

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

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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 impacts than is emission abatement. The hypothesis is barely rejected for Asia but strongly accepted for Latin America and, particularly, Africa. The explanation for the difference is that development (aid) reduces vulnerabilities in some sectors (infectious diseases, water resources, agriculture) but increases vulnerabilities in others (cardiovascular diseases, energy consumption). However, climate change impacts are much higher in Latin America and Africa than in Asia, so that money spent on emission reduction for the sake of avoiding impacts in developing countries is better spent on vulnerability reduction in those countries.

Key words

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

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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 through which the Dutch Government sponsored research in developing countries. He hated how climate change detracted from what he considered to be 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.

Section 2 presents the model used. Section 4 presents the scenarios and the results. Section 4 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, 2002c). Other parts go back to version 2.0 (Tol, 2002a,b). 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. This is a simplified representation of the relevant atmospheric chemistry, but sufficient for our purposes. The carbon cycle is the five-box of Maier-Reimer and Hasselmann (1987), as used by Hammit *et al.* (1992). Radiative forcing for carbon dioxide, methane and nitrous oxide are based on Shine *et al.* (1990). The global mean temperature is governed by a geometric build-up to its equilibrium, with a life-time of 50 years. Global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Global mean sea level is also geometric, with its equilibrium determined by the temperature and a life-time of 50 years. The model is calibrated to Kattenberg *et al.* (1996).

The climate impact module is fully described in Tol (2002a,b). 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 1.

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. On the other hand, CO₂ fertilisation positively influences agriculture.

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 coastal zones (with population growth), heat-related disorders (with urbanisation) and ecosystems and health (with higher values from higher per capita incomes, and loss of biodiversity).

Other systems are projected to become less vulnerable, such as agriculture (with economic growth) and vector-borne diseases (with improved health care). Yet other systems become both more and less vulnerable, such as energy consumption and water resources (with technology and population growth).

The impact module of FUND2.4 is based on that of FUND2.0, fully described in Tol (2002a,b). The following changes were made, following the logic for updating impact estimates outlined in Tol (2002a). Morbidity was added by overlaying the changes in potential disease burdens (Marten *et al.*, 1997) with observed diseases patterns (Murray and Lopez, 1996); morbidity impacts are valued based on Navrud (2001). The effects of CO₂ fertilisation and climate change on forestry and agriculture were separated, while parameters were updated with newly published studies (IEA GHG 1999; Sohngen *et al.*, 1996). The dynamics of water resources, energy consumption and ecosystem impacts were made richer. Specifically, technological change was introduced in the water sector. The linear dependence of energy consumption on climate was replaced by a more realistic non-linear representation. Biodiversity loss is now assumed to lead to an increase in the value of the remaining species, using the specification of Weitzman (1998). See Tol and Heinzow (2002) for an extensive description of the new model; note that the marginal impact estimates of greenhouse gas emissions are not much affected by these changes in the model.

4. Abatement versus development

Table 2 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. Table 2 also shows the marginal costs of carbon dioxide emissions for the whole world, using both a simple addition of dollar values and so-called equity weights (Fankhauser *et al.*, 1997, 1998), through which monetary losses are corrected for their impact on utility.

Speeding up development may help or hinder vulnerability to climate change. Table 2 shows by how much. In 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 175% (308%). For higher discount rates, the investment is not worthwhile: an invested dollar return 63 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.

The marginal costs of carbon dioxide emissions and the returns to investment in development are readily compared. If climate policy is very modest and the marginal costs of emission reduction are only \$1/tC, one can directly compare the marginal costs of carbon dioxide emissions to the returns to investment given in Table 2. A dollar invested in emission reduction is worth less than a dollar invested in development for Africa only. Latin America would rather see the dollar invested in emission reduction, whereas Asia would rather see the dollar not invested (in climate policy). If climate policy is more ambitious, running at marginal abatement costs of \$20/tC (more or less Kyoto), then the returns of investment should be multiplied by 20 before they can be compared to the marginal costs of carbon dioxide emissions. Table 2 shows the results. Africa and, for a sufficiently high discount rate, Latin America would benefit more, in climate change impact terms, from a dollar invested in development than from a dollar invested in emission reduction. Asia would rather not see any such investment, but a dollar invested in emission reduction does less harm than a dollar invested in development.

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, even from the narrow perspective of reducing climate change impacts.

Figure 1 shows the effects on net present welfare (not just associated with climate change impacts) of a small emission reduction and three "equivalent" transfers. In the first transfer, emissions reduction costs \$3.8/tC (the global marginal costs of carbon dioxide emissions at a 1% pure rate of time preference) and development aid is distributed proportional to population. In the second transfer, only \$1.8/tC, the marginal costs to the developing regions, is given in development aid. In the third transfer, \$2.1/tC, the marginal costs to Africa and Latin America, is given in development, this time distributed proportional to the regional marginal costs. Each of the four developing regions clearly prefers to receive aid rather than see greenhouse gas emissions reduced.

The figures in Table 2 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 to development aid for Africa relative to the return to emission reduction for a \$1/tC emission abatement policy is not very sensitive to these parameters, except for the expansion of water demand with economic growth and the

rate of penetration of air conditioning. Even then, the return on aid varies not more than 25% from the base value. For a \$1/tC emission reduction policy and a rapid penetration of air conditioning, Africa would prefer investment in emission abatement to investment in development aid; for all other sensitivity analyses, and for more ambitious emission reduction policy, the reverse would be true. Other regions have similar sensitivities (results not shown). For other discount rates, the picture is similar too (results not shown).

Figure 3 displays the sensitivity to the baseline scenario of the return on development aid relative to emission abatement, for Africa, for a \$1/tC emission reduction policy and a 1% pure rate of time preference. 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 relative to emission reduction ranges from 0.82 to 1.44 for an emission abatement policy of \$1/tC; only under IS92d and SRES A1G does Africa prefer investments in emission reduction over investments in development aid; for more ambitious emission reduction policies, Africa always prefers development aid. The differences in outcome between the scenarios can be to some extent explained from the differences in the assumed growth rates of per capita income, also displayed in Figure 3. Development pays less than does emission reduction if the economic growth rate is high. The intuition behind this scenario dependence is clear, and the same as that behind the differences between the developing regions. Development aid helps the least developed the most. However, the assumed rate of technological progress matters as well. Figure 3 also shows the average AEEI in Africa in the 21st century; a low AEEI has the opposite effect of a high growth rate. With a high AEEI, the costs of air conditioning fall, and the impacts of climate change become less sensitive to the growth rate of the economy (cf. Figure 2). The picture is similar for other climate policies, regions and discount rates (results not shown).

Figure 4 shows the results of a sensitivity analysis on the impacts of climate change in Africa, again focussing on a \$1/tC emission reduction policy and using a pure rate of time preference of 1%. 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 and agriculture, followed by water resources, cooling energy, vector-borne diseases and cardiovascular and respiratory disorders. The return on development aid falls below one only if vector-borne diseases increases much less with climate change than expected or if cardiovascular and respiratory diseases increase much more. With less vector-borne diseases, the impacts of climate change become less sensitive to development. This is reverse for cardiovascular disorder because the dynamics of cold-related deaths dominate in the short run, also in Africa. The picture is similar for other climate policies, regions and discount rates (results not shown).

5. Discussion and Conclusion

The above analysis shows that investing in development may well be 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 if the development aid targets vector-borne infectious diseases and water resources. With generic development aid, the gains in water and infectious diseases would be partly offset by increases in energy consumption for cooling and cardiovascular diseases. The policy conclusion is that money spent on reducing exposure (greenhouse gas emissions) for the sake of poverty-related climate change impacts is better spent on alleviating those vulnerabilities.

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 and water resources in the results, the results should be further investigated with more detailed models of these sectors, and more detailed models of the delivery of foreign aid.

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 and water shortage. In a broader sense, the same money can be spent differently to alleviate malaria and water shortage even more. Only by considering the broader question can we decide how much effort should be expended on greenhouse gas emission abatement.

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References

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

- Hammit, J.K., Lempert, R.J. and Schlesinger, M.E. (1992) 'A Sequential-Decision Strategy for Abating Climate Change', *Nature* **357** 315-318.
- IEA GHG (1999) *LNG Fuel Cycle: Impacts*. **PH3/5**, IEA Greenhouse Gas R&D Programme, London.
- 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., Jetten, T.H. and Focks, D.A. (1997) 'Sensitivity of Malaria, Schistosomiasis and Dengue to Global Warming', *Climatic Change* **35** 145-156.
- Murray, C.J.L. and Lopez, A.D. (1996), *Global Health Statistics*, Harvard School of Public Health, Cambridge.
- Nakicenovic, N. and Swart, R. J., (Eds.) (2001), *IPCC Special Report on Emissions Scenarios*, Cambridge University Press, Cambridge.
- Navrud, S. (2001), 'Valuing Health Impacts in Europe', *Environmental and Resource Economics*, **20** (4), 305-329.
- 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. (2002a), 'New Estimates of the Damage Costs of Climate Change, Part I: Benchmark Estimates', *Environmental and Resource Economics*, **21** (1), 47-73.
- Tol, R.S.J. (2002b), 'New Estimates of the Damage Costs of Climate Change, Part II: Dynamic Estimates', *Environmental and Resource Economics*, **21** (1), 135-160.
- Tol, R.S.J. (2002c), 'Welfare Specification and Optimal Control of Climate Change: An Application of *FUND*', *Energy Economics*, **24** (4), 367-376.
- 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., 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.
- Tol, R.S.J. and T. Heinzow (2002), *Estimates of the External and Sustainability Costs of Climate Change* (draft).
- Weitzman, M.L. (1998) 'The Noah's Ark Problem', *Econometrica* **66** (6), 1279-1298.

Table 1. 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	184	(106)	3.60	(2.07)
OECD-E	212	(116)	3.89	(2.15)
OECD-P	38	(33)	1.20	(1.06)
CEE&fSU	60	(108)	2.10	(3.78)
ME	4	(8)	1.04	(2.15)
LA	-1	(5)	-0.15	(0.58)
S&SEA	-16	(9)	-1.90	(1.13)
CPA	9	(22)	2.00	(5.01)
AFR	-17	(9)	-4.10	(2.21)

Source: Tol (2002a); Tol and Heinzow (2002).

Table 2. Regional marginal costs and benefits of CO₂ 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	0.9	2.3	5.2
S&SEA	0.03	-0.03	-0.06	-0.17	-0.08	-0.02	-99.9	63.9	8.1
CPA	0.01	-0.28	-0.42	-0.65	-0.41	-0.20	-1465.1	29.1	0.0
AFR	2.44	1.46	0.60	3.08	1.75	0.63	25.3	23.9	20.8
Sum	19.93	3.77	-6.59						
EqW	16.13	6.59	-0.50						

Source: Own calculations.

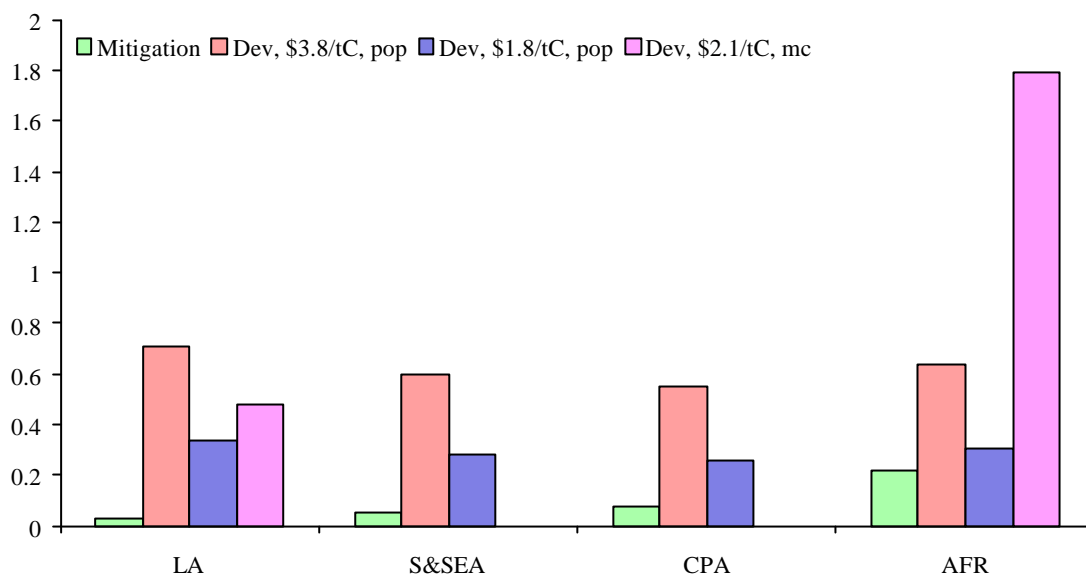


Figure 1. The net present welfare gains (discounted to 2000 at 1% a year) of 10 million metric tonnes of emission reduction between 2000 and 2009, and a transfer of 38. 18 and 21 million US dollar between 2000 and 2009 to four developing regions, distributed proportional to population (pop) or regional marginal costs of carbon dioxide emissions (mc).

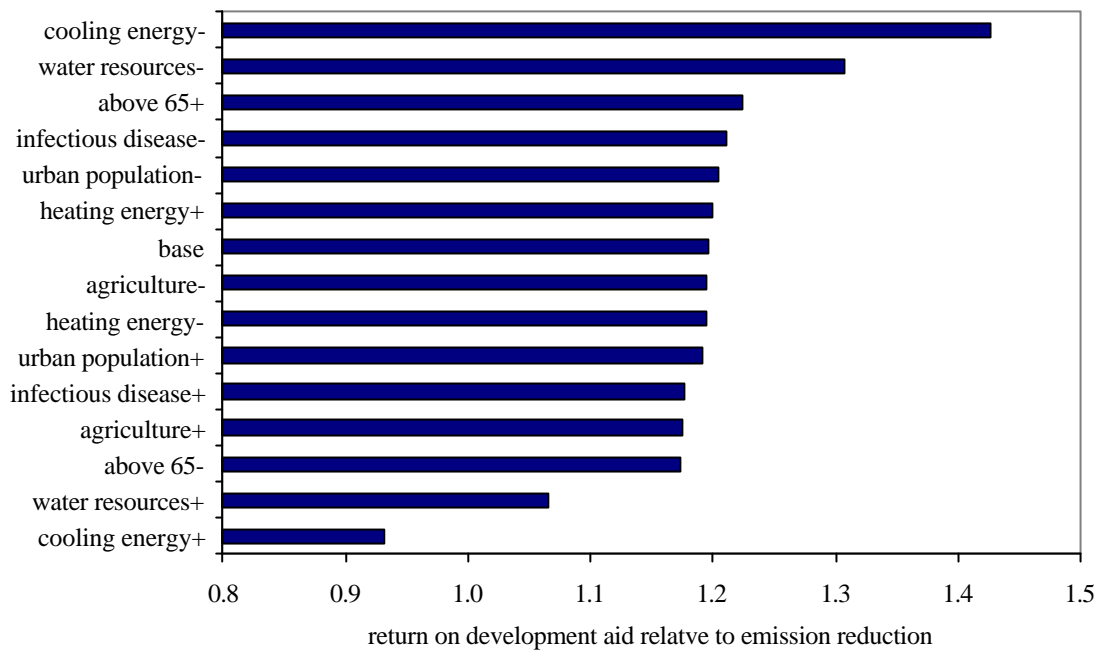


Figure 2. The return on development aid in Africa relative to emission reduction for a climate policy costing \$1/tC as a function of the parameters that govern the sensitivity of climate change impacts to economic development.

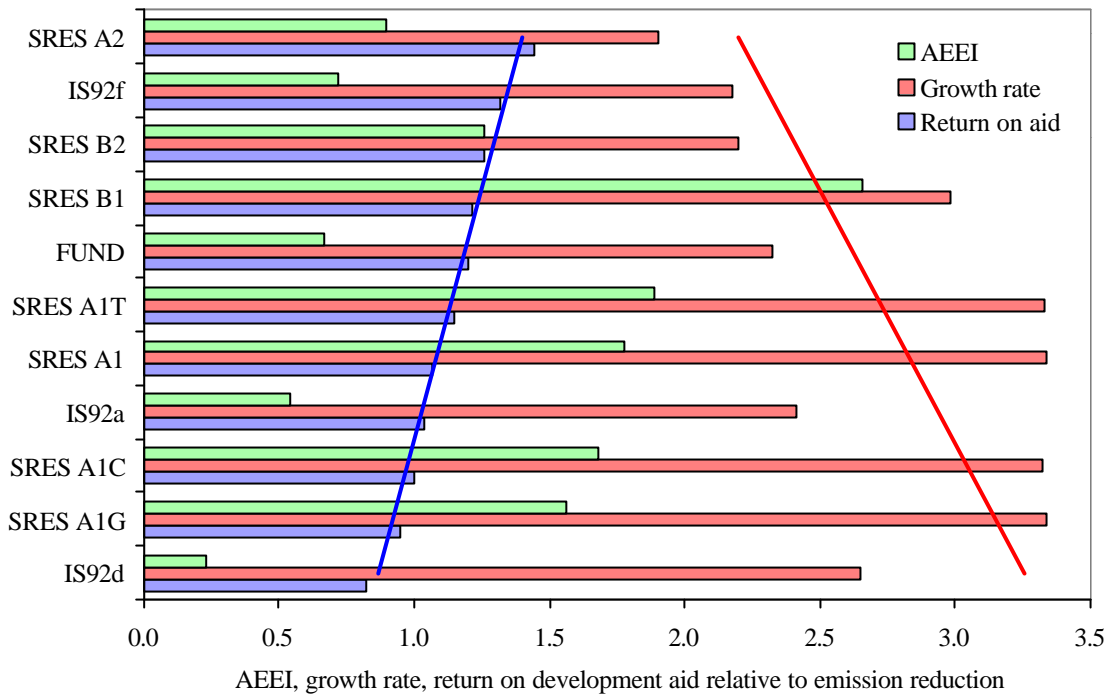


Figure 3. The return on development aid in Africa relative to emission reduction for a climate policy costing \$1/tC as a function of the baseline scenario; also shown is the assumed average growth rate of per capita income in Africa in the 21st century and the Autonomous Energy Efficiency Improvement (AEEI).

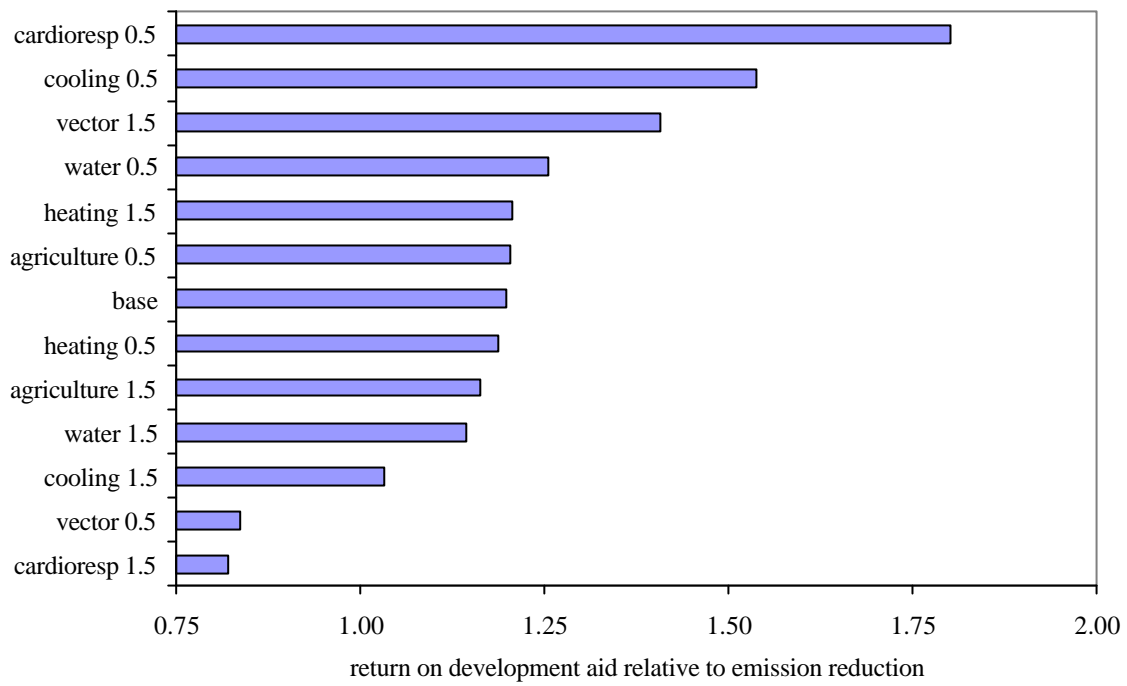


Figure 4. The return on development aid in Africa relative to emission reduction for a climate policy costing \$1/tC as a function of the severity of selected climate change impacts.

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- Rehdanz, K. and Maddison, D. (2003) *Climate and Happiness*, **FNU 20** (submitted).
- Tol, R.S.J., (2003), *The Marginal Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties*, **FNU-19** (submitted).
- Lee, H.C., B.A. McCarl, U.A. Schneider, and C.C. Chen (2003), *Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation*, **FNU-18** (submitted).
- Schneider, U.A. and B.A. McCarl (2003), *Implications of a Carbon Based Energy Tax for U.S. Agriculture*, **FNU-17** (submitted).
- Tol, R.S.J. (2002), *Climate, Development, and Malaria: An Application of FUND*, **FNU-16** (submitted).
- Hamilton, J.M. (2002), *Climate and the Destination Choice of German Tourists*, **FNU-15** (submitted).
- Tol, R.S.J. (2002), *Technology Protocols for Climate Change: An Application of FUND*, **FNU-14** (submitted to *Climate Policy*).
- Rehdanz, K (2002), *Hedonic Pricing of Climate Change Impacts to Households in Great Britain*, **FNU-13** (submitted to *Climatic Change*).
- Tol, R.S.J. (2002), *Emission Abatement Versus Development As Strategies To Reduce Vulnerability To Climate Change: An Application Of FUND*, **FNU-12** (submitted).
- Rehdanz, K. and Tol, R.S.J. (2002), *On National and International Trade in Greenhouse Gas Emission Permits*, **FNU-11** (submitted).
- Fankhauser, S. and Tol, R.S.J. (2001), *On Climate Change and Growth*, **FNU-10** (submitted).
- Tol, R.S.J. and Verheyen, R. (2001), *Liability and Compensation for Climate Change Damages – A Legal and Economic Assessment*, **FNU-9** (forthcoming in *Energy Policy*).
- Yohe, G. and R.S.J. Tol (2001), *Indicators for Social and Economic Coping Capacity – Moving Toward a Working Definition of Adaptive Capacity*, **FNU-8** (*Global Environmental Change*, **12** (1), 25-40).
- Kemfert, C., W. Lise and R.S.J. Tol (2001), *Games of Climate Change with International Trade*, **FNU-7** (submitted to *Environmental and Resource Economics*).
- Tol, R.S.J., W. Lise, B. Morel and B.C.C. van der Zwaan (2001), *Technology Development and Diffusion and Incentives to Abate Greenhouse Gas Emissions*, **FNU-6** (submitted).
- Kemfert, C. and R.S.J. Tol (2001), *Equity, International Trade and Climate Policy*, **FNU-5** (*International Environmental Agreements*, **2**, 23-48).

Tol, R.S.J., Downing T.E., Fankhauser S., Richels R.G. and Smith J.B. (2001), *Progress in Estimating the Marginal Costs of Greenhouse Gas Emissions*, **FNU-4**. (*Pollution Atmosphérique – Numéro Spécial: Combien Vaut l’Air Propre?*, 155-179).

Tol, R.S.J. (2000), *How Large is the Uncertainty about Climate Change?*, **FNU-3** (*Climatic Change*, **56** (3), 265-289).

Tol, R.S.J., S. Fankhauser, R.G. Richels and J.B. Smith (2000), *How Much Damage Will Climate Change Do? Recent Estimates*, **FNU-2** (*World Economics*, **1** (4), 179-206)

Lise, W. and R.S.J. Tol (2000), *Impact of Climate on Tourism Demand*, **FNU-1** (*Climatic Change*, **55** (4), 429-449).