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An Analysis of Mitigation as a Response to Climate Change

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PREFACE

ABSTRACT

The impact of climate change is rather uncertain. Available estimates suggest that the welfare loss induced by climate change in the year 2100 is in the same order as losing a few percent of income. That is, a century worth of climate change is about as bad as losing one or two years of economic growth. The impact of climate policy is better understood. A clever and gradual abatement policy can substantially reduce emissions (e.g., to stabilise greenhouse gas emissions at 650 and 550 ppm CO_{2eq}) at an acceptable cost (1 or 2 years of growth out of 100, respectively). Very stringent targets (e.g., the 2°C of the EU) may be very costly, however, or even infeasible. Suboptimal policy design would substantially add to the costs of emission abatement.

For the Copenhagen Consensus on Climate 2009, this paper considers five alternative policies for carbon dioxide emission reduction. The alternatives differ in scope and intensity only. All five alternatives implement a uniform carbon tax, as that is the cheapest way to reduce emissions. The first policy spends $2.5 trillion on emission reduction in the OECD before 2020. This is rather silly. The benefit-cost ratio is less than 1/100. The second policy spends $2.5 trillion across the world before 2020. This is less silly because non-OECD emission reduction is a lot cheaper, but the benefit-cost ratio is still only 1/100. The third policy continues the same intensity of climate policy between 2020 and 2100. Most negative impacts of climate change are avoided by this policy, but the costs are so large that the benefit-cost ratio is only 1/50. In the fourth policy, $2.5 trillion is invested in a trust fund to finance emission reduction over the century. The benefit-cost ratio is 1/4. In the fifth policy, the trust fund is twenty times as small. The benefit-cost ratio is 3/2. In this policy, a tax of $2/tC is imposed in 2010 on all emissions from all sources in all countries; the tax rises with the rate of discount.

As the analysis ignores uncertainty and equity, one may argue for a more stringent climate policy. However, the analysis also ignores suboptimal implementation, which argues for a more lenient climate policy.

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The Copenhagen Consensus Center has commissioned 21 papers to examine the costs and benefits of different solutions to global warming. The project's goal is to answer the question:

"If the global community wants to spend up to, say $250 billion per year over the next 10 years to diminish the adverse effects of climate changes, and to do most good for the world, which solutions would yield the greatest net benefits?"

The series of papers is divided into Assessment Papers and Perspective Papers. Each Assessment Paper outlines the costs and benefits of one way to respond to global warming. Each Perspective Paper reviews the assumptions and analyses made within an Assessment Paper.

It is hoped that, as a body of work, this research will provide a foundation for an informed debate about the best way to respond to this threat.

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CONTENTS

1. INTRODUCTION

In the Copenhagen Consensus on Climate 2009, options for climate policy are evaluated and ranked. The current paper contributes with an analysis of five alternative policies to reduce carbon dioxide emissions.

Ranking options is a standard tool of decision analysis (Pratt, et al. 1995). It is important to note that options should be ranked on the basis of an internally consistent set of assumptions. That is done here for alternative ways to reduce carbon dioxide. By the same token, the carbon dioxide options presented here cannot be readily compared to the other options for climate policy presented elsewhere in this forum as they are based on different assumptions with regard to (1) the future populations, economies, and emissions; (2) the working of the climate system; (3) the impact of climate change; (4) the impact of emission reduction; and (5) aggregation over space and time.

Although the paper presents five options for carbon dioxide emission reduction, the options differ only in scope and intensity. It is well known that a uniform carbon tax is the cheapest way to abate emissions (Fischer et al. 2003; Pizer 1997; Weitzman 1974). I do therefore not consider other policy instruments, as these necessarily have a lower benefit-cost ratio than the options analysed here.

The paper proceeds as follows. Section 2 presents a rather lengthy review of the literature on the economic impacts of climate change, as this is a crucial and controversial part of any analysis of climate policy. Section 3 continues with a shorter review of the literature on the economic costs of emission reduction. Section 4 describes FUND, the integrated assessment model used in the analysis. Section 5 presents the five policy scenarios. Section 6 discusses the findings. Section 7 concludes.

2. IMPACTS OF CLIMATE CHANGE: A SURVEY

2.1. Estimates of the Total Economic Effect of Climate Change

The first studies of the welfare impacts of climate change were done for the United States by (Cline, 1992; Nordhaus 1991; Smith 1996; Titus 1992). Although (Nordhaus 1991) extrapolated his U.S. estimate to the world, and (Hohmeyer and Gaertner 1992) published some global estimates, the credit for the first serious study of the global welfare impacts of climate change goes to (Fankhauser 1994b; Fankhauser, 1995). Table 1 lists that study and a dozen other studies of the worldwide effects of climate change that have followed.

Any study of the economic effects of climate change begins with some assumptions on future emissions, the extent and pattern of warming, and other possible aspects of climate change, such as sea level rise and changes in rainfall and storminess. The studies must then translate from climate change to economic consequences. A range of methodological approaches are possible here. (Nordhaus 1994) interviewed a limited number of experts.

Table 1. Estimates of the welfare loss due to climate change, expressed as an equivalent income loss, in percent GDP; where available, estimates of the uncertainty are given in brackets, either as standard deviations or as 95% confidence intervals.

Study	Warming	Impact	Worst-off region		Best-off region	
	(°C)	(%GDP)	(%GDP)	(Name)	(%GDP)	(Name)
(Nordhaus, William D. 1994)	3.0	-1.3				
(Nordhaus 1994)	3.0	-4.8 (-30.0 to 0.0)				
(Fankhauser, Samuel 1995)	2.5	-1.4	-4.7	China	-0.7	Eastern Europe and the former Soviet Union
(Tol 1995)	2.5	-1.9	-8.7	Africa	-0.3	Eastern Europe and the former Soviet Union
(Nordhaus and Yang 1996)[a]	2.5	-1.7	-2.1	Developing countries	0.9	Former Soviet Union
(Plamberk and Hope 1996)[a]	2.5	-2.5 (-0.5 to –11.4)	-8.6 (-0.6 to -39.5)	Asia (w/o China)	0.0 (-0.2 to 1.5)	Eastern Europe and the former Soviet Union
(Mendelsohn et al. 2000a)[a,b,c]	2.5	0.0[b] 0.1[b]	-3.6[b] -0.5[b]	Africa	4.0[b] 1.7[b]	Eastern Europe and the former Soviet Union
(Nordhaus, William D. and Boyer, Joseph G. 2000)	2.5	-1.5	-3.9	Africa	0.7	Russia
(Tol 2002a)	1.0	2.3 (1.0)	-4.1 (2.2)	Africa	3.7 (2.2)	Western Europe
(Maddison 2003)[a,d,e]	2.5	-0.1	-14.6	South America	2.5	Western Europe
(Rehdanz and Maddison 2005)[a,c]	1.0	-0.4	-23.5	Sub-Saharan Africa	12.9	South Asia
(Hope 2006)[a,f]	2.5	0.9 (-0.2 to 2.7)	-2.6 (-0.4 to 10.0)	Asia (w/o China)	0.3 (-2.5 to 0.5)	Eastern Europe and the former Soviet Union
(Nordhaus 2006)	2.5	-0.9 (0.1)				

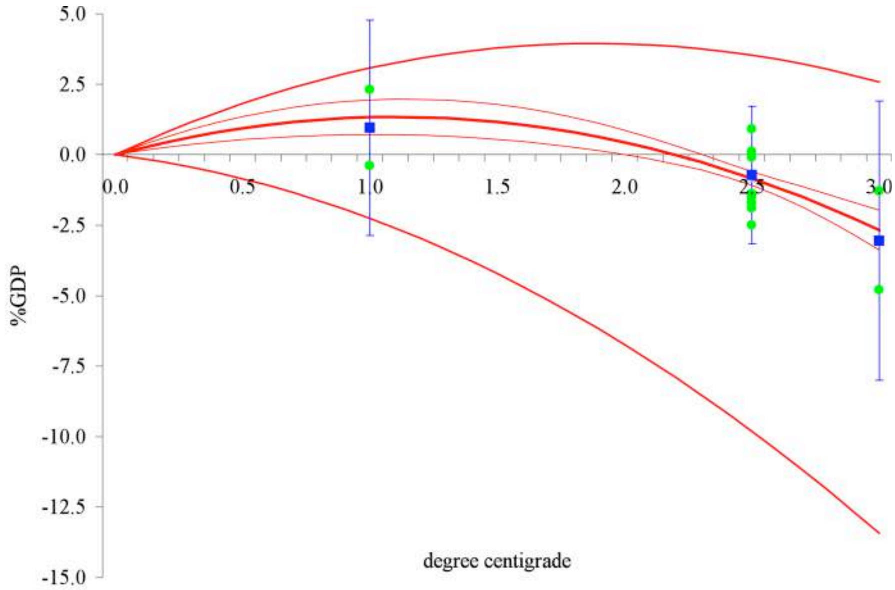
[a] Note that the global results were aggregated by the current author.
[b] The top estimate is for the "experimental" model, the bottom estimate for the "cross-sectional" model.
[c] Note that Mendelsohn et al. only include market impacts.
[d] Note that the national results were aggregated to regions by the current author for reasons of comparability.
[e] Note that Maddison only considers market impacts on households.
[f] The numbers used by Hope are averages of previous estimates by Fankhauser and Tol; Stern *et al.* (2006) adopt the work of Hope.

The studies by Fankhauser, (Nordhaus, 1994), and (Tol 1995; Tol 2002a; Tol 2002b) use the enumerative method. In this approach, estimates of the "physical effects" of climate change are obtained one by one from natural science papers, which in turn may be based on some combination of climate models, impact models and laboratory experiments. The physical impacts must then each be given a price, and added up. For traded goods and services, such as agricultural products, agronomy papers are used to predict the effect of climate on crop yield, and then market prices or economic models are used to value that change in output. As another example, the impact of sea level rise constitutes coastal protection and land lost, estimates of which can be found in the engineering literature; the economic input in this case is not only the cost of dike building and the value of land, but also the decision which properties to protect. For non-traded goods and services, other methods are needed. An ideal approach might be to study how climate change affects human welfare through health and nature in each area around the world, but a series of "primary valuation" studies of this kind would be expensive and time-consuming. Thus, the monetisation of non-market climate change impacts relies on "benefit transfer," in which epidemiology papers are used to estimate effects on health or the environment, and then economic values are applied from studies of the valuation of mortality risks in other contexts than climate change.

An alternative approach, exemplified in Mendelsohn's work (Mendelsohn et al. 2000b; Mendelsohn et al. 2000a) can be called the ***statistical approach***. It is based on direct estimates of the welfare impacts, using observed variations (across space within a single country) in prices and expenditures to discern the effect of climate. Mendelsohn assumes that the observed variation of economic activity with climate over space holds over time as well; and uses climate models to estimate the future impact of climate change. Mendelsohn's estimates are done per sector for selected countries, extrapolated to other countries, and then added up, but physical modelling is avoided. Other studies (Maddison 2003; Nordhaus 2006) use versions of the statistical approach as well. However, Nordhaus uses empirical estimates of the ***aggregate*** climate impact on income across the world (per grid cell), while Maddison looks at patterns of ***aggregate*** household consumption (per country). Like Mendelsohn, Nordhaus and Maddison rely exclusively on observations, assuming that "climate" is reflected in incomes and expenditures – and that the spatial pattern holds over time. (Rehdanz and Maddison 2005) also empirically estimate the aggregate impact, using self-reported happiness for dozens of countries.

The enumerative approach has the advantage that it is based on natural science experiments, models and data; the results are physically realistic and easily interpreted. However, the enumerative approach also raises concerns about extrapolation: economic values estimated for other issues are applied to climate change concerns; values estimated for a limited number of locations are extrapolated to the world; and values estimated for the recent past are extrapolated to the remote future. Tests of benefit transfer methods have shown time and again that errors from such extrapolations can be substantial (Brouwer and Spaninks 1999). But perhaps the main disadvantage of the enumerative approach is that the assumptions about adaptation may be unrealistic —as temperatures increase, presumably private and public-sector reactions would occur to both market and non-market events.

Figure 1. The 14 estimates of the global economic impact of climate change, expressed as the welfare-equivalent income loss, as a functions of the increase in global mean temperature relative to today.



The green dots represent the estimates (cf. Table 1). The blue squares are the sample means (for the specific global warming), and the lines are the sample means plus or minus twice the sample standard deviation. The central red line is the least squares fit to the 14 observations: $D = 2.46\,(1.25)\,T - 1.11\,(0.48)\,T^2$, $R^2 = 0.51$, where D denotes impact and T denotes temperature; standard deviations are between brackets. The thin red inner two lines are the 95% confidence interval for the central line re-estimated with one observation dropped. The thick red outer two lines are the 95% confidence interval, where the standard deviation is the least squares fit to the 5 reported standard deviations or half confidence intervals (cf. Table 1): $S_{optimistic} = 0.87\,(0.28)\,T$, $R^2 = 0.70$, $S_{pessimistic} = 1.79\,(0.87)\,T$, $R^2 = 0.51$ where S is the standard deviation.

In contrast, the statistical studies rely on uncontrolled experiments. These estimates have the advantage of being based on real-world differences in climate and income, rather than extrapolated differences. Therefore, adaptation is realistically, if often implicitly, modelled. However, statistical studies run the risk that all differences between places are attributed to climate. Furthermore, the data often allow for cross-sectional studies only; and some important aspects of climate change, particularly the direct impacts of sea level rise and carbon dioxide fertilization, do not have much spatial variation.

Given that the studies in Table 1 use different methods, it is striking that the estimates are in broad agreement on a number of points – indeed, the uncertainty analysis displayed in Figure 1 reveals that no estimate is an obvious outlier. Table 1 shows selected characteristics of the published estimates. The first column of Table 1 shows the underlying assumption of long-term warming, measured as the increase in the global average surface air temperature. The assumed warming typically presumes a doubling of concentrations of greenhouse gases in the atmosphere. It is reasonable to think of these as the temperature increase in the second half of the 21st century. However, the impact studies in Table 1 are comparative static, and they impose a future climate on today's economy. One can therefore not attach a date to these estimates. The second column of Table 1 shows the impact on welfare at that future time, usually expressed as a percentage of income. For instance, (Nordhaus, 1994) estimates that the impact of 3°C global warming is as bad as losing 1.4% of income. In some cases, a confidence interval (usually at the 95 percent level) appears under the estimate; in other cases, a standard deviation is given; but the majority of studies does not report any estimate of the uncertainty. The rest of Table 1 illustrates differential effects around the world. The third column shows the percentage decrease in annual GDP of the regions hardest-hit by climate change, and the fourth column identifies those regions. The fifth column shows the percentage change in GDP for regions that are least-hurt by climate change—and in most cases would even benefit from a warmer climate—and the final column identifies those regions.

A first area of agreement between these studies is that the welfare effect of a doubling of the atmospheric concentration of greenhouse gas emissions on the current economy is relatively small - a few percentage points of GDP. This kind of loss of output can look large or small, depending on context. From one perspective, it's roughly equivalent to a year's growth in the global economy - which suggests that over a century or so, the economic loss from climate change is not all that large. On the other hand, the damage is not negligible. An environmental issue that causes a permanent reduction of welfare, lasting into the indefinite future, would certainly justify some steps to reduce such costs. Balancing these factors, cost-benefit analyses of climate change typically recommend only limited greenhouse gas emission reduction - for instance, (Nordhaus 1993) argues that the optimal rate of emission reduction is 10-15 percent (relative to the scenario without climate policy) over the course of the 21st century. Recall that the EU calls for 20-30% emission reduction (relative to 2005) by 2020.

A second finding is that some estimates (Hope 2006; Mendelsohn et al. 2000b; Mendelsohn et al. 2000a; Tol 2002b), point to initial benefits of a modest increase in temperature, followed by losses as temperatures increase further. There are no estimates for a warming above 3°C, although climate change may well go beyond that (see below). All studies published after 1995 have regions with net gains and net losses due to global warming, while earlier studies only find net losses. Figure 1 illustrates this pattern. The horizontal axis shows the increase in average global temperature. The vertical index shows the central estimate of welfare loss. The central line shows a best-fit parabolic line from an ordinary least squares regression. Of course, it is something of a stretch to interpret the results of these different studies as if they were a time series of how climate change will affect the economy over time, and so this graph should be interpreted more as an interesting calculation than as hard analysis. But the pattern of modest economic gains due to climate change, followed by substantial losses, appears also in the few studies that report impacts over time (Mendelsohn et al. 2000b; Mendelsohn et al. 2000a; Nordhaus, and Boyer, 2000; Smith et al. 2001; Tol 2002b).

The initial benefits arise partly because more carbon dioxide in the atmosphere reduces "water stress" in plants and may make them grow faster (Long et al. 2006). In addition, the output of the global economy is concentrated in the temperate zone, where warming reduces heating costs and cold-related health problems. Although the world population is concentrated in the tropics, where the initial effects of climate change are probably negative, the relatively smaller size of the economy in these areas means that - at least over the interval of small increases in global temperatures - gains for the high-income areas of the world exceed losses in the low-income areas.

However, this pattern should be interpreted with care. Even if, initially, economic impacts may well be positive, it does not follow that greenhouse gas emissions should be subsidized. The climate responds rather slowly to changes in greenhouse gas emissions. The initial warming can no longer be avoided; it should be viewed as a sunk benefit. The fitted line in Figure 1 suggests that the turning point in terms of economic benefits occurs at about 1.1°C warming (with a standard deviation of 0.7°C). Policy steps to reduce emissions of greenhouse gases in the near future would begin to have a noticeable affect on climate sometime around mid-century - which is to say, at just about the time that any medium-run economic benefits of climate change begin to decline (Hitz and Smith 2004; Tol et al. 2000; Tol 2002b). In short, even though total economic effects of 1-2°C warming may be positive, incremental impacts beyond that level are likely to be negative. Moreover, if one looks further into the future, the incremental effects look even more negative.

Third, although greenhouse gas emissions per person are higher in high-income countries, relative impacts of climate change are greater in low-income countries (Yohe and Schlesinger 2002). Indeed, impact estimates for Sub-Saharan Africa go up to a welfare loss equivalent to the loss of a quarter of income (Table 1). The estimates are higher for several reasons. Low-income countries tend to be in tropical zones closer to the equator. They are already hotter, and their output already suffers to some extent from their higher temperatures in sectors like agriculture. Moreover, low-income countries are typically less able to adapt to climate change both because of a lack of resources and less capable institutions (Adger 2006; Alberini et al. 2006; Smit and Wandel 2006; Tol et al. 2007; Tol 2008a; Tol and Yohe 2007b; Yohe and Tol 2002).

The emissions of greenhouse gases are predominantly from high-income countries while the negative effects of climate change are predominantly in low-income countries. This has two policy implications. First, any justification of stringent abatement for greenhouse gases is at least in part an appeal to consider the plight of citizens of low-income countries around the world and the effects imposed on them by the citizens of high-income countries (Schelling 2000). Second, if pre-existing poverty is the one of the main causes for vulnerability to climate change, one may wonder whether stimulating economic growth or emission abatement is the better way to reduce the effects of climate change. Indeed, (Tol and Dowlatabadi 2001; Tol and Yohe 2006) argue that the economic growth foregone by stringent abatement of greenhouse gases would more than offset the avoided impacts of climate change, at least in the case of malaria. Similarly, (Tol 2005b) shows that development is a cheaper way of reducing climate-change-induced malaria than is emission reduction. Moreover, high-income countries may find it easier and cheaper to compensate poorer countries for the climate change damages caused, rather than to pay for reducing their own greenhouse gas emissions. Such compensation could be explicit, but would more likely take the shape of technical and financial assistance with adaptation (Paavola and Adger 2006).

Although research is scarce (O'Brien et al. 2004) climate change impacts would not be homogeneous within countries; certainly, certain economic sectors (e.g., agriculture), regions (e.g., the coastal zone) and age groups (e.g., the elderly) are more heavily affected than others.
Fourth, estimates of the economic effects of greenhouse gas emissions have become less pessimistic over time. For the studies listed here, the estimates increase by 0.23 percent of GDP per year in which the study was done (with a standard deviation of 0.10 percent

per year). There are several reasons for this change. Projections of future emissions and future climate change have become less severe over time - even though the public discourse has become shriller. The earlier studies focused on the negative impacts of climate change, whereas later studies considered the balance of positives and negatives. In addition, earlier studies tended to ignore adaptation. More recent studies - triggered by (Mendelsohn et al. 1994) - include some provision for agents to change their behaviour in response to climate change. However, more recent studies also tend to assume that agents have perfect foresight about climate change, and have the flexibility and appropriate incentives to respond. Given that forecasts are imperfect, agents are constrained in many ways, and markets are often distorted - particularly in the areas that matter most for the effects of climate change such as water, food, energy, and health - recent studies of the economic effects of climate change may be too optimistic about the possibilities of adaptation and thus tend to underestimate the economic effects of climate change.

A fifth common conclusion from studies of the economic effects of climate change is that the uncertainty is vast and right-skewed. For example, consider only the studies that are based on a benchmark warming of 2.5ºC. These studies have an average estimated effect of climate change on average output of -0.7 percent of GDP, and a standard deviation of 1.2 percent of GDP. Moreover, this standard deviation is only about best estimate of the economic impacts, given the climate change estimates. It does not include uncertainty about future levels of greenhouse gas emissions, or uncertainty about how these emissions will affect temperature levels, or uncertainty about the physical consequences of these temperature changes. Moreover, it is quite possible that the estimates are not independent, as there are only a relatively small number of studies, based on similar data, by authors who know each other well.

Only five of the 14 studies in Table 1 report some measure of uncertainty. Two of these report a standard deviation only - which suggests symmetry in the probability distribution. Three studies report a confidence interval - of these, two studies find that the uncertainty is right-skewed, but one study finds a left-skewed distribution. Although the evidence on uncertainty here is modest and inconsistent, and I suspect less than thoroughly reliable, it seems that negative surprises should be more likely than positive surprises. While it is relatively easy to imagine a disaster scenario for climate change - for example, involving massive sea level rise or monsoon failure that could even lead to mass migration and violent conflict - it is not at all easy to argue that climate change will be a huge boost to economic growth.

Figure 1 has three alternative estimates of the uncertainty around the central estimates. First, it shows the sample statistics. This may be misleading for the reasons outlined above; note that there are only two estimates each for a 1.0˚C and a 3.0˚C global warming. Second, I re-estimated the parabola 14 times with one observation omitted. This exercise shows that the shape of the curve in Figure 1 does not depend on any single observation. At the same time, the four estimates for a 1.0˚C or 3.0˚C warming each have a substantial (but not significant) effect on the parameters of the parabola. Third, five studies report standard deviations or confidence intervals. Confidence intervals imply standard deviations, but because the reported intervals are asymmetric I derived two standard deviations, one for negative deviations from the mean, and one for positive deviations. I assumed that the standard deviation grows linearly with the temperature, and fitted a line to each of the two sets of five "observed" "standard deviations. The result is the asymmetric confidence interval shown in Figure 1. This probably best reflects the considerable uncertainty about the economic impact of climate change, and that negative surprises are more likely than positive ones.

In other words, the level of uncertainty here is large, and probably understated - especially in terms of failing to capture downside risks. The policy implication is that reduction of greenhouse gas emissions should err on the ambitious side.

The kinds of studies presented in Table 1 can be improved in numerous ways, some of which have been mentioned already. In all of these studies, economic losses are approximated with direct costs, ignoring general equilibrium and even partial equilibrium effects.[1]

In the enumerative studies, effects are usually assessed independently of one another, even if there is an obvious overlap - for example, losses in water resources and losses in agriculture may actually represent the same loss. Estimates are often based on extrapolation from a few detailed case studies, and extrapolation is to climate and levels of development that are very different from the original case study. Little effort has been put into validating the underlying models against independent data - even though the findings of the first empirical estimate of the impact of climate change on agriculture by (Mendelsohn et al. 1994) were in stark contrast to earlier results like those of (Parry, 1990), which suggests that this issue may be important. Realistic modeling of adaptation is problematic, and studies typically either assume no adaptation or perfect adaptation. Many effects are unquantified, and some of these may be large (see below). The uncertainties of the estimates are largely unknown. These problems are gradually being addressed, but progress is slow. Indeed, the list of warnings given here is similar to those in (Fankhauser and Tol 1996; Fankhauser and Tol 1997).

A deeper conceptual issue arises with putting value on environmental services. Empirical studies have shown that the willingness to pay (WTP) for improved environmental services may be substantially lower than the willingness to accept compensation (WTAC) for diminished environmental services (Horowith and McConnell 2002). The difference between WTP and WTAC goes beyond income effects, and may even hint at loss aversion and agency effects, particularly around involuntary risks. A reduction in the risk of mortality due to greenhouse gas emission abatement is viewed differently than an increase in the risk of mortality due to the emissions of a previous generation in a distant country. The studies listed in Table 1 all use willingness to pay as the basis for valuation of environmental services, as recommended by (Arrow et al. 1993). Implicitly, the policy problem is phrased as "How much are we willing to pay to buy an improved climate for our children?" Alternatively, the policy problem could be phrased as "How much compensation should we pay our children for worsening their

1 General equilibrium studies of the effect of climate change on agriculture have a long history (Darwin 2004; Kane et al. 1992). These papers show that markets matter, and may even reverse the sign of the initial impact estimate (Yates and Strzepek 1998). (Bosello et al. 2007) and (Darwin and Tol 2001) show that sea level rise would change production and consumption in countries that are not directly affected, primarily through the food market (as agriculture is affected most by sea level rise through land loss and saltwater intrusion) and the capital market (as sea walls are expensive to build). Ignoring the general equilibrium effects probably leads to only a small negative bias in the global welfare loss, but differences in regional welfare losses are much greater. Similarly, (Bosello et al. 2006) show that the direct costs are biased towards zero for health, that is, countries that would see their labour productivity fall (rise) because of climate change would also lose (gain) competitiveness. (Berrittella et al. 2006) also emphasize the redistribution of impacts on tourism through markets.

climate?" This is a different question, and the answer would be different if the current policy makers assume that future generations would differentiate between WTP and WTAC much like the present generation does. The marginal avoided compensation would be larger than the marginal benefit, so that the tax on greenhouse gas emission would be higher.

2.2. Estimates of the Marginal Cost of Greenhouse Gas Emissions

The marginal damage cost of carbon dioxide, also known as the "social cost of carbon," is defined as the net present value of the incremental damage due to a small increase in carbon dioxide emissions. For policy purposes, the marginal damage cost (if estimated along the optimal emission trajectory) would be equal to the Pigouvian tax that could be placed on carbon, thus internalizing the externality and restoring the market to the efficient solution.

A quick glance at the literature suggests that there are many more studies of the marginal cost of carbon than of the total cost of climate change. Table 1 has 13 studies and 14 estimates; in contrast, (Tol 2009) reports 47 studies with 232 estimates. Some of the total cost estimates (Maddison 2003; Mendelsohn et al. 2000b; Mendelsohn et al. 2000a; Nordhaus 2006; Rehdanz and Maddison 2005) have yet to be used for marginal cost estimation. Therefore, the 200-plus estimates of the social cost of carbon are based on nine estimates of the total impact of climate change. The empirical basis for the size of an optimal carbon tax is much smaller than is suggested by the number of estimates.

How can nine studies of total economic cost of climate change yield well over 200 estimates of marginal cost? Remember that the total cost studies are comparative static, and measure the economic cost of climate change in terms of a reduction in welfare below its reference level. This approach to describing total costs can be translated into marginal costs of current emissions in a number of ways. The rate at which future benefits (and costs) are discounted is probably the most important source of variation in the estimates of the social cost of carbon. The large effect of different assumptions about discount rates is not surprising, given that the bulk of the avoidable effects of climate change is in the distant future. Differences in discount rates arise not only from varying assumptions about the rate of pure time preference, the growth rate of per capita consumption, and the elasticity of marginal utility of consumption.[2] Some more recent studies have also analyzed variants of hyperbolic discounting, where the rate of discount falls over time.

However, there are other reasons why two studies with identical estimates of the total economic costs of climate change, expressed as a percent of GDP at some future date, can lead to very different estimates of marginal cost. Studies of the marginal damage costs of carbon dioxide emissions can be based on different projections of CO_2 emissions, different representations of

2 The elasticity of marginal utility with respect to consumption plays several roles. It serves as a measure of risk aversion. It plays an important role in the discount rate (Ramsey 1928), as it also partly governs the substitution of future and present consumption. Furthermore, this parameter drives the trade-offs between differential impacts across the income distribution, both within and between countries. Although conceptually distinct, all climate policy analyses that I am aware of use a single numerical value (Atkinson et al. 2009; Saelen et al. 2008). The reason is simply that although these distinctions are well-recognized, welfare theorists have yet to find welfare and utility functions that make the necessary distinctions and can be used in applied work.

the carbon cycle, different estimates of the rate of warming, and so on. Alternative population and economic scenarios also yield different estimates, particularly if vulnerability to climate change is assumed to change with a country or region's development.

For example, the estimate of (Nordhaus 1991) of the total welfare loss of a 3.0°C warming is 1.3% of GDP. In order to derive a marginal damage cost estimate from this, you would need to assume when in the future 3.0°C would occur, and whether damages are linear or quadratic or some other function of temperature (and precipitation et cetera). And then the future stream of incremental damages due to today's emissions needs to be discounted back to today's value.

Marginal cost estimates further vary with the way in which uncertainty is treated (if it is recognized at all). Marginal cost estimates also differ with how regional effects of climate change are aggregated. Most studies add monetary effects for certain regions of the world, which roughly reflects the assumption that emitters of greenhouse gases will compensate the victims of climate change. Other studies add utility-equivalent effects - essentially assuming a social planner and a global welfare function. In these studies, different assumptions about the shape of the global welfare function can imply widely different estimates of the social cost of carbon (Anthoff et al. 2009; Fankhauser et al. 1997; Fankhauser et al. 1998).

Table 2. The social cost of carbon ($/tC); sample statistics and characteristics of the Fisher-Tippett distribution fitted to 232 published estimates, and to three subsets of these estimates based on the pure rate of time preference.

	Sample (unweighted)				Fitted distribution (weighted)			
	All	Pure rate of time preference			All	Pure rate of time preference		
		0%	1%	3%		0%	1%	3%
Mean	105	232	85	18	151	147	120	50
StDev	243	434	142	20	271	155	148	61
Mode	13	-	-	-	41	81	49	25
33%	16	58	24	8	38	67	45	20
Median	29	85	46	14	87	116	91	36
67%	67	170	69	21	148	173	142	55
90%	243	500	145	40	345	339	272	112
95%	360	590	268	45	536	487	410	205
99%	1500	-	-	-	1687	667	675	270
N	232	38	50	66	-	-	-	

Table 2 shows some characteristics of a meta-analysis of the published estimates of the social cost of carbon. Columns 2-5 show the sample statistics of the 232 published estimates. One key issue in attempting to summarize this work is that just looking at the distribution of the medians or modes of these studies is inadequate, because it does not give a fair sense of the uncertainty surrounding these estimates - it is particularly hard to discern the right tail of the distribution which may dominate the policy analysis (Tol 2003; Tol and Yohe 2007a; Weitzman 2009). Because there are many estimates of the social cost of carbon, this can be done reasonably objectively. (The same would not be the case for the total economic impact estimates.) Thus, the idea here is to use one parameter from each published estimate (the mode) and the standard deviation of the entire sample—and then to build up an overall distribution of the estimates and their surrounding uncertainty on this basis using the methodology in (Tol 2008b).[3] The results are shown in columns 6-8 of Table 2.

Table 2 reaffirms that the uncertainty about the social costs of climate change is very large. The mean estimate in these studies is a marginal cost of carbon of \$105 per metric tonne of carbon, but the modal estimate is only \$13/tC. Of course, this divergence suggests that the mean estimate is driven by some very large estimates - and indeed, the estimated social cost at the 95th percentile is \$360/tC and the estimate at the 99th percentile is \$1500/tC. The fitted distribution suggests that the sample statistics underestimate the marginal costs: the mode is \$41/tC, the mean \$151/tC and the 99th percentile \$1687/tC.

This large divergence is partly explained by the use of different pure rates of time preference in these studies. Columns 3-5 (sample statistics) and 7-9 (fitted distribution) of Table 2 divide up the studies into three subsamples which use the same pure rate of time preference. A higher rate of time preference means that the costs of climate change incurred in the future have a lower present value, and so for example, the sample mean social cost of carbon for the studies with a 3 percent rate of time preference is \$18/tC, while it is \$232/tC for studies that choose a zero percent rate of time preference. But these columns also show that even when the same discount rate is used, the variation in estimates is large. For the fitted distribution, the means are roughly double the modes - showing that the means are being pulled higher by some studies with very high estimated social costs.[4] Table 2 shows that the estimates for the whole sample are dominated by the estimates based on lower discount rates.

3 I fitted a Fisher-Tippett distribution to each published estimate using the estimate as the mode and the *sample* standard deviation. The Fisher-Tippett distribution is the only two-parameter, fat-tailed distribution that is defined on the real line. A few published estimates are negative, and given the uncertainties about risk, fat-tailed distributions seem appropriate (Tol 2003; Weitzman 2009). The joint probability density function follows from addition, using weights that reflect the age and quality of the study as well as the importance that the authors attach to the estimate – some estimates are presented as central estimates, others as sensitivity analyses or upper and lower bounds. See http://www.fnu.zmaw.de/Social-cost-of-carbon-meta-analy.6308.0.html

4 Some readers may wonder why the estimates with a discount rate of zero percent don't look all that substantially higher than the estimates with a discount rate of 1%. The main reason is that most estimates are (inappropriately) based on a finite time horizon. With an infinite time horizon, the social cost of carbon would still be finite, because fossil fuel reserve are finite and the economy would eventually equilibrate with the new climate, but the effect of the zero discount rate would be more substantial. For the record, there is even one estimate (Hohmeyer and Gaertner 1992) based on a zero consumption discount rate (Davidson 2006; Davidson 2008) and thus a *negative* pure rate of time preference.

The sample and distribution characteristics of Table 2 also allow us to identify outliers. On the low side, the results of (Tol 2005b) stand out with a social cost of carbon of -$6.6/tC for a 3% pure rate of time preference and $19.9/tC for a 0% rate. The reason is that Tol's model was the first used for marginal cost estimation that had initial benefits from climate change. In later work by the same author, the early benefits are less pronounced. On the high side, the results of (Ceronsky et al. 2006) stand out, with a social cost estimate of $2400/tC for a 0% pure rate of time preference and $120/tC for a 3% rate. The reason is that Ceronsky et al. consider extreme scenarios only – while they acknowledge that such scenarios are unlikely, they do not specify a probability. At a 1% pure rate of time preference, the $815/tC estimate of (Hope 2008) stands out. Again, this is the result of a sensitivity analysis in which Hope sets risk aversion to zero so that the consumption discount rate equals 1% as well.

Although Table 2 reveals a large estimated uncertainty about the social cost of carbon, there is reason to believe that the actual uncertainty is larger still. First of all, the social cost of carbon derives from the total economic impact estimates - and I argue above that their uncertainty is underestimated too. Second, the estimates only contain those impacts that have been quantified and valued - and I argue below that some of the missing impacts have yet to be assessed because they are so difficult to handle and hence very uncertain. Third, although the number of researchers who published marginal damage cost estimates is larger than the number of researchers who published total impact estimates, it is still a reasonably small and close-knit community who may be subject to group-think, peer pressure and self-censoring.

To place these estimated costs of carbon in context, a carbon tax in the range of $50-$100 per metric tonne of carbon would mean that new electricity generation capacity would be carbon-free, be it wind or solar power or coal with carbon capture and storage (Weyant et al. 2006). In contrast, it would take a much higher carbon tax to de-carbonize transport, as biofuels, batteries and fuel cells are very expensive still (Schaefer and Jacoby 2005; Schaefer and Jacoby 2006). Substantial reduction of carbon emissions thus requires a carbon tax of at least $50/tC - which is just barely justifiable at the mean estimate for a pure rate of time preference of 3 percent.

2.3. Missing Impacts

The effects of climate change that have been quantified and monetized include the impacts on agriculture and forestry, water resources, coastal zones, energy consumption, air quality, and human health. Obviously, this list is incomplete. Even within each category, the assessment is incomplete. I cannot offer quantitative estimates of these missing impacts, but a qualitative and speculative assessment of their relative importance follows. For more detail, see (Tol 2008c).

Many of the omissions seem likely to be relatively small in the context of those items that have been quantified. Among the negative effects, for example, studies of the effect of sea level rise on coastal zones typically omit costs of saltwater intrusion in groundwater (Nicholls and Tol 2006). Increasing water temperatures would increase the costs of cooling power plants (Szolnoky et al. 1997). Redesigning urban water management systems, be it for more of less water, would be costly (Ashley et al. 2005), as would implementing safeguards against increased uncertainty about future circumstances. Extratropical storms may increase, leading to greater damage and higher building standards (Dorland et al. 1999). Tropical storms do more damage, but it is not known how climate change would alter the frequency, intensity, and spread of tropical storms (McDonald et al. 2005). Ocean acidification may harm fisheries (Kikkawa et al. 2004).

The list of relatively small missing effects would also include effects that are probably positive. Higher wind speeds in the mid-latitudes would decrease the costs of wind and wave energy (Breslow and Sailor 2002). Less sea ice would improve the accessibility of Arctic harbours, would reduce the costs of exploitation of oil and minerals in the Arctic, and might even open up new transport routes between Europe and East Asia (Wilson et al. 2004). Warmer weather would reduce expenditures on clothing and food, and traffic disruptions due to snow and ice (Carmichael et al. 2004).

Some missing effects are mixed. Tourism is an example. Climate change may well drive summer tourists towards the poles and up the mountains, which amounts to a redistribution of tourist revenue (Berrittella et al. 2006). Other effects are simply not known. Some rivers may see an increase in flooding, and others a decrease (Kundzewicz et al. 2005; Svensson et al. 2005).

These small unknowns, and doubtless others not identified here, are worth some additional research, but they pale in comparison to the big unknowns: extreme climate scenarios, the very long term, biodiversity loss, the possible effects of climate change on economic development and even political violence.

Examples of extreme climate scenarios include an alteration of ocean circulation patterns - such as the Gulf Stream that brings water north from the equator up through the Atlantic Ocean (Marotzke 2000). This may lead to a sharp drop in temperature in and around the North Atlantic. Another example is the collapse of the West-Antarctic Ice Sheet (Vaughan 2008; Vaughan and Spouge 2002), which would lead to sea level rise of 5-6 meters in a matter of centuries. A third example is the massive release of methane from melting permafrost (Harvey and Zhen 1995), which would lead to rapid warming worldwide. Exactly what would cause these sorts of changes or what effects they would have are not at all well-understood, although the chance of any one of them happening seems low. But they do have the potential to happen relatively quickly, and if they did, the costs could be substantial. Only a few studies of climate change have examined these issues. (Nicholls et al. 2008) find that the impacts of sea level rise increase ten-fold should the West-Antarctic Ice Sheet collapse, but the work of (Olsthoorn et al. 2008) suggests that this may be too optimistic as Nicholls et al. may have overestimated the speed with which coastal protection can be build. (Link and Tol 2004) estimate the effects of a shutdown of the thermohaline circulation. They find that the resulting regional cooling offsets but does not reverse warming, at least over land. As a consequence, the net economic effect of this particular change in ocean circulation is ***positive***.

Another big unknown is the effect of climate change in the very long term. Most static analyses examine the effects of doubling the concentration of atmospheric CO_2; most studies looking at effects of climate change over time stop at 2100. Of course, climate change will not suddenly halt in 2100. In fact, most estimates suggest that the negative effects of climate change are growing, and even accelerating, in the years up to 2100 (cf. Figure 1). It may be that some of the most substantial benefits of addressing climate change occur after 2100, but studies of climate change have not looked seriously at possible patterns of emissions and atmospheric concentrations of carbon after 2100, the potential physical effects on climate, nor the monetary value of those impacts. One may argue that impacts beyond 2100 are irrelevant because of time discounting, but this argument would not hold if the impacts grow faster than the discount rate - because of the large uncertainty, this cannot be excluded.

Climate change could have a profound impact on biodiversity (Gitay et al. 2001), not only through changes in temperature and precipitation, but in the ways climate change might affect land use and nutrient cycles, ocean acidification, and the prospects for invasion of alien species into new habitats. Economists have a difficult time analyzing this issue. For starters, there are few quantitative studies of the effects of climate change on ecosystems and biodiversity. Moreover, valuation of ecosystem change is difficult, although some methods are being developed (Champ et al. 2003). These methods are useful for marginal changes to nature, but may fail for the systematic impact of climate change. That said, valuation studies have consistently shown that, although people are willing to pay something to preserve or improve nature, most studies put the total willingness to pay for nature conservation at substantially less than 1 percent of income (Pearce and Moran, 1994). Unless scientists and economists develop a rationale for placing a substantially higher cost on biodiversity, it will not fundamentally alter the estimates of total costs of climate change.

A cross-sectional analysis of per capita income and temperature may suggest that people are poor because of the climate (Acemoglu et al. 2001; ; Gallup et al. 1999; Masters and McMillan 2001; Nordhaus 2006; van Kooten, G. Cornelis 2004), although others would argue that institutions are more important than geography (Acemoglu et al. 2002; Easterly and Levine 2003). There is an open question about the possible effects of climate change on annual rates of economic growth. For example, one possible scenario is that low-income countries, which are already poor to some extent because of climate, will suffer more from rising temperatures and have less ability to adapt, thus dragging their economies down further. (Fankhauser and Tol 2005) argue that only very extreme parameter choices would imply such a scenario. In contrast, (Dell et al. 2008) find that climate change would slow the annual growth rate of poor countries by 0.6 to 2.9 per cent points. Accumulated over a century, this effect would dominate all earlier estimates of the economic effects of climate change. However, Dell et al. have only a few explanatory variables in their regression, so their estimate may suffer from specification or missing variable bias; they may also have confused weather variability with climate change. One can also imagine a scenario in which climate change affects health, particularly the prevalence of malaria and diarrhoea, in a way that affects long-term economic growth (Galor and Weil 1999); or in which climate-change-induced resource scarcity intensifies violent conflict (Tol and Wagner 2008; Zhang et al. 2006; Zhang et al. 2007) and affect long-term growth rates through that mechanism (Butkiewicz and Yanikkaya 2005). These potential channels have not been modeled in a useful way. But the key point here is that if climate change affects annual rates of growth for a sustained period of time, such effects may dominate what was calculated in the total effects studies shown earlier in Table 1.

Besides the known unknowns described above, there are probably unknown unknowns too. For example, the direct impact of climate change on labor productivity has never featured on any list of "missing impacts", but (Kjellstrom et al. 2008) show that it may well be substantial.

The "missing impacts" are a reason for concern and further emphasize that climate change may spring nasty surprises. This justifies greenhouse gas emission reduction beyond that recommended by a cost-benefit analysis under quantified risk. The size of the "uncertainty premium" is a political decision. However, one should keep in mind that there is a history of exaggeration in the study of climate change impacts. Early research pointed to massive sea level rise (Schneider and Chen 1980), millions dying from infectious diseases (Haines and Fuchs 1991) and widespread starvation (Hohmeyer and Gaertner 1992). Later, more careful research has dispelled these fears.

3. IMPACTS OF EMISSION REDUCTION: A SURVEY

3.1. Options

Carbon dioxide emissions are driven by the Kaya-Bauer identity:

$$(1) \qquad M = P\frac{Y}{P}\frac{E}{Y}\frac{C}{E}\frac{M}{C}$$

where ***M*** is emissions, ***P*** is population, ***Y*** is income, ***E*** is emissions, and ***C*** is carbon dioxide generated. That is, Equation (1) has that emissions are equal to the number of people times their per capita income, times the energy intensity of the economy, times the carbon intensity of the economy, times the fraction of emissions that is vented to the atmosphere.

Although it is an accounting identity, Equation (1) provides insight into how emissions can be abated. One may reduce the number of people. This is generally not considered to be a policy option, but a few governments are actively pursuing this (albeit not for reasons of climate change). One may also reduce economic growth, or induce economic shrink. Again, this is not typically seen as an option for climate policy, but the economic downturn that followed the collapse of the Soviet Union and the current depression have reduced emissions considerably.

The three right-most terms of Equation (1) are seriously considered for climate policy. First, one may increase the overall energy efficiency of the economy, that is, deliver the same economic value using less energy. Second, one may decrease the overall carbon intensity of the energy system, that is, deliver the same amount of energy emitting less carbon. Third, one may prevent carbon dioxide from entering the atmosphere.

None these options is free or easy. Energy is a cost to businesses and households. The market therefore pushes for increased energy efficiency. When energy is cheap, this often means that more services are delivered for the same amount of energy input. When energy is dear, the same services are typically delivered with less energy. Historically, the rate of energy efficiency improvements has ranged between 0.5% and 1.5% per year (Lindmark 2002; Tol et al. 2009). This is quite an achievement considering that this rate is maintained over the long term and applies to often mature technologies.

Suppose for the sake of argument that, in the absence of climate policy, energy efficiency improves by 1% per year, that the economy grows by 2%, and that the carbon intensity is constant. Then, emissions grow by 1% per year. In order to stabilise emissions, the rate of energy efficiency improvement has to double from 1% to 2%. Because of decreasing returns to scale, doubling the rate of technological progress means that the effort that is being put into improving energy efficiency has to be more than doubled. This is easy to do for a specific technology, but hard across the entire economy. Furthermore, only a fraction of appliances, vehicles and machines are replaced each year. That is, technological progress applies to a fraction of the capital stock only. Premature retirement of capital is very expensive.

Similar arguments apply to decarbonisation. Energy supply has shifted dramatically before climate policy. In the early stages of industrial development, biomass was replaced by coal as the main source of energy, leading to a rapid rise of carbon dioxide emissions. Later, oil and gas started to replace coal, reducing the carbon intensity of the energy supply, but not sufficiently so to reduce emissions (Tol et al. 2009). In times of high energy prices, alternative energy sources have established niche applications but never captured the market. At present, non-fossil energy is too expensive for commercial application in the absence of government support.

There are a number of alternative, carbon-free energy sources: biomass, wind, water, wave, tidal, solar, geothermal, and nuclear power. Water and nuclear power have low costs, but are politically constrained. Wave, tidal and geothermal power are experimental technologies, with a few niche applications. Wind power has expanded rapidly on the back of generous subsidies, but its unpredictable nature prevents it from even attaining a dominant position in the market. Biomass energy and solar power are currently very expensive still, but rapid progress is being made piggy-backing on advances in biotechnology and materials science.

Finally, there is the option to capture carbon dioxide just before it would be released into the atmosphere. Carbon capture, transport, and storage are all proven technologies, but have never been applied at the scale needed to reduce emissions. Cost is a major issue with carbon capture. The process significantly increases the capital invested in a power plant, while a substantial part of the energy generated is used to capture carbon. Reliability and safety are main issues with carbon storage. Leaky storage postpones rather than prevents emissions, and accidental releases of a large amount of carbon dioxide may kill animals and humans. At present, there are various plans to build demonstration plants for carbon capture and storage.

3.2. Costs

The IPCC[5] periodically surveys the costs of emission abatement (Barker et al. 2007; Hourcade et al. 1996; Hourcade et al. 2001); there are the EMF[6] overview papers (Weyant 1993; Weyant 1998; Weyant 2004; Weyant et al. 2006; Weyant and Hill 1999), and there a few recent meta-analyses as well (Barker et al. 2002; Fischer and Morgenstern 2006; Kuik et al. 2009; Repetto and Austin 1997). There are two equally important messages from this literature. First, a well-designed, gradual policy can substantially reduce emissions at low cost to society. Second, ill-designed policies, or policies that seek to do too much too soon can be orders of magnitude more expensive. While the academic literature has focussed on the former, policy makers have opted for the latter.

5 Intergovernmental Panel on Climate Change; http://www.ipcc.ch/
6 Energy Modeling Forum; http://emf.stanford.edu/

Figure 2. The average reduction in GDP due to climate policy aiming at three alternative stabilisation targets for atmospheric greenhouse gases; the models used are FUND, GTEM, two versions of MERGE, MESSAGE, MiniCAM, SGM and WITCH.

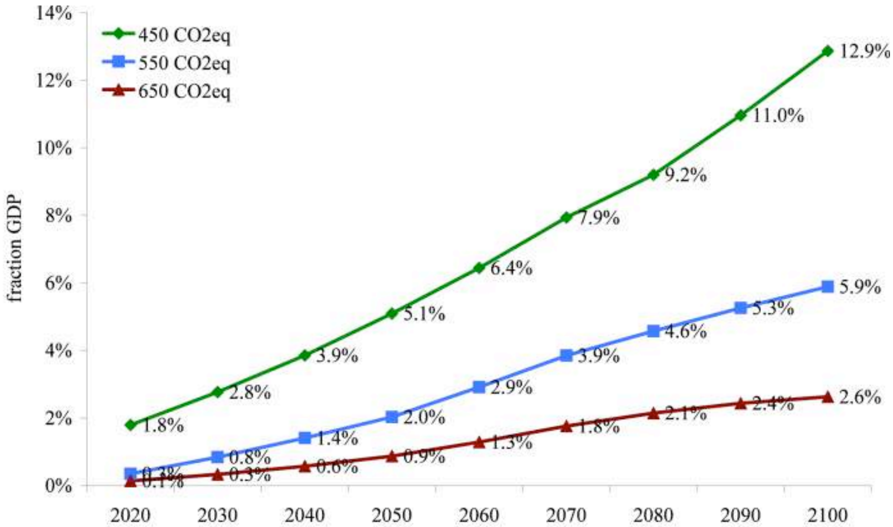


Figure 3. The average carbon tax needed for three alternative stabilisation targets for atmospheric greenhouse gases; the models used are FUND, GTEM, two versions of MERGE, MESSAGE, MiniCAM, SGM and WITCH.

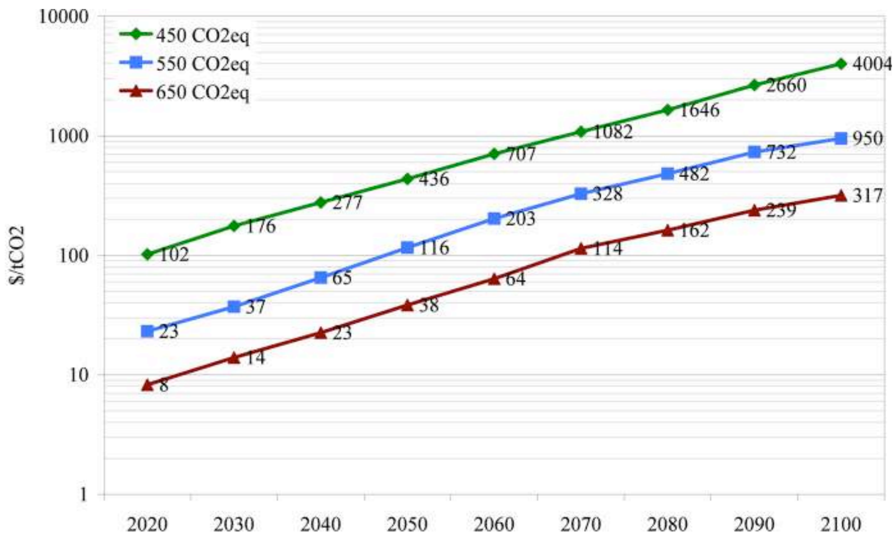


Figure 2 illustrates the costs of emission reduction, here represented as the average reduction in gross world product over eight models participating in EMF22 for three alternative scenarios.[7] Stabilizing the atmospheric concentrations of all greenhouse gases in the atmosphere at a level of 650 ppm $CO_{2equivalent}$ may cost only 2.6% of GDP over a century. This is roughly equal to losing one year of growth in a hundred years. If the target is 550 ppm CO_{2eq}, costs go up to 5.9% of GDP. The costs are twice as high, but still small compared to economic growth. Half of the models cannot meet a target is 450 ppm CO_{2eq}. The other half report an average costs of 12.9%.

The cost estimates of Figure 2 were achieved under the assumption that all greenhouse gas emissions from all sources in all countries are taxed by the same amount, and that the tax rate increases with the discount rate. That is, the stabilisation target is met at the lowest possible cost. Figure 3 shows the estimates of the carbon tax, averaged for the eight (four) models. In order to achieve stabilisation at 650 ppm CO_{2eq}, an \$8/tCO_{2eq} carbon tax in 2020 rising to \$320/tCO_{2eq} may be enough. However, for 450 ppm CO_{2eq}, the carbon tax would need to start at \$100/tCO_{2eq} and rise to \$4,000/tCO_{2eq} - keeping in mind that half of the models suggest that this target cannot be reached. Stabilising at 450 ppm CO_{2eq} is needed to have decent chance of keeping temperatures below 2°C above pre-industrial levels.

The costs of emission reduction increase, and the feasibility of meeting a particular target decreases if:

- different countries, sectors, or emissions face different explicit or implicit carbon prices (Boehringer et al. 2006b; Boehringer et al. 2006a; Boehringer et al. 2008; Manne and Richels 2001; Reilly et al. 2006);
- the carbon prices rises faster or more slowly than the effective discount rate (Manne and Richels 1998; Manne and Richels 2004; Wigley et al. 1996);
- climate policy is used to further other, non-climate policy goals (Burtraw et al. 2003); and
- climate policy adversely interacts with pre-existing policy distortions (Babiker et al. 2003).

Unfortunately, each of these four conditions is likely to be violated in reality. For instance, only select countries have adopted emissions targets. Energy-intensity sectors that compete on the world market typically face the prospect of lower carbon prices than do other sectors. Climate policy often targets carbon dioxide but omits methane and nitrous oxide. Emission trading systems have a provision for banking permits for future use, but not for borrowing permits from future periods. Climate policy is used to enhance energy security and create jobs. Climate policy is superimposed on energy and transport regulation and taxation.

The costs of emission reduction would also increases if emissions grow faster, if the price of fossil fuels is lower, or if the rate of technological progress in alternative fuels is slower than anticipated. This risk is two-sided. Emissions may grow more slowly, the price of fossil energy may be higher, and the alternative fuels may progress faster than expected.

7 Note that the most stringent target is infeasible according to half of the models.

4. THE MODEL

I use Version 2.9e of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Version 2.9 of FUND has the same basic structure as previous versions (Tol 1999; Tol 2005a; Tol 2006). The source code and a complete description of the model can be found at http://fund-model.org. A more succinct description is in Appendix 1.

Essentially, FUND is a model that calculates impacts of climate change and climate policy for 16 regions of the world by making use of exogenous scenarios of socioeconomic variables. The scenarios comprise of projected temporal profiles of population growth, economic growth, autonomous energy efficiency improvements and carbon efficiency improvements (decarbonization), emissions of carbon dioxide from land use change, and emissions of methane and of nitrous oxide. Carbon dioxide emissions from fossil fuel combustion are computed endogenously on the basis of the Kaya identity. The calculated impacts of climate change perturb the default paths of population and economic outputs corresponding to the exogenous scenarios. The model runs from 1950 to 2300 in time steps of a year, though the outputs for the 1950-2000 period is only used for calibration, and the years beyond 2100 are ignored in this paper. The scenario up to the year 2100 is based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al. 1992) and is somewhat similar to the SRES A2 scenario (Nakicenovic and Swart 2001). For the years from 2100 onward, the values are extrapolated from the pre-2100 scenarios. Radiative forcing is based on (Forster et al. 2007). The global mean temperature is governed by a geometric buildup to its equilibrium (determined by the radiative forcing) with a half-life of 50 years. In the base case, the global mean temperature increases by 2.5˚C in equilibrium for a doubling of carbon dioxide equivalents.

The climate impact module (Tol 2002a; Tol 2002b) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, unmanaged ecosystems, and tropical and extra tropical storms. The last two are new additions(Narita et al. 2008; Narita et al. 2009). Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (Tol 2002b).

People can die prematurely due to climate change, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per-capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (Cline 1992). The value of emigration is set to be 3 times the per-capita income (Tol 1995), the value of immigration is 40 per cent of the per-capita income in the host region (Cline 1992). Losses of dryland and wetlands due to sea level rise are modeled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (Fankhauser 1994a). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (Fankhauser 1994a). The wetland value is assumed to have logistic relation to per-capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, storm damage, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units (Tol 2002a). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (Tol 2002b).

The impacts of climate change on coastal zones, forestry, tropical and extratropical storm damage, unmanaged ecosystems, water resources, diarrhoea malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (Tol 2002b).

Vulnerability to climate change 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 urbanization), and ecosystems and health (with higher per-capita incomes). Other systems such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) are projected to become less vulnerable at least over the long term (Tol 2002b). The income elasticities (Tol 2002b) are estimated from cross-sectional data or taken from the literature.

We estimated the SCC cost of carbon by computing the total, monetised impact of climate change along a business as usual path and along a path with slightly higher emissions between 2005 and 2014.[8] Differences in impacts were calculated, discounted back to the current year, and normalised by the difference in emissions.[9] The SCC is thereby expressed in dollars per tonne of carbon at a point in time – the standard measure of how much future damage would be avoided if today's emissions were reduced by one tonne.[10] That is,

$$\text{(1)} \qquad SCC_r = \sum_{t=2005}^{3000} \frac{I_{t,r}\left(\sum_{s=1950}^{t-1} E_s + \delta_s\right) - I_{t,r}\left(\sum_{s=1950}^{t-1} E_s\right)}{\prod_{s=2005}^{t} 1 + \rho + \eta g_{s,r}} \Bigg/ \sum_{t=2005}^{2014} \delta_t$$

where

8 The social cost of carbon of emissions in future or past periods is beyond the scope of this paper.

9 We abstained from levelizing the incremental impacts within the period 2005-14 because the numerical effect of this correction is minimal while it is hard to explain.

10 Full documentation of the *FUND* model, including the assumptions in the Monte Carlo analysis, is available at http://www.fund-model.org.

- SCC_r is the regional social cost of carbon (in US dollar per tonne of carbon);
- r denotes region;
- t and s denote time (in years);
- I are monetised impacts (in US dollar per year);
- E are emissions (in metric tonnes of carbon);
- δ are additional emissions (in metric tonnes of carbon);
- ρ is the pure rate of time preference (in fraction per year);
- η is the elasticity of marginal utility with respect to consumption; and
- g is the growth rate of per capita consumption (in fraction per year).

This paper only considers emission reduction of carbon dioxide. Initially, marginal abatement costs rise more than proportionally with abatement effort, but marginal costs become linear above $100/tC. There are mild intertemporal spillovers between and within regions that reduce costs (Clarke et al. 2008; Gillingham et al. 2008; Tol 2005a). An instantaneous emission reduction of 1% from baseline would cost roughly 0.01% of consumption, and a 10% reduction would cost 1%. Methane (nitrous oxide) emission reduction is two (four) orders of magnitude cheaper, but only carbon dioxide emission reduction can contain climate change. Carbon dioxide emissions are strictly positive in ***FUND***. ***FUND***'s cost estimates are well in line with other models (Kuik et al. 2009).

5. SCENARIOS

The Copenhagen Consensus on Climate 2009 hypothetically dispenses $250 billion per year on climate policy for a period of 10 years. In this chapter, climate policy is restricted to abatement of carbon dioxide emissions from industrial processes (largely cement production) and from fossil fuel combustion.

There are many ways to reduce carbon dioxide emissions. I here restrict the analysis to a carbon tax / cap-and-trade with auctioned permits. As there is no stochasticity in the model, these two options are equivalent. I omit other options (e.g., direct regulation; subsidies) because of the excess costs of such measures.

I consider five scenarios. In the first scenario, the countries of the OECD implement a uniform carbon tax such that the net present value of the abatement cost equals $2 trillion, the net present value of $250 billion per year for ten years. The discount rate is 5% per year. Costs are discounted to 2009. This is achieved by a carbon tax of $700/tC, starting in 2010 and rising with the discount rate. The carbon tax is zero from 2020 onwards.

In the second scenario, all countries implement a carbon tax of $250/tC in 2010, rising with the discount rate, but returning to zero in 2020. This also leads to an abatement cost of $2 trillion.

In the third scenario, I assume that climate policy after 2020 will continue as before. That is, the carbon tax keeps rising with the discount rate between 2020 and 2100.

The fourth scenario is different. For ten years, $250 billion is invested in a trust fund. This trust fund finances a century-long programme of emission abatement such that the net present value of the abatement cost ***over the century*** equals $2 trillion. This is achieved by a uniform carbon tax for all countries, which starts at $12/tC in 2010 and rises with the discount rate. The fifth scenario is different again. Only a part of the $250 billion is invested. The carbon tax in 2010 is set equal to the Pigou tax ($2/tC), also known as the marginal damage costs of carbon dioxide emissions and the social cost of carbon. The carbon tax is applied world wide, and equal for all countries.

6. RESULTS

Figure 4 shows the gross world income for the no abatement case and the five alternative policy scenarios. To cite Thomas Schelling, if these lines would be drawn with a thick pencil, you would not see the difference. This is a recurrent theme in the climate economics literature. Given time and a clever policy design, substantial emission abatement can be achieved at acceptable cost. Even the most drastic policy considered – a worldwide carbon tax of $250/tC in 2010 rising with the rate of discount to over $20000/tC in 2100 – leads to a reduction of income of only 13% in 2100 (while income increases more that sevenfold in the no policy scenario).

Figure 4. Gross world income for the no policy and five alternative policy scenarios.

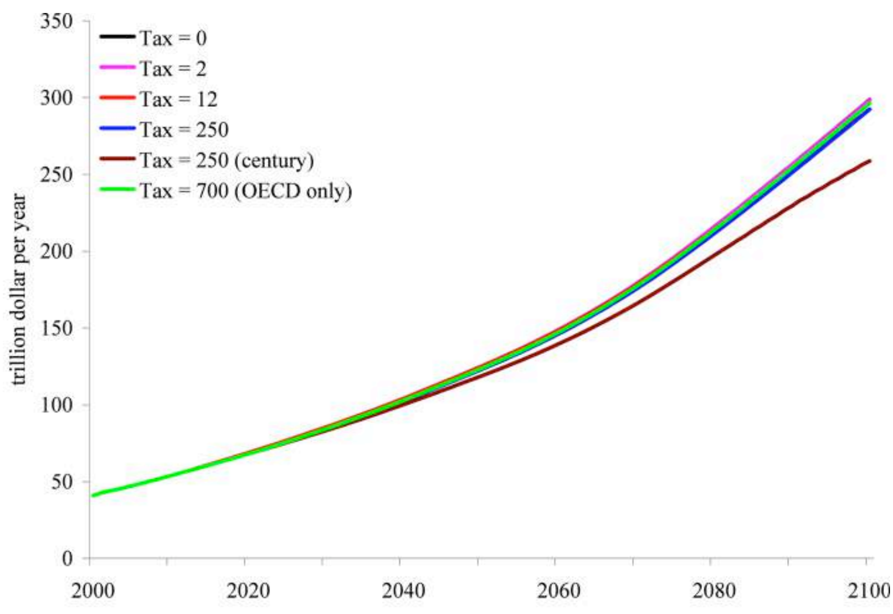


Figure 5. Global carbon dioxide emissions from fossil fuel combustion and industrial processes for the no policy and five alternative policy scenarios.

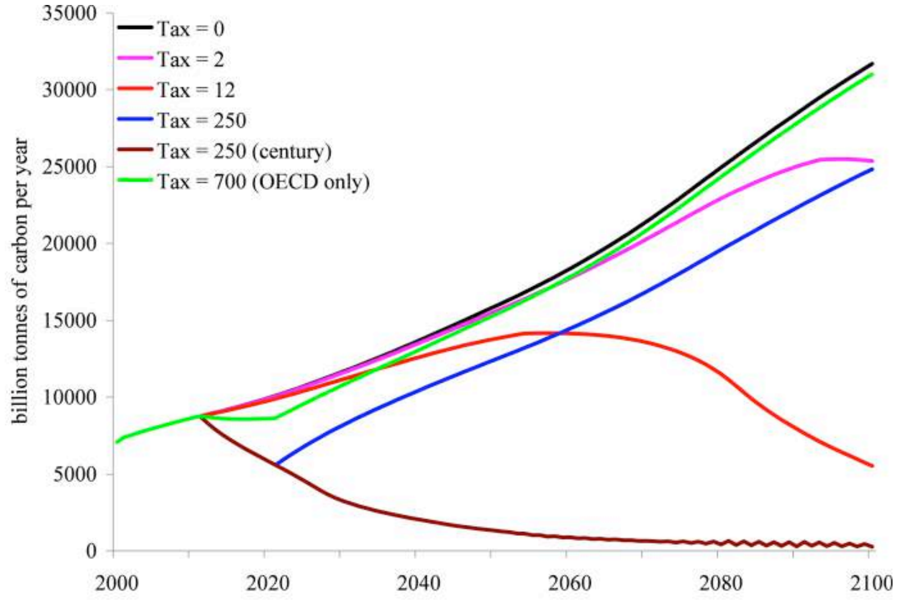


Figure 6. The atmospheric concentration of carbon dioxide for the no policy and five alternative policy scenarios.

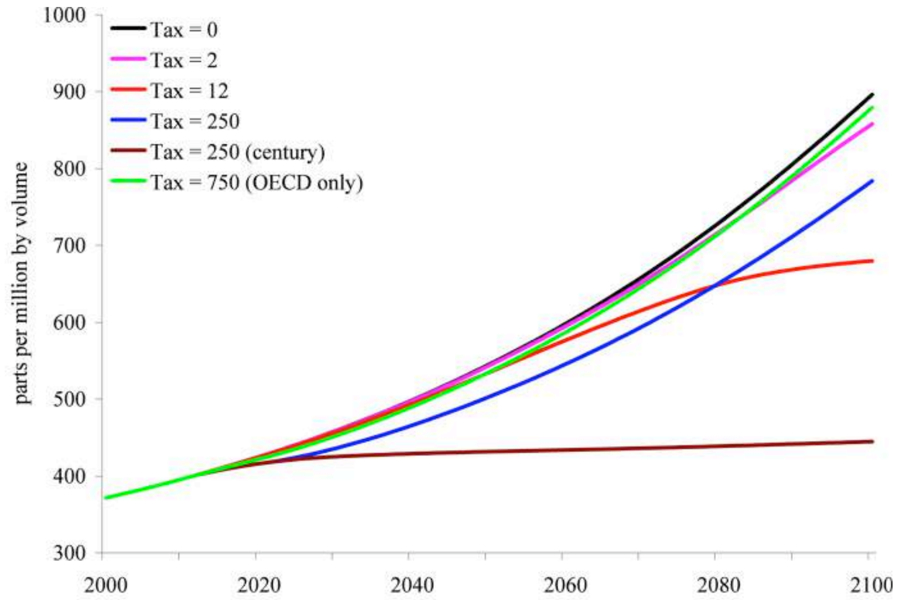
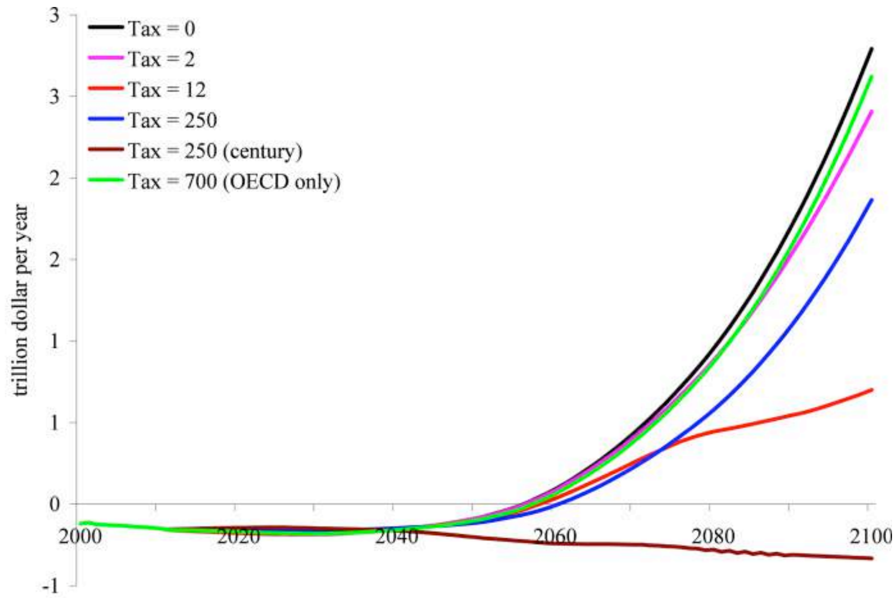


Figure 5 shows just how substantial emission cuts can be. Figure 5 also demonstrates the importance of long-lived climate policy, that is, a climate policy that is in line with the slow turnover of capital and the gradual progress of technology. The two policy scenarios that concentrate effort in the first decade are less effective than the scenario that spends the same amount of money over the century. Even the $2/tC century-long policy is about as effective in the long run as the $250/tC decade-long policy, and at a fraction of the cost. If the $250/tC initial carbon tax is maintained over the century, carbon dioxide emissions fall by more than 90% in 2050 and by almost 100% in 2100 compared to the baseline; [11] 2050 emissions are some 20% of 2000 emissions in this scenario.

Figure 6 shows the impact of the five policy scenarios on the ambient concentration of carbon dioxide. Figure 6 highlights that climate change is a stock problem. Emissions respond only slowly to policy, and concentrations respond even more tardily. A $12/tC initial carbon tax would almost stabilise the CO_2 concentration at around 680 ppm. An initial carbon tax of $250/tC would keep the concentration below 450 ppm; as other greenhouse gas are uncontrolled, the temperature continues to rise to 2.4°C above pre-industrial in 2100.[12]

Figure 7 depicts the economic impacts of climate change. As argued in Section 2, moderate warming has a positive effect. However, these are sunk benefits, hardly affected by emission abatement. In the longer term, the impacts of climate change are decidedly negative and rapid accelerate in the absence of policy. That said, the policy scenarios considered here only slow the negative impacts of climate change, with the exception of the $250/tC century-long policy which has net positive impacts of climate change throughout the century.

Figure 7. Monetised impact of climate change for the no policy and five alternative policy scenarios.



11 Note that this is an artefact of the model which was never designed for such aggressive policy. At such a high carbon tax, it would make economic sense to remove carbon from the atmosphere. *FUND* does not allow for that.

12 Compare this to the vapid announcement of the G8 which calls for a 50% emission reduction in 2050 in order to keep the global mean temperature below 2°C.

Table 3. Net present value of abatement costs and benefits for the five scenarios.

	NPV Cost		NPV Benefit	Benefit-cost ratio
Initial carbon tax \ Period	2010-2020	2010-2100	2010-2100	2010-2100
World: 2 $/tC (century)	$ 0.2 10^9	$ 0.1 10^{12}	$ 0.1 10^{12}	1.51
World: 12 $/tC (century)	$ 5.6 10^9	$ 2.0 10^{12}	$ 0.5 10^{12}	0.26
World: 250 $/tC (decade)	$ 2.0 10^{12}	$ 17.8 10^{12}	$ 0.2 10^{12}	0.01
World: 250 $/tC (century)	$ 2.0 10^{12}	$ 46.7 10^{12}	$ 1.1 10^{12}	0.02
OECD: 700 $/tC (decade)	$ 2.0 10^{12}	$ 13.3 10^{12}	$ 0.0 10^{12}	0.00

Table 3 shows the net present costs and benefits as well as the benefit-cost ratios of the five alternative policy scenarios. The five scenarios are ordered in the intensity of climate policy in the OECD in the coming decade. Starting at the bottom, spending a lot of money on carbon dioxide emission reduction in the near term in the OECD does not pay off. A much greater benefit can be achieved if the same money is used to finance worldwide abatement - essentially because emission reduction is cheaper in poorer countries - but the benefit-cost ratio is about 1 to 100. If the same programme is repeated decade after decade, abatement costs go up considerably but benefits rise even faster. Still, the benefit-cost ratio is only 1 to 50.

The benefit-cost ratio improves considerably if the $250 billion is spent over the century rather than over the decade. A benefit-cost ratio is of 1 to 4 is the result. This policy - a worldwide carbon tax of $12/tC in 2010, rising at 5% per year - does not improve global welfare, but recall that the model ignores the substantial concerns about equity and uncertainty. An equity- and risk-premium of 400% on the benefits would not be outrageous.

If the initial carbon tax is set equal to the estimated marginal damage cost, the benefit-cost ratio unsurprisingly exceeds unity: 3 to 2 (cf. Table 3). Over the century, this policy spends only 1/20th of the funds (hypothetically) available to the Copenhagen Consensus.

Figure 8 shows the benefits as a percentage of Gross World Product over time. Figure 9 shows the costs. Figure 10 shows the benefit-cost ratio per year. As climate change is initially beneficial, emission reduction brings damages at first. There are benefits only after 2040, and the benefits rise rapidly. Costs rise too. In case climate policy only lasts for a decade, costs are roughly constant as fraction of GDP (and thus fall as a fraction of world GDP if abatement only applies to the countries of the OECD). The benefit-cost ratio is thus negative until 2040 (not shown). After that, the benefit-cost ratio rises over time but does not exceed unity. The

$2/tC initial carbon tax scenario is the exception. The benefit-cost ratio exceeds unity after 2055. However, it reaches a maximum in 2078, after which current costs rise faster than current benefits. This suggests that the carbon tax rises too fast. This implies that this policy is not optimal, and that there is a policy with a higher benefit-cost ratio still.

Figure 8. Monetised and normalised benefit of the five alternative policy scenarios.

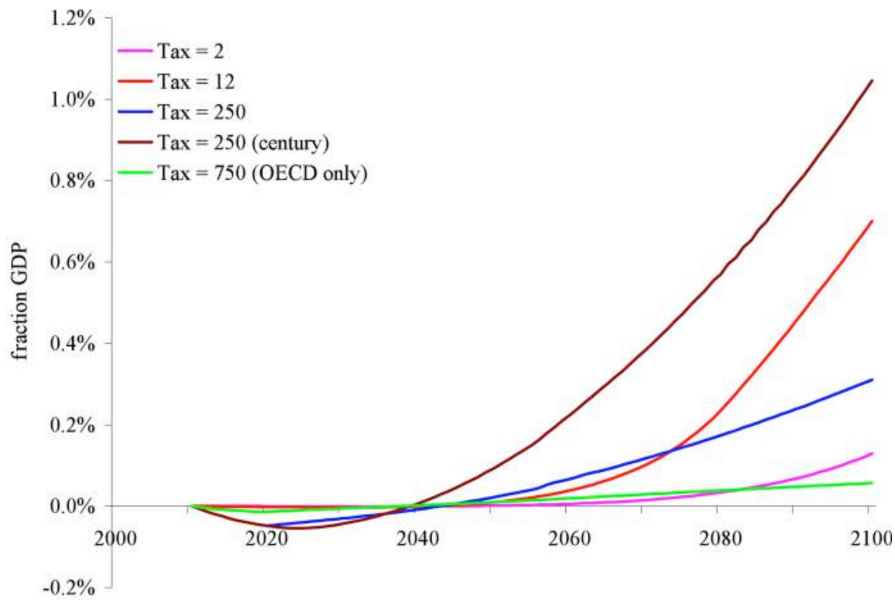


Figure 9. Normalised cost of the five alternative policy scenarios.

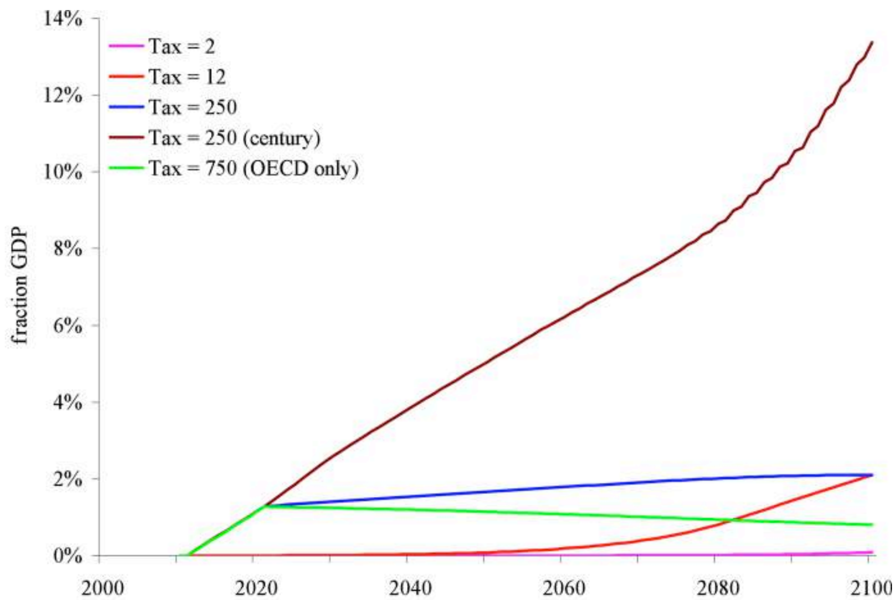
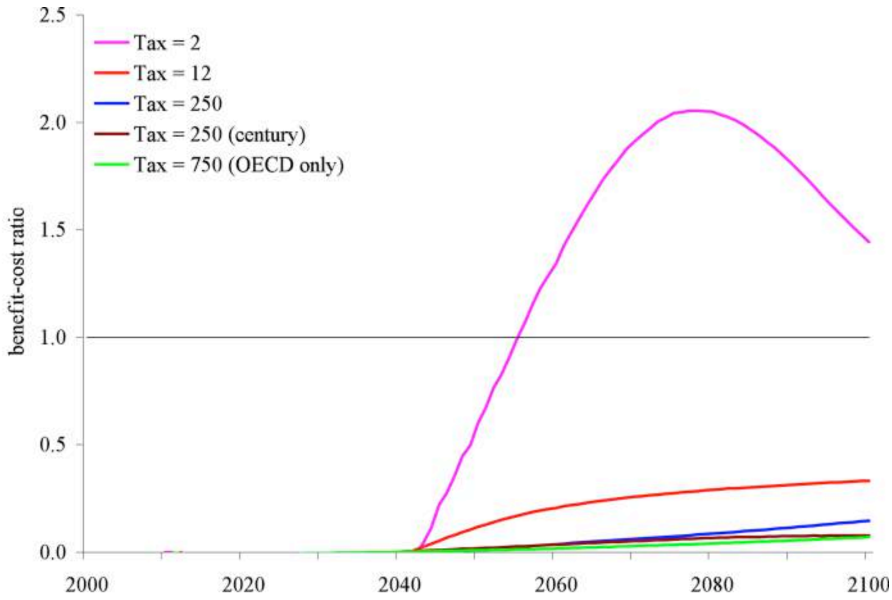


Figure 10. Benefit-cost ratio of the five alternative policy scenarios.



7. DISCUSSION AND CONCLUSION

This paper consists of two parts: literature review and policy analysis. In the first half of the literature review, I argue that the impacts of climate change are very uncertain. On the basis of our current knowledge, climate change seems to be a real problem but not the biggest problem in the world, or even the biggest environmental problem. However, as the marginal impacts are negative, this externality should be regulated. In the second half of the literature review, I argue that emission reduction is feasible and as cheap as policy is clever. Putting the two halves of the literature review together, one may wonder what all the fuss is about. Such speculation would be beyond this paper.

In the second part of the paper, I consider five alternative policy options for carbon dioxide emission reduction. In the first scenario, all funds ($2.5 trillion) of the Copenhagen Consensus on Climate 2009 are spent on emission reduction in the OECD between 2010 and 2020. This is a rather silly thing to do. The benefit-cost ratio is below 1/100. In the second scenario, the same amount of money is spent on emission reduction worldwide, but policy still ceases in 2020. This is a much better plan than scenario 1 because non-OECD abatement is cheaper, but the benefit-cost ratio is still only 1/100. In the third scenario, I assume that there will be Copenhagen Consensus for Climate in 2019, 2029, and so. That is, carbon dioxide abatement continues after 2020. Emission reduction costs are much larger, obviously, but the consequent abatement is so stringent that most of the negative impacts of climate change would be avoided altogether. Nonetheless, this policy does not pay off. The benefit-cost ratio is 1/50. Although the benefits are substantial, the costs are larger still. In the fourth scenario, I do not assume that there will be future Copenhagen Consensus of Climate. Instead, the $2.5 trillion available to the CCC09 is invested in a trust fund. The trust fund finances emission reduction across the world such that it runs out of money in 2100. This policy has a benefit-cost ratio of 1/4. Finally, in the fifth scenario, 1/20 of the money available to the CCC09 is put into the trust fund. In this case, the benefit-cost ratio is 3/2. The fifth scenario is the only project worth funding.

These results are based on many assumptions, none of which is tested in a sensitivity analysis. Given the large uncertainties and the large inequities of climate change, one may justifiably argue that the "right" policy is more stringent than the "optimal" policy shown here. One may similarly argue that the discount rate used here is too high. That said, a cursory look at aid and trade policies do not suggest great care for the welfare of people in faraway lands; and pension policies suggest that the future is not a high priority. Therefore, one may go beyond the policy with a global carbon tax of $2/tC in 2010, rising with the rate of discount. However, the analysis presented here also omits suboptimal policy design. Carbon price differentiation and direct regulation may well increase abatement costs by a substantial margin. Therefore, one should perhaps not go too far beyond the optimal policy outlined here.

APPENDIX1: MODEL DESCRIPTION

Carbon dioxide emissions are calculated on the basis of the Kaya identity:

$$\text{(A1.1)}\quad M_{t,r} = \frac{M_{t,r}}{E_{t,r}}\frac{E_{t,r}}{Y_{t,r}}\frac{Y_{t,r}}{P_{t,r}}P_{t,r} =: \psi_{t,r}\varphi_{t,r}Y_{t,r}$$

where M denotes emissions, E denote energy use, Y denotes GDP and P denotes population; t is the index for time, r for region. The carbon intensity of energy use, and the energy intensity of production follow from:

$$\text{(A1.2)}\quad \psi_{t,r} = g^{\psi}_{t-1,r}\psi_{t-1,r} - \alpha_{t-1,r}\tau^{\psi}_{t-1,r}$$

and

$$\text{(A1.3)}\quad \varphi_{t,r} = g^{\varphi}_{t-1,r}\varphi_{t-1,r} - \alpha_{t-1,r}\tau^{\varphi}_{t-1,r}$$

where τ is policy intervention and α is a parameter. The exogenous growth rates g are referred to as the Autonomous Energy Efficiency Improvement (AEEI) and the Autonomous Carbon Efficiency Improvement (ACEI). The values are specified at http://fund-model.org/ Policy also affects emissions via

$$\text{(A1.1')}\quad M_{t,r} = \left(\psi_{t,r} - \chi^{\psi}_{t,r}\right)\left(\varphi_{t,r} - \chi^{\varphi}_{t,r}\right)Y_{t,r}$$

$$\text{(A1.4)}\quad \chi^{\psi}_{t,r} = \kappa_{\psi}\chi_{t-1,r} + (1-\alpha_{t-1,r})\tau^{\psi}_{t-1,r}$$

and

$$\text{(A1.5)}\quad \chi^{\varphi}_{t,r} = \kappa_{\varphi}\chi_{t-1,r} + (1-\alpha_{t-1,r})\tau^{\varphi}_{t-1,r}$$

Thus, the variable $0<\alpha<1$ governs which part of emission reduction is ***permanent*** (reducing carbon and energy intensities at all future times) and which part of emission reduction is ***temporary*** (reducing current energy consumptions and carbon emissions), fading at a rate of $0<\kappa<1$. In the base case, $\kappa_{\psi}=\kappa_{\phi}=0.9$ and

$$\text{(A1.6)}\quad \alpha_{t,r} = 1 - \frac{\tau_{t,r}/100}{1+\tau_{t,r}/100}$$

So that $\alpha=0.5$ if $\tau=\$100/tC$. One may interpret the difference between permanent and temporary emission reduction as affecting commercial technologies and capital stocks, respectively. The emission reduction module is a reduced form way of modelling that part of the emission reduction fades away after the policy intervention is reversed, but that another part remains through technological lock-in. Learning effects are described below. The parameters of the model are chosen so that FUND roughly resembles the behaviour of other models, particularly those of the Energy Modeling Forum (Weyant 2004; Weyant et al. 2006).

The costs of emission reduction *C* are given by

$$(A1.7)\quad \frac{C_{t,r}}{Y_{t,r}} = \frac{\beta_{t,r}\tau_{t,r}^{2}}{H_{t,r}H_{t}^{g}}$$

H denotes the stock of knowledge. Equation (A1.6) gives the costs of emission reduction in a particular year for emission reduction in that year. In combination with Equations (A1.2)-(A1.5), emission reduction is cheaper if smeared out over a longer time period. The parameter β follows from

$$(A1.8)\quad \beta_{t,r} = 0.784 - 0.084\sqrt{\frac{M_{t,r}}{Y_{t,r}} - \min_{s}\frac{M_{t,s}}{Y_{t,s}}}$$

That is, emission reduction is relatively expensive for the region that has the lowest emission intensity. The calibration is such that a 10% emission reduction cut in 2003 would cost 1.57% (1.38%) of GDP of the least (most) carbon-intensive region; this is calibrated to (Hourcade et al. 1996; Hourcade et al. 2001). An 80% (85%) emission reduction would completely ruin the economy. Later emission reductions are cheaper by Equations (A1.7) and (A1.8). Emission reduction is relatively cheap for regions with high emission intensities. The thought is that emission reduction is cheap in countries that use a lot of energy and rely heavily on fossil fuels, while other countries use less energy and less fossil fuels and are therefore closer to the technological frontier of emission abatement. For relatively small emission reduction, the costs in ***FUND*** correspond closely to those reported by other top-down models, but for higher emission reduction, ***FUND*** finds higher costs, because ***FUND*** does not include backstop technologies, that is, a carbon-free energy supply that is available in unlimited quantities at fixed average costs.

The regional and global knowledge stocks follow from

$$(A1.9)\quad H_{t,r} = H_{t-1,r}\sqrt{1+\gamma_{R}\tau_{t-1,r}}$$

and

$$(A1.10)\quad H_{t}^{G} = H_{t-1}^{G}\sqrt{1+\gamma_{G}\tau_{t,r}}$$

Knowledge accumulates with emission abatement. More knowledge implies lower emission reduction costs. The parameters γ determine which part of the knowledge is kept within the region, and which part spills over to other regions as well. In the base case, γ_R=0.9 and γ_G=0.1. The model is similar in structure and numbers to that of (Goulder and Mathai 2000; Goulder and Schneider 1999).

Emissions from land use change and deforestation are exogenous as specified at http://www.fund-model.org/ and cannot be mitigated.

Table A1. Parameters of the methane and nitrous oxide emission reduction cost curve; the 67% confidence interval is given in brackets.

	Methane		Nitrous oxide	
USA	5.74E-04	(4.15E-04 7.90E-04)	2.14E-05	(1.91E-05 2.39E-05)
CAN	1.20E-03	(8.70E-04 1.64E-03)	6.92E-05	(6.29E-05 7.60E-05)
WEU	3.71E-04	(2.34E-04 5.80E-04)	7.26E-06	(6.60E-06 7.98E-06)
JPK	1.27E-04	(8.75E-05 1.84E-04)	5.32E-07	(3.21E-07 8.57E-07)
ANZ	4.12E-03	(3.03E-03 5.57E-03)	2.08E-04	(1.89E-04 2.29E-04)
EEU	3.90E-03	(2.81E-03 5.38E-03)	9.39E-05	(8.89E-05 9.93E-05)
FSU	8.87E-03	(7.49E-03 1.05E-02)	1.05E-05	(1.00E-05 1.10E-05)
MDE	6.32E-03	(4.86E-03 8.19E-03)	1.05E-05	(1.00E-05 1.10E-05)
CAM	3.65E-03	(2.87E-03 4.62E-03)	2.35E-04	(2.19E-04 2.53E-04)
SAM	2.75E-02	(1.81E-02 4.14E-02)	1.05E-05	(1.00E-05 1.10E-05)
SAS	3.16E-02	(2.43E-02 4.08E-02)	5.64E-04	(5.29E-04 6.01E-04)
SEA	1.43E-02	(1.06E-02 1.91E-02)	2.55E-15	(2.16E-15 3.01E-15)
CHI	1.26E-02	(9.50E-03 1.67E-02)	2.16E-05	(2.02E-05 2.30E-05)
NAF	1.43E-02	(1.06E-02 1.91E-02)	1.05E-05	(1.00E-05 1.10E-05)
SSA	1.43E-02	(1.06E-02 1.91E-02)	1.05E-05	(1.00E-05 1.10E-05)
SIS	1.43E-02	(1.06E-02 1.91E-02)	1.05E-05	(1.00E-05 1.10E-05)

Table A2. Determinants of SF_6 emissions.

	C	GDP	GDP/cap
1990	1.6722E-01	5.0931E-06	-5.7537E-05
	(1.9297E-01)	(2.3482E-07)	(1.8505E-05)
1995	1.6255E-01	5.7234E-06	-6.0384E-05
	(2.1143E-01)	(2.3082E-07)	(1.8727E-05)
Used	1.6489E-01	5.4083E-06	-5.8961E-05
	(1.4312E-01)	(1.6464E-07)	(1.3164E-05)

SF_6 emissions are in million metric tonnes of carbon dioxide equivalent. GDP is in million dollar (1995, MEX). GDP/capita is in dollar (1995, MEX).

Table A3. Parameters of equation (A1.11).

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
Sulphur hexafluoride (SF_6)	0.0398	1/3200	0.04 ppt

[a] The parameter α translates emissions (in million metric tonnes) into concentrations (in parts per billion or trillion 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.

Methane emissions are exogenous, specified at http://www.fund-model.org/. There is a single scenario only, based on IS92a (Leggett et al. 1992). The costs of emission reduction are quadratic. Table A1 specifies the parameters, which are calibrated to (Tol 2006; USEPA 2003).

Nitrous oxide emissions are exogenous, specified at http://www.fund-model.org/. There is a single scenario only, based on IS92a (Leggett et al. 1992). The costs of emission reduction are quadratic. Table A1 specifies the parameters, which are calibrated to (Tol 2006; USEPA 2003).

SF_6 emissions are linear in GDP and GDP per capita. Table A2 gives the parameters. The numbers for 1990 and 1995 are estimated from IEA data (http://data.iea.org/ieastore/product.asp?dept_id=101&pf_id=305). There is no option to reduce SF_6 emissions.

Sulphur dioxide emissions follow grow with population (elasticity 0.33), fall with per capita income (elasticity 0.45), and fall with the sum of energy efficiency improvements and decarbonisation (elasticity 1.02). The parameters are estimated on the IMAGE scenarios (IMAGE Team 2001). There is no option to reduce SO_2 emissions.

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

(A1.11) $$C_t = C_{t-1} + \alpha E_t - \beta\left(C_{t-1} - C_{pre}\right)$$

where ***C*** denotes concentration, ***E*** emissions, ***t*** year, and ***pre*** pre-industrial. Table A3 displays the parameters α and β for all gases. Parameters are taken from (Schimel et al. 1996).

The atmospheric concentration of carbon dioxide follows from a five-box model:

(A1.12a) $$Box_{i,t} = \rho_i Box_{i,t} + 0.000471 \alpha_i E_t$$

with

(A1.12b) $$C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t}$$

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 ρ the decay-rate of the boxes (ρ = exp(-1/lifetime), with life-times infinity, 363, 74, 17 and 2 years, respectively). The model is due to (Maier-Reimer and Hasselmann 1987), its parameters are due to (Hammitt et al. 1992). Thus, 13% of total emissions remains forever in the atmosphere, while 10% is—on average—removed in two years. Carbon dioxide concentrations are measured in parts per million by volume.

There is a feedback from climate change on the amount of carbon dioxide that is stored and emitted by the terrestrial biosphere. Instead of modelling the full dynamics, I keep the uptake by the terrestrial biosphere as it is – that is, Equation (A1.12) is not affected – and add emissions from the terrestrial biosphere, primarily due to forest dieback. Emissions from the terrestrial biosphere follow:

(A1.13a) $$E_t^B = \beta\left(T_t - T_{2000}\right)\frac{B_t}{B_{max}}$$

with

(A1.13b) $$B_t = B_{t-1} - E_{t-1}^B$$

where E^B are emissions (in million metric tonnes of carbon); t denotes time; T is the global mean temperature (in degree Celsius); B_t is the remaining stock of potential emissions (in million metric tonnes of carbon); B_{max} is the total stock of potential emissions; B_{max} = 1,900 gigatonnes of carbon; β is a parameter; β = 2.6 GtC/°C, with a lower and upper bound of 0.6 and 7.5 GtC/°C. The model is calibrated to (Denman et al. 2007).

Radiative forcing is specified as follows:

(A1.14) $$\begin{aligned} RF_t = {} & 5.35\ln\left(\frac{CO_2}{275}\right) + 0.036\left(\sqrt{CH_4} - \sqrt{790}\right) + 0.12\left(\sqrt{N_2O} - \sqrt{285}\right) - \\ & 0.47\ln\left(1 + 2.01\cdot 10^{-5} CH_4^{0.75} 285^{0.75} + 5.31\cdot 10^{-15} CH_4^{2.52} 285^{1.52}\right) + \\ & 0.47\ln\left(1 + 2.01\cdot 10^{-5} 790^{0.75} N_2O^{0.75} + 5.31\cdot 10^{-15} 790^{2.52} N_2O^{1.52}\right) + \\ & 0.00052(SF_6 - 0.04) - 0.03\frac{SO_2}{14.6} - 0.08\frac{\ln\left(1 + SO_2/34.4\right)}{\ln\left(1 + 14.6/34.4\right)} \end{aligned}$$

Parameters are taken from (Forster et al. 2007).

REFERENCES

Acemoglu, D., S.Johnson, and J.A.Robinson (2001), 'The Colonial Origins of Comparative Development: An Empirical Investigation', *American Economic Review*, 91, (4), 1369-1401.

Acemoglu, D., S.Johnson, and J.A.Robinson (2002), 'Reversal of fortune: Geography and institutions in the making of the modern world income distribution', *Quarterly Journal of Economics*, 117, (4), 1231-1294.

Adger, W.N. (2006), 'Vulnerability', *Global Environmental Change*, 16, (3), 268-281.

Alberini, A., A.Chiabai, and L.Muehlenbachs (2006), 'Using Expert Judgement to Assess Adaptive Capacity to Climate Change: Evidence from a Conjoint Choice Survey', *Global Environmental Change*, 16, (2), 123-144.

Anthoff, D., C.J.Hepburn, and R.S.J.Tol (2009), 'Equity weighting and the marginal damage costs of climate change', *Ecological Economics*, 68, (3), pp. 836-849.

Arrow, K.J., R.M.Solow, P.R.Portney, E.E.Leamer, R.Radner, and H.Schuman (1993), 'Report of the NOAA Panel on Contingent Valuation', *Federal Register*, 58, (10), 4016-4064.

Ashley, R.M., D.J.Balmforth, A.J.Saul, and J.D.Blanksby (2005), 'Flooding in the future - Predicting climate change, risks and responses in urban areas', *Water Science and Technology*, 52, (5), 265-273.

Atkinson, G.D., S.Dietz, J.Helgeson, C.J.Hepburn, and H.Saelen (2009), *Siblings, not Triplets: Social Preferences for Risk, Inequality and Time in Discounting Climate Change*, Economics Discussion Papers 2009-14 ,Kiel Institute of the World Economy, Kiel.

Babiker, M.H., G.E.Metcalf, and J.M.Reilly (2003), 'Tax distortions and global climate policy', *Journal of Environmental Economics and Management,* 46, 269-287.

Barker, T., I.Bashmakov, A.Alharthi, M.Amann, L.Cifuentes, J.Drexhage, M.Duan, O.Edenhofer, B.P.Flannery, M.J.Grubb, M.Hoogwijk, F.I.Ibitoye, C.J.Jepma, W.A.Pizer, and K.Yamaji (2007), 'Mitigation from a Cross-Sectoral Perspective', in *Climate Change 2007: Mitigation - Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, B. Metz et al. (eds.), Cambridge University Press, Cambridge, pp. 619-690.

Barker, T., J.Koehler, and M.Villena (2002), 'The Costs of Greenhouse Gas Abatement: A Meta-Analysis of Post-SRES Mitigation Scenarios', *Environmental Economics and Policy Studies,* 5, 135-166.

Berrittella, M., A.Bigano, R.Roson, and R.S.J.Tol (2006), 'A General Equilibrium Analysis of Climate Change Impacts on Tourism', *Tourism Management,* 27, (5), 913-924.

Boehringer, C., T.Hoffmann, and C.Manrique-de-Lara-Penate (2006a), 'The Efficiency Costs of Separating Carbon Markets under the EU Emissions Trading Scheme: A Quantitative Assessment for Germany', *Energy Economics*, 28, (1), 44-61.

Boehringer, C., H.Koschel, and U.Moslener (2008), 'Efficiency Losses from Overlapping Regulation of EU Carbon Emissions', *Journal of Regulatory Economics*, 33, (3), 299-317.

Boehringer, C., A.Loeschel, and T.F.Rutherford (2006b), 'Efficiency Gains from "What"-Flexibility in Climate Policy: An Integrated CGE Assessment', *Energy Journal* (Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue), 405-424.

Bosello, F., R.Roson, and R.S.J.Tol (2006), 'Economy-wide estimates of the implications of climate change: Human health', *Ecological Economics*, 58, (3), 579-591.

Bosello, F., R.Roson, and R.S.J.Tol (2007), 'Economy-Wide Estimates of the Implications of Climate Change: Sea Level Rise', *Environmental and Resource Economics*, 37, (3), 549-571.

Breslow, P.B. and D.J.Sailor (2002), 'Vulnerability of wind power resources to climate change in the continental United States', *Renewable Energy*, 27, (4), 585-598.

Brouwer, R. and F.A.Spaninks (1999), 'The Validity of Environmental Benefits Transfer: Further Empirical Testing', *Environmental and Resource Economics*, 14, (1), 95-117.

Burtraw, D., A.Krupnick, K.Palmer, A.Paul, M.Toman, and C.Bloyd (2003), 'Ancillary benefits of reduced air pollution in the US from moderate greenhouse gas mitigation policies in the electricity sector', *Journal of Environmental Economics and Management,* 45, 650-673.

Butkiewicz, J.L. and H.Yanikkaya (2005), 'The Impact of Sociopolitical Instability on Economic Growth: Analysis and Implications', *Journal of Policy Modeling*, 27, (5), 629-645.

Carmichael, C.G., W.A.Gallus, Jr., B.R.Temeyer, and M.K.Bryden (2004), 'A winter weather index for estimating winter roadway maintenance costs in the Midwest', *Journal of Applied Meteorology*, 43, (11), pp. 1783-1790.

Ceronsky, M., D.Anthoff, C.J.Hepburn, and R.S.J.Tol (2006), *Checking the Price Tag on Catastrophe: The Social Cost of Carbon under Non-linear Climate Response*, Working Paper 87 ,Research unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

Champ, P.A., K.J.Boyle, and T.C.Brown (eds.) (2003), *A Primer on Nonmarket Valuation,* Kluwer Academic Publishers, Dordrecht/Boston/London.

Clarke, L.E., J.P.Weyant, and J.Edmonds (2008), 'On the sources of technological change: What do the models assume', *Energy Economics*, 30, (2), 409-424.

Cline, W.R. (1992), *Global Warming - The Benefits of Emission Abatement*, OECD, Paris.

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

Darwin, R.F. (2004), 'Effects of Greenhouse Gas Emissions on World Agriculture, Food Consumption, and Economic Welfare', *Climatic Change*, 66, (1-2), 191-238.

Darwin, R.F. and R.S.J.Tol (2001), 'Estimates of the Economic Effects of Sea Level Rise', *Environmental and Resource Economics*, 19, (2), 113-129.

Davidson, M.D. (2006), 'A social discount rate for climate damage to future generations based on regulatory law', *Climatic Change*, 76, (1-2), 55-72.

Davidson, M.D. (2008), 'Wrongful Harm to Future Generations: The Case of Climate Change', *Environmental Values*, 17, 471-488.

Dell, M., B.F.Jones, and B.A.Olken (2008), *Climate Change and Economic Growth: Evidence from the Last Half Century*, Working Paper 14132, National Bureau of Economic Research, Washington,DC.

Denman, K.L., G.P.Brasseur, A.Chidthaisong, P.Ciais, P.M.Cox, R.E.Dickinson, D.Hauglustaine, C.Heinze, E.Hollad, D.Jacob, U.Lohmann, S.Ramachandran, P.L.de Silva Dias, S.C.Wofsy, and X.Zhang (2007), 'Couplings Between Changes in the Climate System and Biogeochemistry', in *Climate Change 2007: The Physical Science Basis - Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon et al. (eds.), Cambridge University Press, Cambridge, pp. 499-587.

Dorland, C., R.S.J.Tol, and J.P.Palutikof (1999), 'Vulnerability of the Netherlands and Northwest Europe to Storm Damage under Climate Change', *Climatic Change*, 43, (3), 513-535.

Easterly, W. and R.Levine (2003), 'Tropics, germs, and crops: how endowments influence economic development', *Journal of Monetary Economics*, 50, (1), 3-39.

Fankhauser, S. (1994a), 'Protection vs. Retreat - The Economic Costs of Sea Level Rise', *Environment and Planning A*, 27, 299-319.

Fankhauser, S. (1994b), 'The Economic Costs of Global Warming Damage: A Survey', *Global Environmental Change*, 4, (4), 301-309.

Fankhauser, S. (1995), *Valuing Climate Change - The Economics of the Greenhouse*, 1 edn, EarthScan, London.

Fankhauser, S. and R.S.J.Tol (1996), 'Climate Change Costs - Recent Advancements in the Economic Assessment', *Energy Policy*, 24, (7), 665-673.

Fankhauser, S. and R.S.J.Tol (1997), 'The Social Costs of Climate Change: The IPCC Second Assessment Report and Beyond', *Mitigation and Adaptation Strategies for Global Change*, 1, (4), 385-403.

Fankhauser, S. and R.S.J.Tol (2005), 'On climate change and economic growth', *Resource and Energy Economics*, 27, (1), 1-17.

Fankhauser, S., R.S.J.Tol, and D.W.Pearce (1997), 'The Aggregation of Climate Change Damages: A Welfare Theoretic Approach', *Environmental and Resource Economics*, 10, (3), 249-266.

Fankhauser, S., R.S.J.Tol, and D.W.Pearce (1998), 'Extensions and Alternatives to Climate Change Impact Valuation: On the Critique of IPCC Working Group III's Impact Estimates', *Environment and Development Economics*, 3, 59-81.

Fischer, C. and R.D.Morgenstern (2006), 'Carbon Abatement Costs: Why the Wide Range of Estimates?', *Energy Journal*, 272, 73-86.

Fischer, C., I.W.H.Parry, and W.A.Pizer (2003), 'Instrument choice for environmental protection when technological innovation is endogenous', *Journal of Environmental Economics and Management*, 45, 523-545.

Forster, P., V.Ramaswamy, P.Artaxo, T.K.Berntsen, R.A.Betts, D.W.Fahey, J.Haywood, J.Lean, D.C.Lowe, G.Myhre, J.Nganga, R.Prinn, G.Raga, M.Schulz, and R.van Dorland (2007), 'Changes in Atmospheric Constituents and in Radiative Forcing', in *Climate Change 2007: The Physical Science Basis - Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon et al. (eds.), Cambridge University Press, Cambridge, pp. 129-234.

Gallup, J.L., J.D.Sachs, and A.D.Mellinger (1999), *Geography and Economic Development*, CAER II Discussion Papers 39, Harvard Institute for International Development, Cambridge/USA.

Galor, O. and D.N.Weil (1999), 'From Malthusian Stagnation to Modern Growth', *American Economic Review*, 89, (2), 150-154.

Gillingham, K., R.G.Newell, and W.A.Pizer (2008), 'Modeling endogenous technological change for climate policy analysis', *Energy Economics*, 30, (6), pp. 2734-2753.

Gitay, H., S.Brown, W.E.Easterling, III, B.P.Jallow, J.M.Antle, M.Apps, R.J.Beamish, F.S.Chapin, W.Cramer, J.Frangi, J.K.Laine, E.Lin, J.J.Magnuson, I.R.Noble, J.Price, T.D.Prowse, T.L.Root, E.-D.Schulze, O.D.Sirotenko, B.L.Sohngen, and J.-F.Soussana (2001), 'Ecosystems and their Goods and Services', in *Climate Change 2001: Impacts, Adaptation and Vulnerability - Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J.J. McCarthy et al. (eds.), Cambridge University Press, Cambridge, pp. 235-342.

Goulder, L.H. and K.Mathai (2000), 'Optimal CO_2 Abatement in the Presence of Induced Technological Change', *Journal of Environmental Economics and Management*, 39, 1-38.

Goulder, L.H. and S.H.Schneider (1999), 'Induced technological change and the attractiveness of CO_2 abatement policies', *Resource and Energy Economics*, 21, 211-253.

Haines, A. and C.Fuchs (1991), 'Potential Impacts on Health of Atmospheric Change', *Journal of Public Health Medicine*, 13, (2), 69-80.

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

Harvey, L.D.D. and H.Zhen (1995), 'Evaluation of the potential impact of methane clathrate destabilization on future global warming', *Journal of Geophysical Research*, 100, (D2), 2905-2926.

Hitz, S. and J.B.Smith (2004), 'Estimating global impacts from climate change', *Global Environmental Change*, 14, (3), 201-218.

Hohmeyer, O. and M.Gaertner (1992), *The Costs of Climate Change - A Rough Estimate of Orders of Magnitude*, Fraunhofer-Institut fur Systemtechnik und Innovationsforschung, Karlsruhe.

Hope, C.W. (2006), 'The Marginal Impact of CO2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern', *Integrated Assessment Journal*, 6, (1), 19-56.

Hope, C.W. (2008), 'Optimal Carbon Emissions and the Social Cost of Carbon over Time under Uncertainty', *Integrated Assessment Journal*, 8, (1), 107-122.

Horowith, J.K. and K.E.McConnell (2002), 'A Review of WTA/WTP Studies', *Journal of Environmental Economics and Management*, 44, (3), 426-447.

Hourcade, J.-C., K.Halsneas, M.Jaccard, W.D.Montgomery, R.G.Richels, J.Robinson, P.R.Shukla, and P.Sturm (1996), 'A Review of Mitigation Cost Studies', in *Climate Change 1995: Economic and Social Dimensions - Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, J.P. Bruce, H. Lee, and E.F. Haites (eds.), Cambridge University Press, Cambridge, pp. 297-366.

Hourcade, J.-C., P.R.Shukla, L.Cifuentes, D.Davis, J.A.Edmonds, B.S.Fisher, E.Fortin, A.Golub, O.Hohmeyer, A.Krupnick, S.Kverndokk, R.Loulou, R.G.Richels, H.Segenovic, and K.Yamaji (2001), 'Global, Regional and National Costs and Ancillary Benefits of Mitigation', in *Climate Change 2001: Mitigation - Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, O.R. Davidson and B. Metz (eds.), Cambridge University Press, Cambridge, pp. 499-559.

IMAGE Team (2001), *The IMAGE 2.2 Implementation of the SRES Scenarios: A Comprehensive Analysis of Emissions, Climate Change, and Impacts in the 21st Century*, RIVM CD-ROM Publication 481508018 ,National Institute for Public Health and the Environment, Bilthoven.

Kane, S., J.M.Reilly, and J.Tobey (1992), 'An Empirical Study of the Economic Effects of Climate Change on World Agriculture', *Climatic Change*, 21, (1), 17-35.

Kikkawa, T., J.Kita, and A.Ishimatsu (2004), 'Comparison of the lethal effect of CO2 and acidification on red sea bream (Pagrus major) during the early developmental stages', *Marine Pollution Bulletin*, 48, (1-2), pp. 108-110.

Kjellstrom, T., R.S.Kovats, S.L.Lloyd, M.T.Holt, and R.S.J.Tol (2008), *The Direct Impact of Climate Change on Regional Labour Productivity*, Working Paper 260 ,Economic and Social Research Institute, Dublin.

Kuik, O., L.Brander, and R.S.J.Tol (2009), 'Marginal abatement costs of greenhouse gas emissions: A meta-analysis', *Energy Policy*, 37, (4), pp. 1395-1403.

Kundzewicz, Z.W., D.Graczyk, T.Maurer, I.Pinkswar, M.Radziejeswki, C.Svensson, and M.Szwed (2005), 'Trend detection in river flow series: 1. Annual maximum flow', *Hydrological Sciences Journal*, 50, (5), pp. 797-810.

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

Lindmark, M. (2002), 'An EKC-Pattern in Historical Perspective: Carbon Dioxide Emissions, Technology, Fuel Prices and Growth in Sweden 1870-1997', *Ecological Economics*, 42, 333-347.

Link, P.M. and R.S.J.Tol (2004), 'Possible economic impacts of a shutdown of the thermohaline circulation: an application of FUND', *Portuguese Economic Journal*, 3, (2), 99-114.

Long, S.P., E.A.Ainsworth, A.D.B.Leakey, J.Noesberger, and D.R.Ort (2006), 'Food for Thought: Lower-than-Expected Crop Yield Stimulation with Rising CO2 Concentrations', *Science*, 312, (5811), 1918-1921.

Maddison, D.J. (2003), 'The amenity value of the climate: the household production function approach', *Resource and Energy Economics*, 25, (2), 155-175.

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

Manne, A.S. and R.G.Richels (1998), 'On Stabilizing CO_2 Concentrations - Cost-Effective Emission Reduction Strategies', *Environmental Modeling and Assessment*, 2, 251-265.

Manne, A.S. and R.G.Richels (2001), 'An alternative approach to establishing trade-offs among greenhouse gases', *Nature*, 410, 675-677.

Manne, A.S. and R.G.Richels (2004), 'US Rejection of the Kyoto Protocol: The Impact on Compliance Costs and CO_2 Emissions', *Energy Policy*, 32, 447-454.

Marotzke, J. (2000), 'Abrupt climate change and thermohaline circulation: Mechanisms and predictability', *Proceedings of the National Academy of Science*, 97, (4), 1347-1350.

Masters, W.A. and M.S.McMillan (2001), 'Climate and Scale in Economic Growth', *Journal of Economic Growth*, 6, (3), 167-186.

McDonald, R.E., D.G.Bleaken, D.R.Cresswell, V.D.Pope, and C.A.Senior (2005), 'Tropical storms: Representation and diagnosis in climate models and the impacts of climate change', *Climate Dynamics*, 25, (1), pp. 19-36.

Mendelsohn, R.O., W.N.Morrison, M.E.Schlesinger, and N.G.Andronova (2000a), 'Country-specific market impacts of climate change', *Climatic Change*, 45, (3-4), 553-569.

Mendelsohn, R.O., W.D.Nordhaus, and D.Shaw (1994), 'The Impact of Climate on Agriculture: A Ricardian Analysis', *American Economic Review*, 84, (4), 753-771.

Mendelsohn, R.O., M.E.Schlesinger, and L.J.Williams (2000b), 'Comparing Impacts across Climate Models', *Integrated Assessment*, 1, (1), 37-48.

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

Narita, D., D.Anthoff, and R.S.J.Tol (2008), *Damage Costs of Climate Change through Intensification of Tropical Cyclone Activities: An Application of FUND*, Working Paper 259 ,Economic and Social Research Institute, Dublin.

Narita, D., D.Anthoff, and R.S.J.Tol (2009), *Economic Costs of Extratropical Storms under Climate Change: An Application of FUND*, Working Paper 274 ,Economic and Social Research Institute, Dublin.

Nicholls, R.J. and R.S.J.Tol (2006), 'Impacts and Responses to Sea Level Rise: A Global Analysis of the SRES Scenarios over the Twenty-First Scenario', *Philosophical Transactions of the Royal Society A*, 364, (1849), 1073-1095.

Nicholls, R.J., R.S.J.Tol, and A.T.Vafeidis (2008), 'Global estimates of the impact of a collapse of the West Antarctic ice sheet: An application of FUND', *Climatic Change*, 91, (1-2), pp. 171-191.

Nordhaus, W.D. (1991), 'To Slow or Not to Slow: The Economics of the Greenhouse Effect', *Economic Journal*, 101, (444), 920-937.

Nordhaus, W.D. (1993), 'Rolling the 'DICE': An Optimal Transition Path for Controlling Greenhouse Gases', *Resource and Energy Economics*, 15, (1), 27-50.

Nordhaus, W.D. (1994), 'Expert Opinion on Climate Change', *American Scientist*, 82, (1), 45-51.

Nordhaus, W.D. (1994), *Managing the Global Commons: The Economics of Climate Change* The MIT Press, Cambridge.

Nordhaus, W.D. (2006), 'Geography and Macroeconomics: New Data and New Findings', *Proceedings of the National Academy of Science*, 103, (10), 3510-3517.

Nordhaus, W.D. and J.G.Boyer (2000), *Warming the World: Economic Models of Global Warming* The MIT Press, Cambridge, Massachusetts - London, England.

Nordhaus, W.D. and Z.Yang (1996), 'RICE: A Regional Dynamic General Equilibrium Model of Optimal Climate-Change Policy', *American Economic Review*, 86, (4), 741-765.

O'Brien, K.L., L.Sygna, and J.E.Haugen (2004), 'Vulnerable or Resilient? A Multi-scale Assessment of Climate Impacts and Vulnerability in Norway', *Climatic Change*, 64, (1-2), 193-225.

Olsthoorn, A.A., P.E.van der Werff, L.M.Bouwer, and D.Huitema (2008), 'Neo-Atlantis: The Netherlands under a 5-m sea level rise', *Climatic Change*, 91, (1-2), pp. 103-122.

Paavola, J. and W.N.Adger (2006), 'Fair Adaptation to Climate Change', *Ecological Economics*, 56, (4), 594-609.

Parry, M.L. (1990), *Climate Change and World Agriculture* EarthScan, London.

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

Pizer, W.A. (1997), *Prices vs. Quantities Revisited: The Case of Climate Change*, Discussion Paper 98-02 ,Resources for the Future, Washington,D.C.

Plamberk, E.L. and C.W.Hope (1996), 'PAGE95 - An Updated Valuation of the Impacts of Global Warming', *Energy Policy*, 24, (9), 783-793.

Pratt, J.W., H.Raiffa, and R.Schlaifer (1995), *Introduction to Statistical Decision Theory*, 1 edn, The MIT Press, Cambridge.

Ramsey, F. (1928), 'A Mathematical Theory of Saving', *Economic Journal*, 38, 543-549.

Rehdanz, K. and D.J.Maddison (2005), 'Climate and happiness', *Ecological Economics*, 52, (1), 111-125.

Reilly, J.M., M.Sarofim, S.Paltsev, and R.Prinn (2006), 'The Role of Non-CO2 GHGs in Climate Policy: Analysis Using the MIT IGSM', *Energy Journal* (Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue), 503-520.

Repetto, R. and D.Austin (1997), *The Costs of Climate Protection: A Guide for the Perplexed* ,World Resources Institute, Washington, D.C.

Saelen, H., G.D.Atkinson, S.Dietz, J.Helgeson, and C.J.Hepburn (2008), *Risk, Inequality and Time in the Welfare Economics of Climate Change: Is the Workhorse Model Underspecified?*, Discussion Paper 400 ,Department of Economics, Oxford University, Oxford.

Schaefer, A. and H.D.Jacoby (2005), 'Technology Detail in a Multisector CGE Model: Transport under Climate Policy', *Energy Economics*, 27, (1), 1-24.

Schaefer, A. and H.D.Jacoby (2006), 'Vehicle Technology under CO2 Constraint: A General Equilibrium Analysis', *Energy Policy*, 34, (9), 975-985.

Schelling, T.C. (2000), 'Intergenerational and International Discounting', *Risk Analysis*, 20, (6), 833-837.

Schimel, D., D.Alves, I.Enting, M.Heimann, F.Joos, M.Raynaud, R.Derwent, D.Ehhalt, P.Fraser, E.Sanhueza, X.Zhou, P.Jonas, R.Charlson, H.Rodhe, S.Sadasivan, K.P.Shine, Y.Fouquart, V.Ramaswamy, S.Solomon, J.Srinivasan, D.L.Albritton, I.S.A.Isaksen, M.Lal, and D.J.Wuebbles (1996), 'Radiative Forcing of Climate Change', in *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, J.T. Houghton et al. (eds.), Cambridge University Press, Cambridge, pp. 65-131.

Schneider, S.H. and R.S.Chen (1980), 'Carbon dioxide warming and coastline flooding: physical factors and climatic impact', *Annual Review of Energy*, 5, pp. 107-140.

Smit, B. and J.Wandel (2006), 'Adaptation, Adaptive Capacity and Vulnerability', *Global Environmental Change*, 16, (3), 282-292.

Smith, J.B. (1996), 'Standardized Estimates of Climate Change Damages for the United States', *Climatic Change*, 32, (3), 313-326.

Smith, J.B., H.-J.Schellnhuber, M.Q.Mirza, S.Fankhauser, R.Leemans, L.Erda, L.Ogallo, A.B.Pittock, R.G.Richels, C.Rosenzweig, U.Safriel, R.S.J.Tol, J.P.Weyant, and G.W.Yohe (2001), 'Vulnerability to Climate Change and Reasons for Concern: A Synthesis', in *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, J.J. McCarthy et al. (eds.), Press Syndicate of the University of Cambridge, Cambridge, UK, pp. 913-967.

Svensson, C., Z.W.Kundzewicz, and T.Maurer (2005), 'Trend detection in river flow series: 2. Flood and low-flow index series', *Hydrological Sciences Journal*, 50, (5), pp. 811-824.

Szolnoky, C., K.Buzas, and A.Clement (1997), 'Impacts of the climate change on the operation of a freshwater cooled electric power plant', *Periodica Polytechnica: Civil Engineering*, 41, (2), pp. 71-94.

Titus, J.G. (1992), 'The Costs of Climate Change to the United States', in *Global Climate Change: Implications, Challenges and Mitigation Measures*, S.K. Majumdar et al. (eds.), Pennsylvania Academy of Science, Easton, pp. 384-409.

Tol, R.S.J., S.W.Pacala, and R.H.Socolow (2009), 'Understanding Long-Term Energy Use and Carbon Dioxide Emissions in the USA', *Journal of Policy Modeling*, 31, (3), pp. 425-445.

Tol, R.S.J. (1995), 'The Damage Costs of Climate Change Toward More Comprehensive Calculations', *Environmental and Resource Economics*, 5, (4), 353-374.

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

Tol, R.S.J. (2002a), 'Estimates of the Damage Costs of Climate Change - Part 1: Benchmark Estimates', *Environmental and Resource Economics*, 21, (1), 47-73.

Tol, R.S.J. (2002b), 'Estimates of the Damage Costs of Climate Change - Part II: Dynamic Estimates', *Environmental and Resource Economics*, 21, (2), 135-160.

Tol, R.S.J. (2003), 'Is the uncertainty about climate change too large for expected cost-benefit analysis?', *Climatic Change*, 56, (3), 265-289.

Tol, R.S.J. (2005a), 'An Emission Intensity Protocol for Climate Change: An Application of FUND', *Climate Policy*, 4, 269-287.

Tol, R.S.J. (2005b), 'Emission Abatement versus Development as Strategies to Reduce Vulnerability to Climate Change: An Application of FUND', *Environment and Development Economics*, 10, (5), 615-629.

Tol, R.S.J. (2006), 'Multi-Gas Emission Reduction for Climate Change Policy: An Application of FUND', *Energy Journal* (Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue), 235-250.

Tol, R.S.J. (2008a), 'Climate, development and malaria: An application of FUND', *Climatic Change*, 88, (1), 21-34.

Tol, R.S.J. (2008b), 'The Social Cost of Carbon: Trends, Outliers and Catastrophes', *Economics - the Open-Access, Open-Assessment E-Journal*, 2, (25), 1-24.

Tol, R.S.J. (2008c), 'Why Worry About Climate Change? A Research Agenda', *Environmental Values*, 17, (4), 437-470.

Tol, R.S.J. (2009), 'Why Worry About Climate Change?', *Research Bulletin*, 09, (1), 2-7.

Tol, R.S.J. and H.Dowlatabadi (2001), 'Vector-borne diseases, development & climate change', *Integrated Assessment*, 2, (4), 173-181.

Tol, R.S.J., K.L.Ebi, and G.W.Yohe (2007), 'Infectious Disease, Development, and Climate Change: A Scenario Analysis', *Environment and Development Economics*, 12, 687-706.

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

Tol, R.S.J. and S.Wagner (2008), *Climate Change and Violent Conflict in Europe over the Last Millennium*, Working Paper 154 ,Research unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

Tol, R.S.J. and G.W.Yohe (2006), 'Of Dangerous Climate Change and Dangerous Emission Reduction', in *Avoiding Dangerous Climate Change*, H.-J. Schellnhuber et al. (eds.), Cambridge University Press, Cambridge, pp. 291-298.

Tol, R.S.J. and G.W.Yohe (2007a), 'Infinite Uncertainty, Forgotten Feedbacks, and Cost-Benefit Analysis of Climate Change', *Climatic Change*, 83, (4), 429-442.

Tol, R.S.J. and G.W.Yohe (2007b), 'The Weakest Link Hypothesis for Adaptive Capacity: An Empirical Test', *Global Environmental Change*, 17, (2), 218-227.

USEPA (2003), *International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21* ,United States Environmental Protection Agency, Washington, D.C.

van Kooten, G.C. (2004), *Climate Change Economics - Why International Accords Fail* Edward Elgar, Cheltenham, UK - Northampton, MA, USA.

Vaughan, D.G. (2008), 'West Antarctic Ice Sheet collapse - The fall and rise of a paradigm', *Climatic Change*, 91, (1-2), pp. 65-79.

Vaughan, D.G. and J.R.Spouge (2002), 'Risk estimation of collapse of the West Antarctic Sheet', *Climatic Change*, 52, (1-2), 65-91.

Weitzman, M.L. (1974), 'Prices vs. Quantities', *Review of Economic Studies*, 41, (4), 477-491.

Weitzman, M.L. (2009), 'On Modelling and Interpreting the Economics of Catastrophic Climate Change', *Review of Economics and Statistics*, 91, (1), 1-19.

Weyant, J.P. (1993), 'Costs of Reducing Global Carbon Emissions', *Journal of Economic Perspectives*, 7, (4), 27-46.

Weyant, J.P. (1998), 'The Costs of Greenhouse Gas Abatement', in *Economics and Policy Issues in Climate Change*, W.D. Nordhaus (ed.), Resources for the Future, Washington, D.C., pp. 191-214.

Weyant, J.P. (2004), 'Introduction and overview', *Energy Economics*, 26, 501-515.

Weyant, J.P., F.C.de la Chesnaye, and G.J.Blanford (2006), 'Overview of EMF-21: Multigas Mitigation and Climate Policy', *Energy Journal* (Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue), 1-32.

Weyant, J.P. and J.N.Hill (1999), 'Introduction and Overview of the Special Issue', *Energy Journal Special Issue on the Costs of the Kyoto Protocol: A Multi-Model Evaluation*, vii-xliv.

Wigley, T.M.L., R.G.Richels, and J.A.Edmonds (1996), 'Economic and Environmental Choices in the Stabilization of Atmospheric CO2 Concentrations', *Nature*, 379, 240-243.

Wilson, K.J., J.Falkingham, H.Melling, and R.A.de Abreu (2004), 'Shipping in the Canadian Arctic: Other possible climate change scenarios', *International Geoscience and Remote Sensing Symposium*, 3, 1853-1856.

Yates, D.N. and K.M.Strzepek (1998), 'An Assessment of Integrated Climate Change Impacts on the Agricultural Economy of Egypt', *Climatic Change*, 38, (3), 261-287.

Yohe, G.W. and M.E.Schlesinger (2002), 'The economic geography of the impacts of climate change', *Journal of Economic Geography*, 2, (3), 311-341.

Yohe, G.W. and R.S.J.Tol (2002), 'Indicators for Social and Economic Coping Capacity - Moving Towards a Working Definition of Adaptive Capacity', *Global Environmental Change*, 12, (1), 25-40.

Zhang, D.D., C.Y.Jim, G.C.S.Lin, Y.-Q.He, J.J.Wang, and H.F.Lee (2006), 'Climatic Change, Wars and Dynastic Cycles in China over the Last Millennium', *Climatic Change*, 76, 459-477.

Zhang, D.D., J.Zhang, H.F.Lee, and Y.-Q.He (2007), 'Climate Change and War Frequency in Eastern China over the Last Millennium', *Human Ecology*, 35, (4), 403-414.

COPENHAGEN CONSENSUS ON CLIMATE

The science is clear. Human-caused global warming is a problem that we must confront.

But which response to global warming will be best for the planet? The Copenhagen Consensus Center believes that it is vital to hold a global discussion on this topic.

The world turned to scientists to tell us about the problem of global warming. Now, we need to ensure that we have a solid scientific foundation when we choose global warming's solution. That is why the Copenhagen Consensus Center has commissioned research papers from specialist climate economists, outlining the costs and benefits of each way to respond to global warming.

It is the Copenhagen Consensus Center's view that the best solution to global warming will be the one that achieves the most 'good' for the lowest cost. To identify this solution and to further advance debate, the Copenhagen Consensus Center has assembled an Expert Panel of five world-class economists – including three recipients of the Nobel Prize –to deliberate on which solution to climate change would be most effective.

It is the Copenhagen Consensus Center's hope that this research will help provide a foundation for an informed debate about the best way to respond to this threat.

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