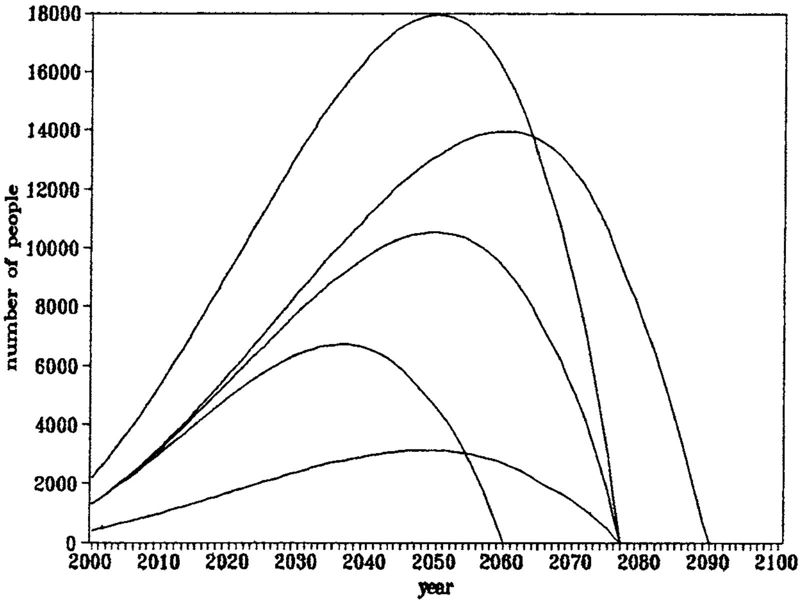

Figure 10. A sensivity analysis around the increase in vector-borne mortality due to climate change. The sensitivity, and the per capita income at which people have sufficient means to effectively protect themselves are varied between their central estimates plus or minus their standard deviations.

the assumed cut-off per capita income. The uncertainty about the sensitivity of vector- borne morality to climate change is more important for the total number of additional diseases. In Figure 11, the uncertainty about this sensitivity is also more important, albeit slightly, than the uncertainty about the value of a statistical life. In all cases, the total welfare loss is low, due in part to the relatively small number of premature deaths, and due in part to the fact that only poor people suffer from vector-born diseases.

11. Heat and Cold Stress

11.1. MODEL

Cardiovascular and respiratory disorders are worsened by both extreme cold and extreme hot weather. Martens (1998) assesses the increase in mortality for 17 countries. Tol (1999) extrapolates these findings to all other countries, based on formulae of the shape:

$$\Delta M = a + \beta T_B \tag{14}$$

where ΔM denotes the change in mortality due to a one degree global warming; T_B is the current temperature in the country; and α and β are parameters. Equation (14) is specified for populations above and below 65 years of age for cardiovascular

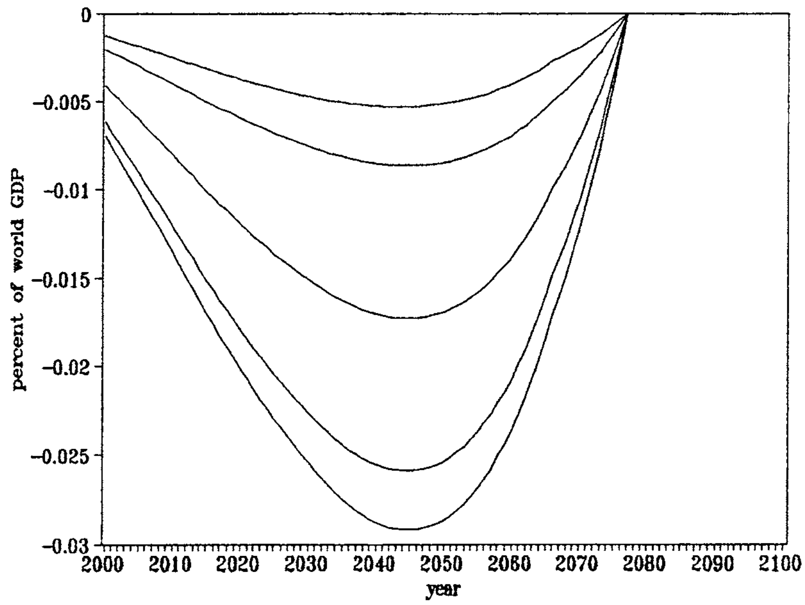

Figure 11. A sensivity analysis around the costs of increased vector-borne mortality. The central line depicts the case in which all parameters assume their central estimate. In the inner interval, the value of a statistical life is varied between its central estimate plus or minus its standard deviation. In the outer interval, the sensitivity of vector-borne mortality is varied between its central estimate plus or minus its standard deviation.

disorders. Cardiovascular mortality is affected by both heat and cold. In the case of heat, T_B denotes the average temperature of the warmest month. In the case of cold, T_B denotes the average temperature of the coldest month. Respiratory mortality is not age-specific.

Equation (14) is readily extrapolated. If warming exceeds one degree, the baseline temperature T_B changes. If this change is proportional to the change in the global mean temperature, the equation becomes quadratic. Summing country-specific quadratic functions results in quadratic functions for the regions:

$$\Delta M = aT + \beta T^2 \tag{15}$$

where T denotes the change in global mean temperature; α and β are parameters, derived, as described above, from the benchmark estimates of Table V.

One problem with (15) is that it is a non-linear exrtrapolation based on a data-set that is limited to 17 countries and, more importantly, a single climate change scenario. A global warming of 1 °C leads to changes in cardiovascular and respiratory mortality in the order of magnitude of 1% of baseline mortality due to such disorders. Per cause, the total change in mortality is restricted to a maximum of 5% of baseline mortality. (This restriction is effective.) Baseline cardiovascular and respiratory mortality derives from the share of the population above 65 in the

Table V. Additional deaths (in thousands) due to cardiovascular and respiratory diseases for a 1 °C global warming.

OECD-A	−64.4 (4.4)	11.4 (5.9)	3.0 (9.7)
OECD-E	−99.8 (2.6)	11.7 (4.0)	−2.8 (5.7)
OECD-P	−13.1 (2.2)	3.5 (2.8)	1.0 (4.8)
CEE&fSU	−87.5 (5.2)	10.7 (4.4)	4.5 (11.0)
ME	−8.9 (1.3)	2.5 (0.4)	9.9 (2.6)
LA	−20.0 (3.5)	8.1 (1.8)	11.1 (7.0)
S&SEA	−63.8 (16.9)	17.5 (2.9)	141.2 (34.1)
CPA	−103.4 (21.7)	24.3 (4.6)	62.8 (44.4)
AFR	−18.2 (3.0)	4.7 (0.5)	24.8 (6.0)

Source: Tol (2002).

total population. If the fraction of people over 65 increases by 1%, cardiovascular mortality increases by 0.0259% (0.0096%). For respiratory mortality, the change is 0.0016% (0.0005%). These parameters are estimated from the variation in population above 65 and cardiovascular and respiratory mortality over the nine regions in 1990.

Mortality as in equations (14) and (15) is expressed as a fraction of population size. Cardiovascular mortality, however, is separately specified for younger and older people. In 1990, the per capita income elasticity of the share of the population over 65 is 0.25, with a standard deviation of 0.08. This is used to generate the scenario of people over 65. Heat-related mortality is assumed to be limited to urban populations. The scenario for urbanization is based on Tol (1996, 1997).

11.2. RESULTS

Figure 12 displays some results. In the central case, climate change reduces mortality, peaking at half a million avoided deaths around 2050. The uncertainty is rather large. Changes in the population over 65 and consequent changes in baseline mortality have a minor effect. Capping mortality changes at a small fraction of baseline mortality has a major impact. The largest uncertainty, however, is the sensitivity of cardiovascular and respiratory mortality to climate change. In the year 2200, climate change may help to avoid almost 2.5 million premature deaths, but also cause an additional 1 million deaths.

12. Total Impact

Figure 13 displays the aggregated impact for the nine regions. The picture is mixed, with positive and negative climate change impacts for different regions at different times. Overall, the impact of climate change on the OECD is positive, although

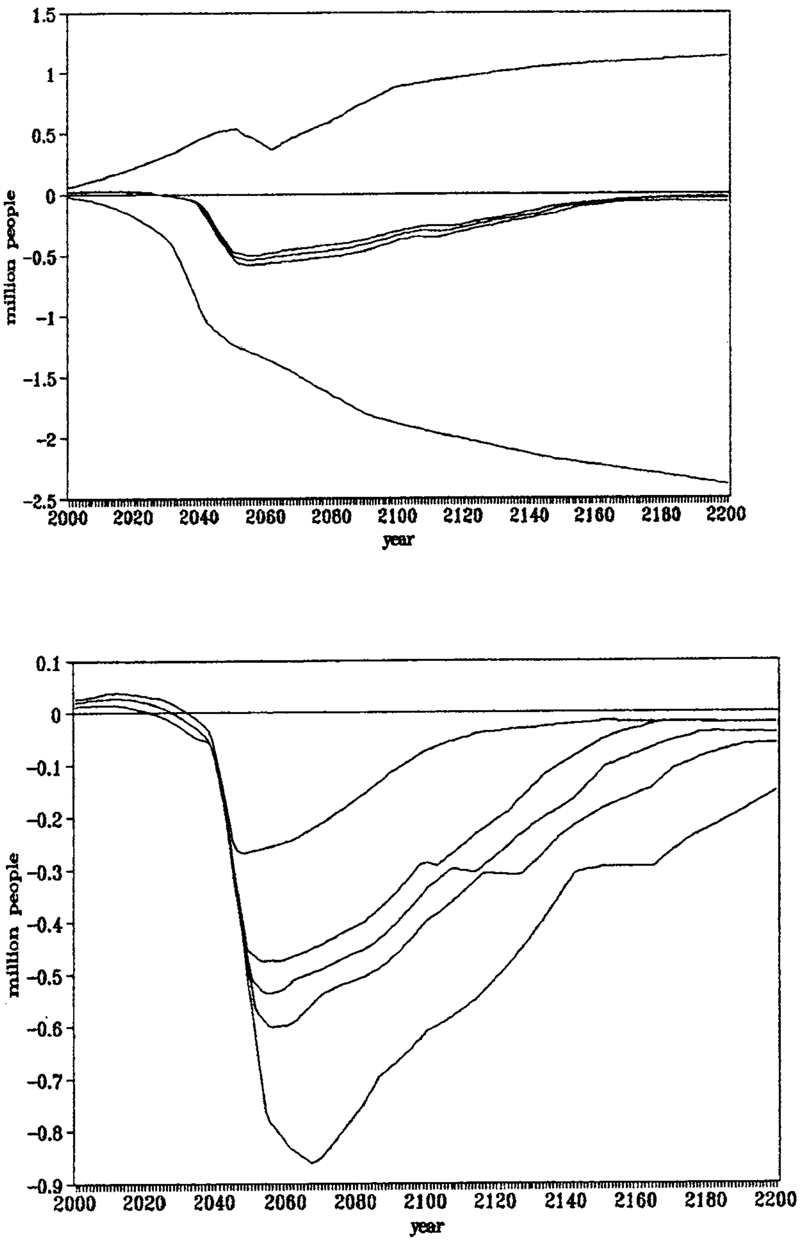

Figure 12. A sensivity analysis around the change in cardiovascular and respiratory mortality due to climate change. In both panels, the central line depicts the case with all parameters set to their central estimate. In the upper panel, in the inner interval, the reaction of the age composition to changes in per capita income is varied bewteen its central estimate plus or minus its standard deviation. In the lower panel, in the inner interval, the reaction of baseline mortality to changes in age composition is varied between its central estimate plus or minus its standard deviation. In the outer interval, the maximum allowed change in mortality is varied between its central estimate plus or minus its standard deviation.

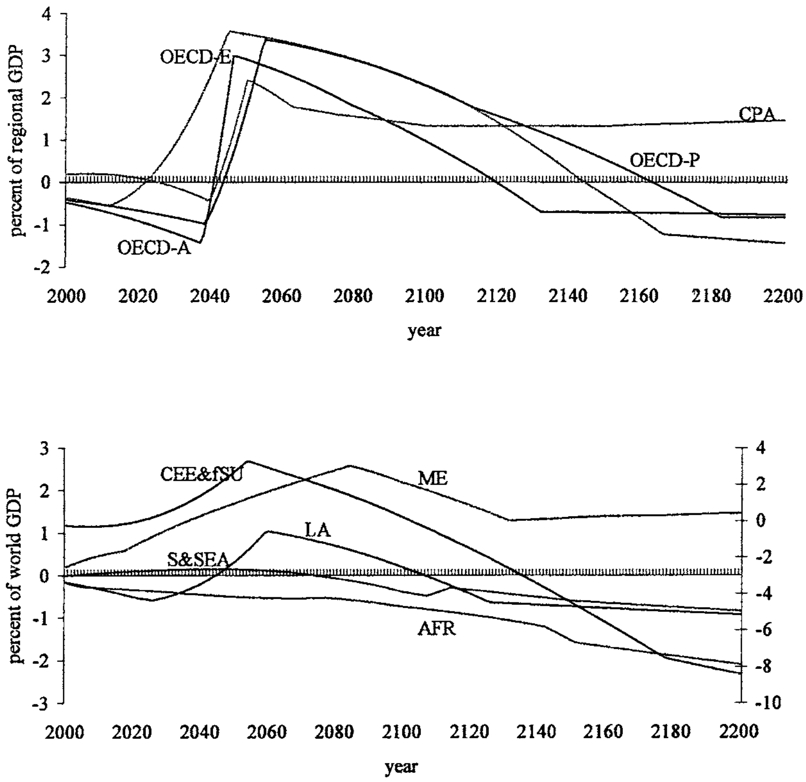

Figure 13. Aggregated impact of climate change for nine world regions. The impact on CEE&fSU is displayed at the left y-axis.

starting and ending in the negative. Latin America follows a similar pattern. So do the Middle East and Centrally Planned Asia, but there the whole curve is shifted towards the negative. The impact of climate change on South and Southeast Asia, Central and Eastern Europe and the former Soviet Union is, on the whole, negative. Africa sees only negative impacts. For comparison, the positive impact on the OECD never exceeds 4% of their GDP whereas the negative impact on CEE&fSU exceeds 8% of its GDP.

Aggregate impacts do not follow a smooth, readily simplified curve. Separate modelling of impacts therefore seems necessary to paint a realistic picture of aggregate impacts.

13. Discussion and Conclusions

Building a model of the impacts of climate change that takes proper account of dynamics of the impact's response to climate change and the changes in society's vulnerability proves to be a task which is beset with uncertainties and the need

for heroic assumptions. Despite that, a number of insights can be derived from the model attempted here.

Climate change impacts can be positive as well as negative, depending on the sector, region, and time one is looking at. The impact on social welfare thus depends on how one decides to aggregate (cf. Fankhauser et al., 1997). In the poorer regions, and in later times, the negative impacts tend to dominate the positive impacts. The former reconfirms that climate change and greenhouse gas abatement policy is essentially a problem of justice (cf. Arrow et al., 1996; Banuri et al., 1996; Lind and Schuler, 1998). The latter makes that even countries which are likely to gain from climate change have an incentive to reduce their greenhouse gas emissions. For, the workings of the climate system are slow, and so are the political, economic and technological mechanisms to abate emissions.

At the short term, the uncertainty about the sensitivity of a sector to climate change is most important. As time progresses, however, the change in vulnerability and the importance of that sector become the more important driving factors. These factors may be subject to a proactive adaptation policy (Fankhauser et al., 1998).

One should be careful, however, to base policy conclusions on the findings of this paper. Total climate change impacts, derived here, are less informative than marginal costs of greenhouse gas emissions. The complexity of the dynamics suggests that marginal costs are not trivially estimated. Uncertainty, although estimated, are not assessed. Above, parameters are varied one at a time. Uncertainties about scenarios for population and economic growth, and about the workings of the climate systems are ignored. These issues will be treated in future papers.

Most of all, one should be careful because so many of assumptions are not properly founded on a good understanding of the system. A lot of research remains to be done regarding vulnerabilities to climate change.

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Note

1. The optimal temperatures in Table I are relative to 1990. The model, however, uses temperatures relative to pre-industrial times. 1990 was about 0.5 °C warmer than the pre-industrial climate.

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