Emission Abatement versus Development as Strategies to Reduce Vulnerability to Climate Change: An Application of FUND

Article *in* Environment and Development Economics · February 2005

DOI: 10.1017/S1355770X05002354 · Source: RePEc

Richard S.J. Tol
University of Sussex

EMISSION ABATEMENT VERSUS DEVELOPMENT AS STRATEGIES TO REDUCE VULNERABILITY TO CLIMATE CHANGE: AN APPLICATION OF *FUND*

Richard S.J. Tol

Centre for Marine and Climate Research, Hamburg University

Institute for Environmental Studies, Vrije Universiteit, Amsterdam

Center for Integrated Study of the Human Dimensions of Global Change, Carnegie Mellon University, Pittsburgh, PA

ZMK, Troplowitzstrasse 7, 22529 Hamburg, Germany

February 19, 2002

Abstract

Poorer countries are generally believed to be more vulnerable to climate change than richer countries because poorer countries are more exposed and have less adaptive capacity. This suggests that, in principle, there are two ways of reducing vulnerability to climate change: economic growth and greenhouse gas emission reduction. Using a complex climate change impact model, in which development is an important determinant of vulnerability, the hypothesis is tested whether development aid is more effective in reducing vulnerability than is emission abatement. The hypothesis is rejected in all cases, except for one important one. In general, investing a dollar in emission reduction reduces impacts further than investing that dollar in general development aid. However, this is not the case for vector-borne infectious diseases (malaria) and for regions where such diseases dominate total climate change impacts (Africa). In this case, more climate-change-induced disease is avoided by stimulating development than by reducing emissions.

Key words

climate change, climate change impacts, vulnerability, adaptive capacity, development

EMISSION ABATEMENT VERSUS DEVELOPMENT AS STRATEGIES TO REDUCE VULNERABILITY TO CLIMATE CHANGE: AN APPLICATION OF *FUND*

Richard S.J. Tol

Hamburg, Vrije and Carnegie Mellon Universities

His last big project in a long career, Jan Feenstra managed the Netherlands Climate Change Assistance Programme. He hated how climate change detracted from the real issues. This paper is dedicated to his memory.

1. Introduction

It is often noted that the level of (economic) development is one of the main determinants of vulnerability to climate change. The reason is twofold. First, a larger share of the economy of poorer countries directly depends weather and climate, for instance, in agriculture. Second, poorer countries have less means to defend themselves against the vagaries of the weather. As their exposure is higher, and adaptive capacity is lower, poorer countries are more vulnerable. Global climate change impact studies indeed confirm this, although one may wonder how of this is "assumption" and how much "result".

A corollary of "poor is vulnerable" is that accelerating development is a strategy to reduce vulnerability to climate change, and – apart from the side benefits – perhaps a more effective one than reducing greenhouse gas emissions. This point is also noted with some regularity. However, to date, this is an assertion only. The relative strengths of development versus emission abatement in reducing vulnerability to climate change have yet to be quantified.

Tol and Dowlatabadi (2001) is an exception. However, that paper is limited to malaria only, and the argument is the other way around. Tol and Dowlatabadi use a model in which the incidence of malaria increases with global warming and decreases with economic growth; the model also includes international trade and investment. They show that the economic growth forgone (in developing countries) because of ambitious emission reduction (in developed countries) would affect public health care such that malaria actually increases.

This paper attempts a direct comparison between the two effects. It estimates the marginal costs of climate change, and then estimates what would happen (at the margin) to the impacts of climate change if the same amount of money were invested in development rather than in emission abatement. Framed like this, we also avoid the tricky issue of estimating the impacts of emission reduction in the North on economic growth in the South.

A second difference between this paper and Tol and Dowlatabadi (2001) is that we here consider all impacts of climate change, rather than malaria only. Infectious diseases and development are negatively correlated. However, other diseases, notably cardiovascular and respiratory disorders, are positively correlated to income (via diet and longevity). The issue is broader than health. Some vulnerabilities fall with income (e.g., agriculture), whereas others rise (e.g., energy consumption). Only if we include all impacts in a consistent way, we can genuinely investigate the trade-off between development and emission reduction as means to reduce climate change vulnerability.

A study like this is necessarily built upon a large number of assumptions. These include scenarios of future developments, climate change, climate change impacts, and the relationship between vulnerability and development. These elements are all uncertain. Other assumptions are not just uncertain, but also controversial. These include how different impacts are aggregated, and how impacts are aggregated over nations and over time. Although the model used and the underlying assumptions are "mainstream", and although sensitivities are analysed, it is clear that this paper is only a first attempt at a complicated subject.

Sections 2 and 3 present the model used Section 2 is a brief summary of material published elsewhere. Section 3 introduces in more detail new elements of the model. Section 4 describes the scenarios run. Section 5 presents the results. Section 6 concludes.

2. The Model

This paper uses version 2.4 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Parts of the model go back to version 1.6 (see Tol, 1999a-e, forthcoming, a). Other parts go back to version 2.0 (Tol, forthcoming, b, c). Relevant for this paper, compared to previous versions, version 2.4 has updated estimates of the impacts of climate change. See Smith *et al.* (2001) and Tol *et al.* (2001) for a discussion of the impacts of climate change.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations, specified for nine major world-regions, namely OECD-America, OECD-Europe, OECD-Pacific, Central and Eastern Europe and the former Soviet Union, Middle East, Latin America, South and South-East Asia, Centrally Planned Asia, and Africa.

The model runs from 1950 to 2200, in time steps of a year. The prime reason for extending the simulation period into the past is the necessity to initialise the climate change impact module. In *FUND*, some climate change impacts are assumed to depend on the impact of the year before, so as to reflect the process of adaptation to climate change. Without a proper initialisation, climate change impacts are thus misrepresented in the first decades. Scenarios for the period 1950-1990 are based on historical observation, viz. the *IMAGE* 100-year database (Battjes and Goldewijk, 1994). The period 1990-2100 is based on the *FUND* scenario, which lies somewhere in between the IS92a and IS92f scenarios (Leggett *et al.*, 1992). Note that the original IPCC scenarios had to be adjusted to fit *FUND*'s nine regions and yearly time-step. The period 2100-2200 is based on extrapolation of the population, economic and technological trends in 2050-2100, that is, a gradual shift to a steady state of population, economy and technology. The model and scenarios are so far extrapolated that the results for the period 2100-2200 are not to be relied upon. This period is only used to provide the forward-looking agents in *FUND* with a proper perspective.

The exogenous scenarios concern economic growth, population growth, urban population, autonomous energy efficiency improvements, decarbonisation of the energy use, nitrous oxide emissions, and methane emissions.

Incomes and population are perturbed by the impact of climate change. Population falls with climate change deaths, resulting from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to affect only the elderly, non-reproductive population; heat stress only affects urban population. Population also changes with climate-induced migration between the regions. Economic impacts of climate change are modelled as deadweight losses to disposable income. Scenarios are only slightly perturbed by climate change impacts, however, so that income and population are largely exogenous.

The endogenous parts of *FUND* consist of carbon dioxide emissions, the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, and the impact of climate change on coastal zones, agriculture, extreme weather, natural ecosystems and malaria.

Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted:

(1) $$C_t = C_{t-1} + \alpha E_t - \beta(C_{t-1} - C_{pre})$$

where C denotes concentration, E emissions, t year, and *pre* pre-industrial. Table 1 displays the parameters for both gases. Equation (1) is a simplified representation of the relevant atmospheric chemistry. Particularly, the atmospheric life-time is not constant, but depends on the concentrations and emissions of other chemical species.

Table 1. Parameters of Equation (1).

Gas	α[a]	β[b]	Pre-industrial concentration
Methane (CH_4)	0.3597	1/8.6	790 ppb
Nitrous oxide (N_2O)	0.2079	1/120	285 ppb

[a] The parameter α translates emissions (in million metric tonnes of CH_4 or N_2O) into concentrations (in parts per billion by volume).

[b] The parameter β determines how fast concentrations return to their pre-industrial (and assumedly equilibrium) concentrations; $1/\beta$ is the atmospheric life-time (in years) of the gases.

The carbon cycle is a five-box model:

(2a) $$Box_{i,t} = \rho_i Box_{i,t-1} + 0.000471 \alpha_i E_t$$

with

(2b) $$C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t}$$

where α_i denotes the fraction of emissions E (in million metric tonnes of carbon) that is allocated to box i (0.13, 0.20, 0.32, 0.25 and 0.10, respectively) and ρthe decay-rate of the boxes (ρ = exp(-1/lifetime), with life-times infinity, 363, 74, 17 and 2 years, respectively). Thus, 13% of total emissions remains forever in the atmospheric, while 10% is -- on average -- removed in two years. The model is due to Maier-Reimer and Hasselmann (1987), its parameters to Hammitt *et al.* (1992). It assumes, incorrectly, that the carbon cycle is independent of climate change. Carbon dioxide concentrations are measured in parts per million by volume.

Radiative forcing for carbon dioxide, methane and nitrous oxide are based on Shine *et al.* (1990). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by radiative forcing RF), with a life-time of 50 years. In the base case, global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents, so:

$$T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50} \frac{2.5}{6.3 \ln(2)} RF_t \tag{3}$$

Global mean sea level is also geometric, with its equilibrium determined by the temperature and a life-time of 50 years. These life-times result from a calibration to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996). The climate impact module is fully described in Tol (forthcoming, b,c). The impact module has two units of measurement: people and money. People can die prematurely and migrate. These effects, like all other impacts, are monetised. Damage can be due to either the rate of change or the level of change. Benchmark estimates can be found in Table 2.

Table 2. Estimated impacts of a 1°C increase in the global mean temperature. Standard deviations are given in brackets.

	Billion dollar		percent of GDP	
OECD-A	175	(107)	3.4	(2.1)
OECD-E	203	(118)	3.7	(2.2)
OECD-P	32	(35)	1.0	(1.1)
CEE&fSU	57	(108)	2.0	(3.8)
ME	4	(8)	1.1	(2.2)
LA	-1	(5)	-0.1	(0.6)
S&SEA	-14	(9)	-1.7	(1.1)
CPA	9	(22)	2.1	(5.0)
AFR	-17	(9)	-4.1	(2.2)

Source: Tol (forthcoming, b).

Impacts of climate change on energy consumption, agriculture and cardiovascular and respiratory diseases explicitly recognise that there is a climate optimum. The climate optimum is determined by a mix of factors, including physiology and behaviour. Impacts are positive or negative depending on whether climate is moving to or away from that optimum climate. Impacts are larger if the initial climate is further away from the optimum climate. The optimum climate concerns the potential impacts. Actual impacts lag behind potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to the new climate are always negative.

Other impacts of climate change, on coastal zones, forestry, unmanaged ecosystems, water resources, malaria, dengue fever and schistosomiasis, are modelled as simple power functions. Impacts are either negative or positive, but do not change sign.

Vulnerability changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanisation) and ecosystems and health (with higher values from higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector-borne diseases (with improved health care).

3. An Update

Agriculture

Tol (forthcoming, b,c) 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). In this paper, we add results from the AIM model (Morita *et al.,* 1994) as presented in Audus (1998) and IEA GHG (1999). 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. Some of the studies report results without CO_2 fertilisation, some with, and some do both. This allows us to separate out the effects of CO_2 fertilisation. This is important, particularly for multiple gas studies (nitrous oxide, for example, contributes to warming but not to carbon dioxide concentrations). Table 3 reports the results for a 2.5°C increase in the global mean temperature, a rate of 0.04°C/year, and a doubling of the atmospheric concentration of carbon dioxide.

Table 3. Impacts of climate change on agriculture.

Region	rate of change (%GAP/0.04º)		level of change (%GAP/2.5ºC)		optimal temperature (ºC)		CO_2 fertilisation (%GAP/2xCO_2)	
OECD-A	-.030	(.033)	0.77	(0.84)	1.73	(2.55)	0.32	(1.99)
OECD-E	-.034	(.028)	0.63	(0.60)	1.70	(2.49)	1.82	(1.65)
OECD-P	-.018	(.036)	-0.17	(1.51)	1.23	(4.10)	1.07	(1.65)
CEE&fSU	-.041	(.024)	0.54	(0.90)	1.69	(2.36)	2.45	(1.64)
ME	-.030	(.012)	-0.40	(0.32)	1.51	(2.79)	0.90	(0.68)
LA	-.040	(.017)	-0.85	(0.48)	1.44	(3.58)	1.29	(0.99)
S&SEA	-.038	(.010)	-0.86	(0.43)	1.44	(3.23)	1.38	(0.51)
CPA	-.043	(.026)	0.29	(1.11)	1.68	(2.00)	2.52	(1.13)

AFR	-.020	(.007)	-0.31	(0.21)	0.51	(2.30)	0.67	(0.40)

Source: Own calculations based on references in main text.

Forestry

Tol (forthcoming, b,c) is based on one single forestry study only (Perez-Garcia *et al*., 1996). Since then, Sohngen *et al*. (1996) published their results for the impact of climate change on the global timber market. The results here – see Table 4 – are based on the average of the two studies. Note that the results of Perez-Garcia dominate the average, as they show less variation between scenarios. The estimates of the two studies are the means of the normalised scenarios and cases reported; the standard deviation is the variation between the scenarios and cases.

Table 4. Estimates of the impact of a 1°C global warming on forestry.

	Sohngen		Perez-Garcia		Combined	
OECD-A	510	(535)	218	(36)	219	(36)
OECD-E	595	(190)	134	(24)	141	(24)
OECD-P	267	(235)	93	(57)	103	(55)
CEE&fSU	360	(360)	-136	(148)	-65	(137)
ME	0	(185)	0	(10)	0	(10)
LA	392	(143)	10	(5)	10	(5)
S&SEA	102	(29)	14	(52)	81	(25)
CPA	248	(36)	0	(2)	1	(2)
AFR	142	(61)	0	(5)	1	(5)

Source: Own calculations, based on Perez-Garcia *et al.* () and Sohngen *et al.* ().

Biodiversity

Climate change is expected to impact heavily on species, ecosystems and landscapes. Yet, this aspect has been paid relatively little attention to by economists, primarily so because the physical impact is still to a large extent unknown (Watson *et al.*, 1996), but also because the value of an ecosystem or a species cannot be easily estimated (Bjorn-stad and Kahn, 1996; Braden and Kolstad, 1991; Freeman, 1993; Hausman, 1993; Mitchell and Carson, 1989; Pearce and Moran, 1994). Climate economists therefore face a double problem, i.e., how to derive a value of something which is unknown in quantity and price.

Tol (forthcoming) uses a valuation procedure that is based on the “warm-glow” effect, described in the valuation literature (e.g., Andreoni, 1988, 1990). This effect suggests that people contribute to good causes; the amount is unrelated to the nature of the good cause. The underlying assumptions are that people perceive the impacts of climate change on ecosystems as bad, but that such impacts cannot readily be measured or attributed.

The problem with Tol's (forthcoming, b,c) formulation is that it is unrelated to climate change. Therefore, we add the assumption that more people would be aware of climate change and its impacts on ecosystems, if climate change is faster and its impacts more pronounced. For this, we use a logistic relationship, calibrated such that half the people would sense ecosystems losses if the globe warms by 0.025°C a year.

Another problem is that Tol (forthcoming, b,c) neglects the scarcity value of biodiversity. Weitzman (1998) argues that, for practical purposes, one should rank biodiversity conservation practices according to

(4) $$R_{species} = \left(D_{species} + U_{species}\right)\frac{\Delta P_{species}}{C_{species}}$$

where R is the index used for ranking, the expression between brackets is the value of the species, and the ratio is the "cost-effectiveness" (change in the chance of survival over the cost of the intervention that brings about that change).

The value of the species consists of two components, i.e., its contribution to biodiversity (D) and its own total economic value (U). Weitzman (1992, 1993) argues that half the Shannon index (H) is a reasonable way of measuring biodiversity. Weitzman's index (W) is defined as

(5) $$W = \frac{H}{2} = -\frac{1}{2}\sum_{species} P_{species}\log_2 P_{species} = -\frac{1}{2\ln 2}\sum_{species} P_{species}\ln P_{species}$$

where P is the contribution of a species to all living beings. One way of thinking about P is the fraction of a species' biomass in total biomass.

In a climate change context, we do not know which species gets lost, so we set $P=1/N$, where N is the total number of species. The biodiversity value of a species getting lost is then proportional to

(6)
$$D = \frac{\partial W}{\partial N} = -\frac{\partial}{\partial N}\left(\frac{1}{2\ln 2}\sum_{species} P_{species}\ln P_{species}\right) = -\frac{1}{2\ln 2}\frac{\partial}{\partial N}\left(\sum_{N}\frac{1}{N}\ln\frac{1}{N}\right) = \frac{1}{2\ln 2}\frac{1}{N}$$

The current number of species is estimated to be about 14 million, with an uncertainty range of 2-100 million. At the moment, the diversity value of a species getting lost is in the order of one in ten million. However, a more and more species are going extinct, the diversity value will increase. In addition, climate change will enhance the rate of extinction.

We assume that, of the current amount people are willing to pay for nature protection, 5% has to do with preserving biodiversity (with a standard deviation of 5%); the rest has to do with recreation, aesthetics, the species intrinsic value, and so on. The biodiversity part of the value increase with N_0/N_t. The expected rate of species extinction is about 0.4% a year. We assume that 0.3% (with a standard deviation of 0.3%) is autonomous;

0.1% (with a standard deviation of 0.1%) is due to an annual temperature increase of 0.025°C; this relationship is quadratic.

Wetlands

Biodiversity is not the only thing that will get scarcer. Coastal wetlands are also in decline. Sea level rise and coastal protection measures are assumed to be the sole causes of wetland loss. In analogy to the biodiversity losses, other 95% of the value people currently assign to wetland loss (some $5 million per square kilometre in the OECD; Tol, forthcoming, b,c) are due to more generic, and therefore substitutable, recreation, nature conservation and extraction activities; the remaining 5% is due to the general scarcity of coastal wetlands This value increases proportionally to the ratio of current wetland and remaining wetlands, but no more than 20 times. In some regions, almost all wetlands disappear before 2200. The total wetland value thus increases not more than 100%.

Morbidity

Tol (forthcoming, b,c) estimates the impacts of climate change on human mortality through 6 pathways: malaria, schistosomiasis, dengue fever, cold-related cardiovascular diseases, heat-related cardiovascular diseases, and heat-related respiratory disorders, based on EUROWINTER Group (1997), Martens (1996, 1997, 1998), Martens *et al.* (1995, 1997), Martin and Lefebvre (1995), Matsuoko and Kai (1995). Estimates of the changes in the disease burden due to climate change were overlaid with data on the mortality burden (Murray and Lopez, 1996a,b). Here, we follow the same procedure for data on the morbidity burden.

Table 5. Number of additional years of life disabled (1000s) for 1ºC global warming.

	Malaria	Schisto[a]	Dengue	C-Heat[b]	C-Cold[c]	Resp.[d]	Total
OECD-A	0.0	0.0	0.0	11.0	-61.9	26.3	-24.6
	(0.0)	(0.0)	(0.0)	(5.7)	(4.2)	(85.0)	
OECD-E	0.0	0.0	0.0	11.2	-95.9	-24.5	-109.2
	(0.0)	(0.0)	(0.0)	(3.8)	(2.5)	(50.0)	
OECD-P	0.0	0.0	0.0	3.4	-12.6	8.8	-0.5
	(0.0)	(0.0)	(0.0)	(2.7)	(2.1)	(42.1)	
CEE&fSU	0.0	0.0	0.0	9.6	-78.6	53.1	-15.9
	(0.0)	(0.0)	(0.0)	(4.0)	(4.7)	(129.9)	
ME	5.0	-5.2	0.0	3.4	-12.0	215.9	207.1
	(2.5)	(0.0)	(0.0)	(0.5)	(1.7)	(56.7)	
LA	5.0	-6.9	0.0	10.2	-25.1	245.9	229.1
	(3.7)	(0.0)	(0.0)	(2.3)	(4.4)	(155.1)	

S&SEA	53.9	-0.6	2.1	24.2	-88.2	2509.9	2501.3
	(38.7)	(0.0)	(0.4)	(4.0)	(23.4)	(606.1)	
CPA	0.0	-1.1	0.0	30.1	-128.2	521.7	422.5
	(0.0)	(0.0)	(0.0)	(5.7)	(26.9)	(368.8)	
AFR	211.6	-133.1	0.0	6.3	-24.3	536.2	596.7
	(153.2)	(26.6)	(0.0)	(0.7)	(8.0)	(129.7)	

[a] Schistosomiasis.
[b] Heat-related, cardiovascular mortality.
[c] Cold-related, cardiovascular mortality.
[d] Heat-related, respiratory mortality.

Source: Own calculations based on references in the main text.

Morbidity is valued at 80% of per capita income per year of illness, with a standard deviation of 1.2, based on the assumptions of Navrud (2001).

Urban Population

In earlier versions of *FUND*, an exogenous scenario specified the fraction of the population living in the city. In the current version, we assume that urbanisation is a function of per capita income and population density:

$$U_t = \frac{\alpha\sqrt{y_t} + \beta\sqrt{PD_t}}{1+\alpha\sqrt{y_t} + \beta\sqrt{PD_t}} \tag{7}$$

where U is the fraction of people living in cities, y is per capita income, PD is population density and t is time; α and β are parameters, estimated from national data for the year 1995; α=0.031 (0.002) and β=-0.011 (0.005); R^2=0.66.

Water

Earlier versions of *FUND* incorrectly assumed that water technologies are constant. *FUND*'s impact estimates are based on Downing *et al.* (1995, 1996), and they also assume that there is no technological change in water. In reality, however, there are considerable improvements, both for water supply (e.g., desalinisation) and water demand (e.g., drip irrigation). In the revised impacts module, we assume that water technology progress by 0.5% a year, with a standard deviation of 0.5%. This manifests itself in that the sensitivity of the water sector to climate change falls by 0.5% a year.

Energy consumption

FUND's impact estimates for energy consumption are based on Downing *et al.* (1995, 1996). As Downing *et al.* do not provide details on the functional form, earlier versions of FUND assume that the demand for heating decreases linearly with temperature, while the demand for cooling increases linearly. There is obviously a limit to the savings on heating, whereas the additional demand for cooling may actually rise faster than linearly. Therefore, cooling energy demand is assumed to rise with temperature to the power 1.5, and heating energy demand is assumed to fall with the square root of temperature.

4. Marginal Cost Estimates

Marginal costs of carbon dioxide are estimated as follows. First, a base run is made with the model. Second, a perturbed run is made in which one million metric tonnes of carbon are added to the atmosphere for the period 2000-2009. In both runs, relative impacts, GDP and population are saved. Marginal costs are estimated using:

$$\frac{\sum_{r=1}^{9}\sum_{t=0}^{150}\left(\frac{D_{r,t}^{P}}{Y_{r,t}^{P}}-\frac{D_{r,t}^{B}}{Y_{r,t}^{B}}\right)\frac{Y_{r,t}^{B}}{(1+\rho+g_{r,t}^{B})^{t}}(\$)}{10000000(tC)} \tag{8}$$

where D is monetised damage; Y is GDP, g is the growth rate of per capita income; ρ is the pure rate of time preference; the subscript t is time; and the superscript denotes base (B) or perturbed (P) run. That is, the change in *relative* impacts is evaluated against the baseline economic growth – this is to avoid the complications of differential effects on the economic growth path (see Fankhauser and Tol, 2001, for a discussion). Impact are discounted using the standard neo-classical discount rate, viz., the sum of the pure rate of time preference and the growth rate of per capita consumption.

Marginal benefits of development aid are estimated as follows. First, a base run is made. Second, a perturbed run is made in which the three OECD regions each transfer a third of a million dollar to a non-OECD region for each of the years 2000-09. Marginal benefits follow from

$$\frac{\sum_{t=0}^{150}\left(\frac{D_{r,t}^{P}}{Y_{r,t}^{P}}-\frac{D_{r,t}^{B}}{Y_{r,t}^{B}}\right)\frac{Y_{r,t}^{B}}{(1+\rho+g_{r,t}^{B})^{t}}(\$)}{10000000(\$)} \tag{9}$$

where all symbols have the same interpretation as above. Equation (9) is calculated separately for each non-OECD region, whereas (8) sums over the regions.

Figure 1 displays the effect of the changes described in Section 3 on the marginal costs of carbon dioxide emissions. For reference, the marginal damages according to *FUND*1.6 and *FUND*2.0 are given. Starting from *FUND*2.0, incremental changes are made, in the same order as above, to arrive at the marginal cost estimates of *FUND*2.4. The updated agriculture impact estimates slightly reduce the marginal costs. This is because the *AIM* model, newly added, is quite optimistic about the impacts of climate change on agriculture. The new forestry estimates leave the marginal costs largely unchanged, which is no surprise as the Perez-Garcia estimates dominate the Sohngen estimates, and forestry is a tiny economic sector. The new "detection" formulation for ecosystem impacts drives up the marginal costs (recall they were zero – at the margin – before). Adding the increasing scarcity of biodiversity and wetlands does not change much, as this effect is small. Adding morbidity increases the marginal costs, but only by a little bit. This is because there are positive as well as negative morbidity effects, and although the total number of life years disabled is clearly negative, the positive effects are concentrated in the richer countries. The new urbanisation scenario works to reduce marginal impacts. In the new scenario, urbanisation is somewhat lower worldwide, but particularly so in Latin America. Less people in hot cities implies less heat-related cardiovascular and respiratory disorders. Adding technological progress to the water sector decreases the marginal costs, but changing the curvature of energy consumption increases the marginal costs. Overall, *FUND*2.4 has somewhat higher marginal cost estimates than does *FUND*2.0.

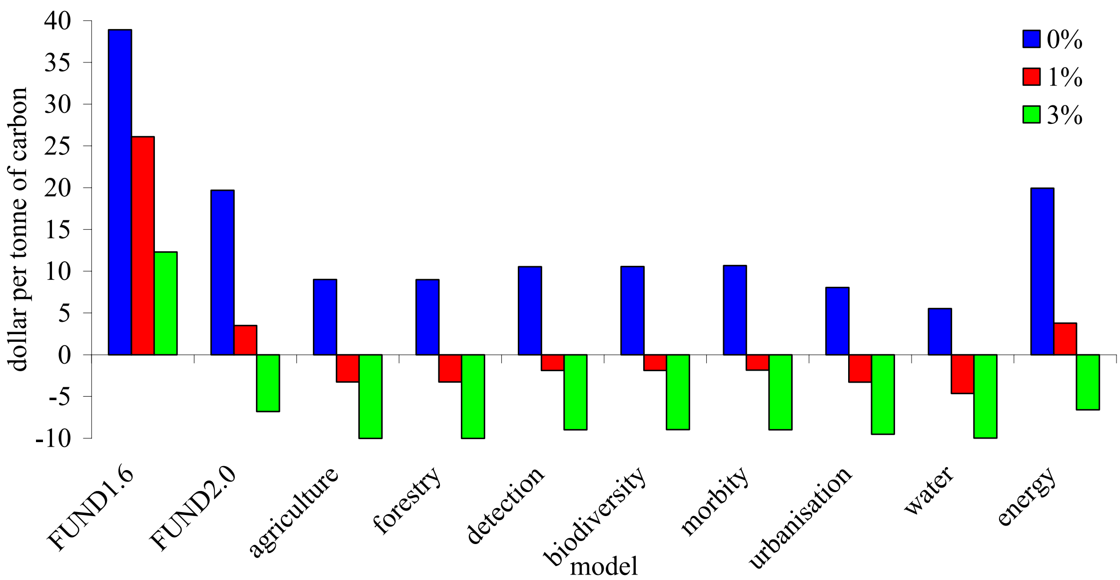


Figure 1. The marginal costs of carbon dioxide emissions according to different versions of the *FUND* model. Results for *FUND*1.6 (Tol, 1999a) are leftmost, next to *FUND*2.0 (Tol and Downing, 2000). Moving to the right, incremental changes are made to *FUND*2.0 as described in the text. The rightmost results are from the *FUND*2.4 model. Results are given for pure rates of time preference of 0, 1 and 3% per year.

5. Abatement versus development

Table 1 shows the effect of a small change in carbon dioxide emissions. Western Europe, particularly its health and energy consumption, is the most vulnerable of the OECD regions; the other parts of the OECD even substantially benefit from climate change in the short run, mostly because of reductions in cold-related mortality and morbidity. The countries of Central and Eastern Europe and the former Soviet Union suffer from climate change, particularly with regard to water resources. South and Southeast Asia and China also benefit from climate change, particularly in agriculture and energy.

However, Latin America and Africa are, on balance, negatively affected, with water resources, energy consumption and health being the main contributors.

Speeding up development may help or hinder vulnerability to climate change. In South and Southeast Asia, faster development increases vulnerability, because agriculture becomes less important – climate change affects agriculture positively – and because heat-related cardiovascular and respiratory disorders are more prominent in wealthier societies. In Latin America, the health balance is more towards poverty-related (i.e., vector-borne, infectious) diseases and cold-related cardiovascular disorders, so that there faster development reduces vulnerability. However, the return on such investments is small: for every dollar invested, 5 to 8 cents worth of avoided impacts is gained.

In Africa, investing in development does pay off, at least for low discount rates. With a pure rate of time preference of 1% (0%), every invested dollar yields a return of 255% (752%). For higher discount rates, the investment is not worthwhile: an invested dollar return 38 cents if the pure rate of time preference equals 3%. The climate-related benefits of faster development in Africa are dominated by human health, with energy consumption a distant second.

Of the four developing regions, Africa is the largest contributor to the worldwide marginal impacts of climate change. South and Southeast Asia and China have positive, but small marginal impacts, while Latin America's marginal impacts are intermediate and negative. Any investment in greenhouse gas emission reduction on behalf of the developing countries is thus to a large extent on behalf of Africa. Africa, however, would rather see the money invested in development.

Table 1. Regional marginal costs and benefits of CO_2 emissions and development aid.

	Marginal costs of CO_2 emissions			Marginal benefits of development aid			Cost-benefit ratio		
	0%	1%	3%	0%	1%	3%	0%	1%	3%
OECD-A	4.04	-0.39	-3.15						
OECD-E	9.07	4.10	0.40						
OECD-P	-4.33	-5.01	-4.39						
CEE&fSU	7.65	3.41	0.31						
ME	-0.09	-0.15	-0.13						
LA	1.10	0.66	0.25	0.05	0.08	0.06	0.06	0.05	0.02
S&SEA	0.03	-0.03	-0.06	-0.17	-0.08	-0.02	-0.01	0.00	0.00
CPA	0.01	-0.28	-0.42	-0.65	-0.41	-0.20	-0.01	0.12	0.08
AFR	2.44	1.46	0.60	3.08	1.75	0.63	7.52	2.55	0.38

The figures in Table 1 are very uncertain. A large number of assumptions underlie these estimates, including future developments, the climate sensitivity, the sensitivity of society to climate change, and the sensitivity of vulnerability to development. Agriculture, water resources, energy consumption and human health are the most important impacts for developing countries. Figure 2 displays a sensitivity analysis around the parameters that govern the sensitivity of these sectors to development. These parameters are the elasticity of the demand for energy, water and agriculture to per capita income, and the relationship between wealth on the one hand and age structure, urbanisation and infectious diseases on the other. These seven parameters are varied with one standard deviation from the mean. The return of development aid for Africa, that is, the climate change impacts avoided per dollar of aid, is not very sensitive to these parameters, except for the income at which vector-borne diseases are eliminated and the rate of penetration of air conditioning. Even then, the return on aid varies not more than 20 cents from the base value of $1.75 to the dollar. Other regions have similar sensitivities (results not shown).

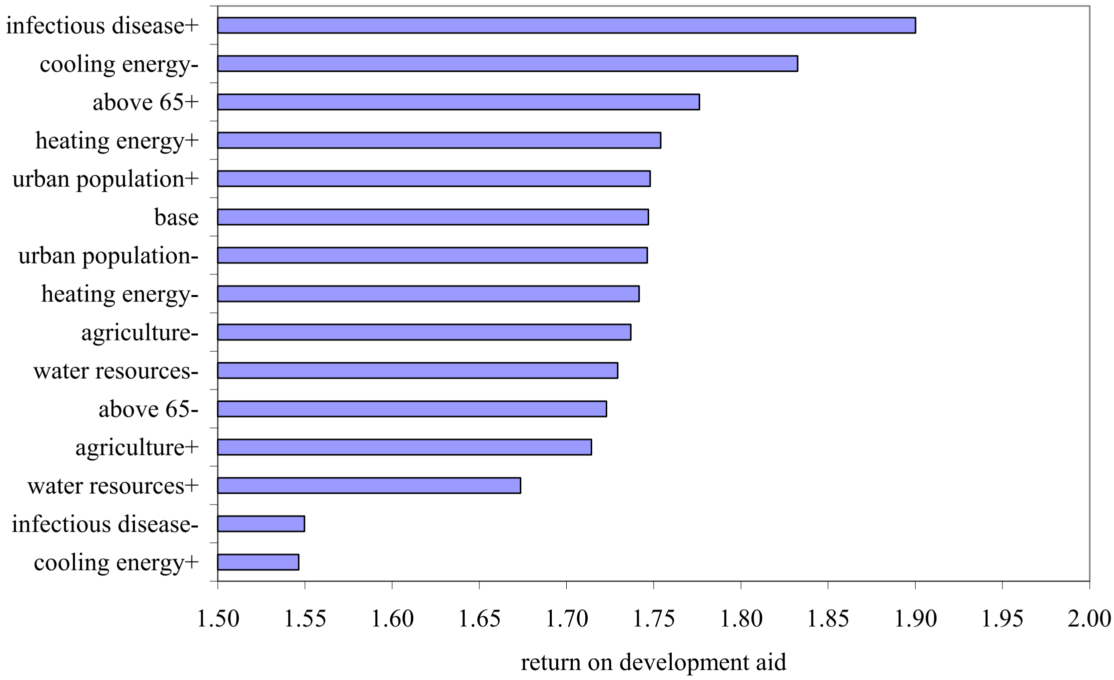
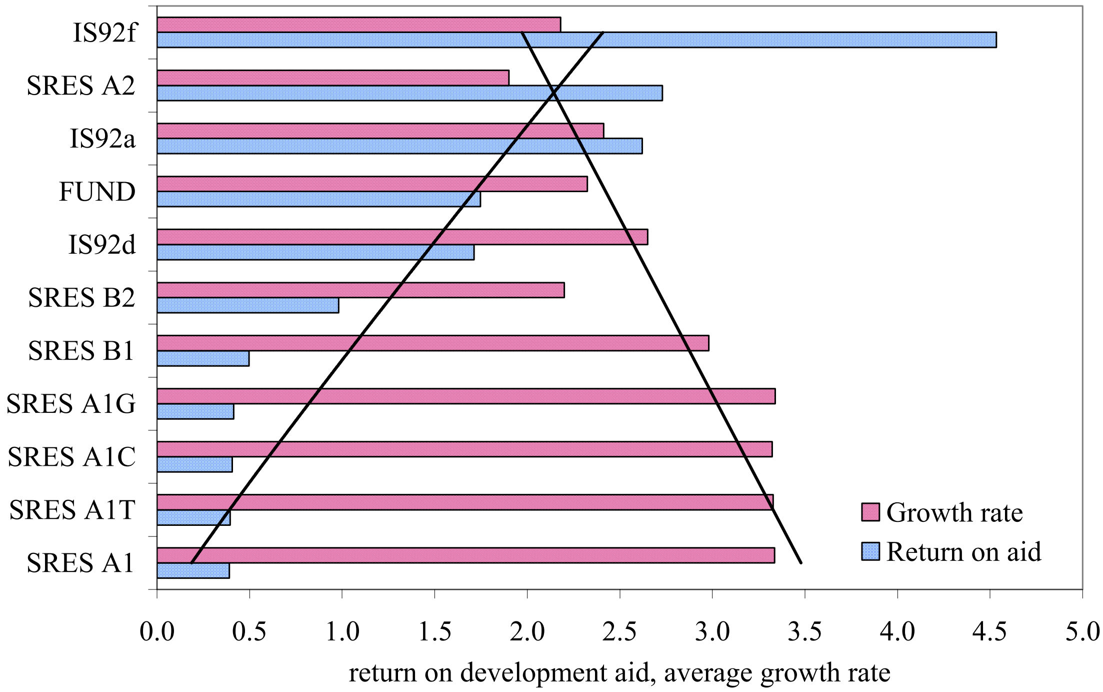


Figure 2. The return on development aid in Africa as function of the parameters that govern the sensitivity of climate change impacts to economic development.

Figure 3 displays the sensitivity of the return on development aid to the baseline scenario. Results are presented for 11 scenarios. The FUND scenario is the basis. Three older IPCC scenarios are used, viz. IS92a (business as usual), IS92d (low emissions) and IS92f (high emissions); see Leggett *et al.* (1992). The four newer IPCC scenarios are also used, viz. A1, A2, B1, and B2 with three variants on A1 namely A1C, A1G and A1T; see Nakicenovic and Swart (2001). The return on development aid ranges from $0.39 to $4.53 to the dollar. The differences in outcome between the scenarios can be to a large extent explained from the differences in the assumed growth rates of per capita income, also displayed in Figure 3. Development does not pay under those scenarios that assume a growth rate of 3% or higher (A1(X), B1), but it does under low growth rates (the other scenarios); the SRES B2 scenario is an exception, assuming both moderate growth and rapid technological development in the energy sector. The intuition behind this scenario dependence is clear, and the same as that behind the differences be-



tween the developing regions. Development aid helps the least developed the most.

Figure 3. The return on development aid in Africa as function of the scenarios; also shown is the assumed average growth rate of per capita income in Africa in the 21st century.

Figure 4 shows the results of a sensitivity analysis on the impacts of climate change. The effects on energy consumption, water resources, agriculture, vector-borne diseases, and cardiovascular and respiratory mortality and morbidity are increased and decreased by 50%. The return on development aid in Africa is least sensitive to the assumed impact on heating energy, followed by agriculture, water resources, cardiovascular and respiratory disorders, cooling energy, and it is most sensitive to vector-borne diseases. The return on development aid falls below one only if vector-borne diseases increases much less with climate change than expected.

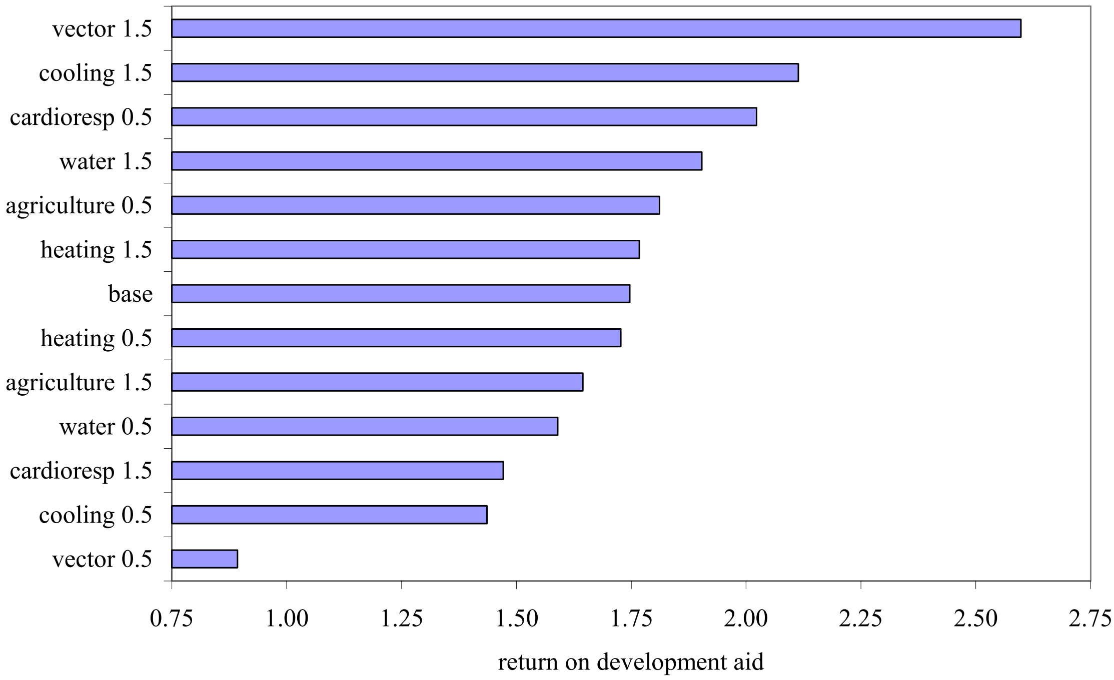


Figure 4. The return on development aid in Africa as function of the severity of selected climate change.

6. Discussion and Conclusion

The above analysis shows that, in some cases, investing in development is a better strategy for reducing the impacts of climate change than is greenhouse gas emission reduction. Regional comparisons and sensitivity analyses shows that this is particularly the case for vector-borne infectious diseases. The policy conclusion is that money spent on greenhouse gas emission reduction for the sake of slowing the spread of malaria, dengue and other vector-borne diseases is better spent on health care. For other impacts of climate change, emission abatement appears to be the better way to reduce vulnerability.

This paper does not address the trade-off between environmental protection and development in general, or even between emission reduction and development aid. The paper is restricted to comparing two strategies to reduce the impact of climate change. Broader questions are obviously important, but would require a more extensive model than the current version of *FUND*.

The conclusions drawn from this paper should be treated with caution. After all, despite the extensive sensitivity analyses, the findings are based on one single model. Given the importance of vector-borne diseases in the results, the results should be further investigated with more detailed models of the health sector, and more detailed models of the delivery of foreign aid.

One may be surprised by the negative results for other impact categories. Agriculture, water resources and coastal zones are also sensitive to both development and climate change. Here, climate change dominates, but perhaps the model is not sophisticated enough, or perhaps its spatial resolution is too crude.

This paper puts spending on greenhouse gas emission reduction in a broader context, and demonstrates that that may change the conclusions. In a narrow sense, cutting emissions helps alleviating malaria. In a broader sense, the same money can be spend differently to alleviate malaria even more. Only by considering the broader question can we decide how much effort should be expended on greenhouse gas emission abatement.

Acknowledgements

References

Andreoni, J. (1990) 'Impure Altruism and Donations of Public Goods: A Theory of Warm-Glow Giving', *Economic Journal* **100** 464-477.

Andreoni, J. (1988) 'Privately Provided Public Goods in a Large Economy: The Limits of Altruism', *Journal of Public Economics* **35** 57-73.

Audus, H., (Ed.) (1998) *The Assessment of Climate Change Damages*. **IEAGHG/SR6**, pp.1-146. IEA Greenhouse Gas R&D Programme, Cheltenham.

Batjes, J.J. and Goldewijk, C.G.M. (1994) *The IMAGE 2 Hundred Year (1890-1990) Database of the Global Environment (HYDE)*. **410100082**, RIVM, Bilthoven.

Bjornstad, D. J. and Kahn, J. R., (Eds.) (1996), *The Contingent Valuation of Environmental Resources -- Methodological Issue and Research Needs*, Edward Elgar, Cheltenham.

Braden, J. B. and Kolstad, C. D., (Eds.) (1991), *Measuring the Demand for Environmental Quality*, Elsevier, Amsterdam.

Darwin, R.F., Tsigas, M., Lewandrowski, J. and Raneses, A. (1995) *World Agriculture and Climate Change - Economic Adaptations*. **703**, pp.1-86. U.S. Department of Agriculture, Washington, D.C.

Downing, T.E., Eyre, N., Greener, R. and Blackwell, D. (1996) *Full Fuel Cycle Study: Evaluation of the Global Warming Externality for Fossil Fuel Cycles with and without CO2 Abatament and for Two Reference Scenarios*. pp.1-72. Environmental Change Unit, University of Oxford, Oxford.

Downing, T.E., Eyre, N., Greener, R. and Blackwell, D. (1996) *Projected Costs of Climate Change for Two Reference Scenarios and Fossil Fuel Cycles*. Environmental Change Unit, Oxford.

Downing, T.E., Greener, R.A. and Eyre, N. (1995) *The Economic Impacts of Climate Change: Assessment of Fossil Fuel Cycles for the ExternE Project*. pp.1-48. Oxford and Lonsdale, Environmental Change Unit and Eyre Energy Environment.

EUROWINTER Group (1997) 'Cold Exposure and Winter Mortality from Ischaemic Heart Diseases, Cerebrovascular Disease, Respiratory Disease, and All Causes in Warm and Cold Regions of Europe', *Lancet* **349** 1341-1346.

Fankhauser, S. and R.S.J. Tol (2001), *On Climate Change and Growth*, Research Unit Sustainability and Global Change **FNU-10**, Centre for Marine and Climate Research, Hamburg University, Hamburg.

Freeman, A.M., III (1993), *The Measurement of Environmental and Resource Values*, Resources for the Future, Washington,D.C.

Hammitt, J.K., Lempert, R.J. and Schlesinger, M.E. (1992) 'A Sequential-Decision Strategy for Abating Climate Change', *Nature* **357** 315-318.

Hausman, J. A., (Ed.) (1993), *Contingent Valuation -- A Critical Assessment*, North-Holland, Amsterdam.

IEA GHG (1999) *LNG Fuel Cycle: Impacts*. **PH3/5**, IEA Greenhouse Gas R&D Programme, London.

Kane, S., Reilly, J.M. and Tobey, J. (1992) 'An Empirical Study of the Economic Effects of Climate Change on World Agriculture', *Climatic Change* **21** 17-35.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G.A., Mitchell, J.F.B., Stouffer, R.J., Tokioka, T., Weaver, A.J. and Wigley, T.M.L. (1996) 'Climate Models - Projections of Future Climate', In Houghton, J.T., Meiro Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K., (Eds.) (eds.) *Climate Change 1995: The Science of Climate Change -- Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, 1 edn. pp. 285-357. Cambridge University Press, Cambridge.

Leggett, J., Pepper, W.J. and Swart, R.J. (1992) 'Emissions Scenarios for the IPCC: An Update', In Houghton, J.T., Callander, B.A. and Varney, S.K., (Eds.) (eds.) *Climate Change 1992 - The Supplementary Report to the IPCC Scientific Assessment*, 1 edn. pp. 71-95. Cambridge University Press, Cambridge.

Maier-Reimer, E. and Hasselmann, K. (1987) 'Transport and Storage of Carbon Dioxide in the Ocean: An Inorganic Ocean Circulation Carbon Cycle Model', *Climate Dynamics* **2** 63-90.

Martens, W.J.M. (1996) 'Global Atmospheric Change and Human Health: An Integrated Modelling Approach', *Climate Research* **6** (2),107-112.

Martens, W.J.M. (1997), *Health Impacts of Climate Change and Ozone Depletion -- An Eco-Epidemiological Modelling Approach*, University of Maastricht, Maastricht.

Martens, W.J.M. (1998) 'Climate Change, Thermal Stress and Mortality Changes', *Social Science and Medicine* **46** (3),331-344.

Martens, W.J.M., Jetten, T.H. and Focks, D.A. (1997) 'Sensitivity of Malaria, Schistosomiasis and Dengue to Global Warming', *Climatic Change* **35** 145-156.

Martens, W.J.M., Jetten, T.H., Rotmans, J. and Niessen, L.W. (1995) 'Climate Change and Vector-Borne Diseases -- A Global Modelling Perspective', *Global Environmental Change* **5** (3),195-209.

Martin, P.H. and Lefebvre, M.G. (1995) 'Malaria and Climate: Sensitivity of Malaria Potential Transmission to Climate', *Ambio* **24** (4),200-207.

Matsuoka, Y. and Kai, K. (1995) 'An Estimation of Climatic Change Effects on Malaria', *Journal of Global Environment Engineering* **1** 43-58.

Mitchell, J.F.B. and Johns, T.C. (1997) 'On Modification of Global Warming by Sulfate Aerosols', *Journal of Climate* **10** 245-267.

Morita, T., Kainuma, M., Harasawa, H., Kai, K., Dong-Kun, L. and Matsuoka, Y. (1994) *Asian-Pacific Integrated Model for Evaluating Policy Options to Reduce Greenhouse Gas Emissions and Global Warming Impacts*. pp.1-18. National Institute for Environmental Studies, Tsukuba.

Murray, C.J.L. and Lopez, A.D. (1996a), *Global Health Statistics*, Harvard School of Public Health, Cambridge.

Murray, C. J. L. and Lopez, A. D., (Eds.) (1996b), *The Global Burden of Disease -- A Comprehensive Assessment of Mortality and Disability from Diseases, Injuries, and Risk Factors in 1990 and Projected to 2020*, Harvard University Press, Cambridge.

Nakicenovic, N. and Swart, R. J., (Eds.) (2001), *IPCC Special Report on Emissions Scenarios*, Cambrigde University Press, Cambridge.

Navrud, S. (2001), 'Valuing Health Impacts in Europe', *Environmental and Resource Economics*, **20** (4), 305-329.

Pearce, D.W. and Moran, D. (1994), *The Economic Value of Biodiversity*, EarthScan, London.

Perez-Garcia, J.M., L. Joyce, C. Binkley, and D.A. McGuire (1996), 'Economic impacts of climate change on the global forest sector: an integrated ecological/economic assessment' in Sedjo, Sampson and Wisniewski (Eds.), *The Economics of Terrestrial Carbon Sequestration,* CRC Press Inc., Boca Raton, FL.

Reilly, J.M., Hohmann, N. and Kane, S. (1994) 'Climate Change and Agricultural Trade: Who Benefits, Who Loses?', *Global Environmental Change* **4** (1),24-36.

Rosenzweig, C. and Parry, M.L. (1994) 'Potential Impact of Climate Change on World Food Supply', *Nature* **367** 133-138.

Shine, K.P., Derwent, R.G., Wuebbles, D.J. and Morcrette, J.-J. (1990) 'Radiative Forcing of Climate', In Houghton, J.T., Jenkins, G.J. and Ephraums, J.J., (Eds.) (eds.) *Climate Change - The IPCC Scientific Assessment*, 1 edn. pp. 41-68. Cambridge University Press, Cambridge.

Smith, J.B., H.-J. Schellnhuber, M.M.Q. Mirza, S. Fankhauser, R. Leemans, E. Lin, L. Ogallo, B. Pittock, R.G. Richels, C. Rosenzweig, R.S.J. Tol, J.P. Weyant and G.W. Yohe (2001), 'Vulnerability to Climate Change and Reasons for Concern: A Synthesis', Chapter 19, pp. 913-967, in J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White (eds.), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, Cambridge University Press, Cambridge.

Sohngen, B., R. Sedjo, R. Mendelsohn, and K. Lyon, (1996), *Analyzing the Economic Impact of Climate Change on Global Timber Markets*, Discussion Paper 96-08, Washington, D.C.: Resources For the Future.

Tol, R.S.J. (1999a), 'The Marginal Costs of Greenhouse Gas Emissions', *The Energy Journal,* **20** (1), 61-81.

Tol, R.S.J. (1999b), 'Time Discounting and Optimal Control of Climate Change: An Application of *FUND*', *Climatic Change*, **41** (3-4), 351-362.

Tol, R.S.J. (1999c), 'Kyoto, Efficiency, and Cost-Effectiveness: Applications of *FUND*', *Energy Journal Special Issue on the Costs of the Kyoto Protocol: A Multi-Model Evaluation*, 130-156.

Tol, R.S.J. (1999d), 'Spatial and Temporal Efficiency in Climate Policy: Applications of *FUND*', *Environmental and Resource Economics*, **14** (1), 33-49.

Tol, R.S.J. (1999e), 'Safe Policies in an Uncertain Climate: An Application of *FUND*', *Global Environmental Change*, **9**, 221-232.

Tol, R.S.J. (forthcoming a), 'Welfare Specification and Optimal Control of Climate Change: An Application of *FUND*', *Energy Economics*.

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

Tol, R.S.J. (forthcoming c), 'New Estimates of the Damage Costs of Climate Change, Part II: Dynamic Estimates', *Environmental and Resource Economics*.

Tol, R.S.J. and H. Dowlatabadi (2001), 'Vector-borne Diseases, Climate Change, and Economic Growth', *Integrated Assessment*, **2**, 173-181.

Tol, R.S.J. and T.E. Downing (2000), *The Marginal Costs of Climate Changing Gases*, Institute for Environmental Studies **D00/08**, Vrije Universiteit, Amsterdam.

Tol, R.S.J., T.E. Downing, S. Fankhauser, R.G. Richels and J.B. Smith (2001), 'Progrès dans l'Estimation des Coûts des Dommages des Émissions des Gas à Effet de

Serre', *Pollution Atmosphérique – Numéro Spécial: Combien Vaut l'Air Propre?*, 155-179.

Tsigas, M.E., G.B. Frisvold and B. Kuhn (1996). Global Climate Change in Agriculture. In: Hertel, T.W. (Ed). *Global Trade Analysis: Modeling and Applications*. Cambridge: Cambridge University Press.

Watson, R. T., Zinyowera, M. C., and Moss, R. H., (Eds.) (1996), *Climate Change 1995: Impacts, Adaptation, and Mitigation of Climate Change -- Scientific-Technical Analysis -- Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, 1 edn. Cambridge University Press, Cambridge.

Weitzman, M.L. (1992) 'On Diversity', *Quarterly Journal of Economics* 364-405.

Weitzman, M.L. (1998) 'The Noah's Ark Problem', *Econometrica* **66** (6),1279-1298.

Weitzman, M.L. (1993) 'What to preserve? An application of diversity theory to crane conservation', *The Quarterly Journal of Economics* 157-183.