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The Economic Effects of Climate Change

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Greenhouse gas emissions are fundamental both to the world's energy system and to its food production. The production of CO_2, the predominant gas implicated in climate change, is intrinsic to fossil fuel combustion; specifically, thermal energy is generated by breaking the chemical bonds in the carbohydrates oil, coal, and natural gas and oxidizing the components to CO_2 and H_2O. One cannot have cheap energy without carbon dioxide emissions. Similarly, methane (CH_4) emissions, an important greenhouse gas in its own right, are necessary to prevent the build-up of hydrogen in anaerobic digestion and decomposition. One cannot have beef, mutton, dairy, or rice without methane emissions.

Climate change is the mother of all externalities: larger, more complex, and more uncertain than any other environmental problem. The sources of greenhouse gas emissions are more diffuse than any other environmental problem. Every company, every farm, every household emits some greenhouse gases. The effects are similarly pervasive. Weather affects agriculture, energy use, health, and many aspects of nature—which in turn affects everything and everyone. The causes and consequences of climate change are very diverse, and those in low-income countries who contribute least to climate change are most vulnerable to its effects. Climate change is also a long-term problem. Some greenhouse gases have an atmospheric life-time measured in tens of thousands of years. The quantities of emissions involved are enormous. In 2000, carbon dioxide emissions alone (and excluding land use change) were 24 billion metric tons of carbon dioxide (tCO_2).

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If all emissions were priced at the January 2009 price of €15/tCO_2, that applied in the Emissions Trading System of the European Union, carbon dioxide would be worth 1.5 percent of world income. Finally, the uncertainties about climate change are vast—indeed, so vast that the standard tools of decision making under uncertainty and learning may not be applicable.[1]

In this essay, I begin with a review of the estimates of the total economic effects of climate change. I then focus on marginal cost estimates, which are especially important for economists thinking about policy design. I will also discuss many of the large gaps in current research on this topic. After the last two decades or so of study, I am reasonably confident that we know the scope of the research agenda in this area. For some economic effects of climate change, we have reasonable estimates; for others, we know at least an order of magnitude. We also have a clear idea of the sensitivities of these estimates to particular assumptions, even though in some cases we do not really know what to assume. Research in this area has reached the point that we can now identify our areas of ignorance; I believe that there are no more unknown unknowns, or at least no sizeable ones. But my belief here may suffer from overconfidence. In a survey article I co-authored more than a decade ago on the social costs of climate change, we suggested that all aspects of the problem were roughly known, and that research would be complete within a few years (Pearce et al., 1996). This view turned out to be so overoptimistic as to be entirely mistaken.

Estimates of the Total Economic Effect of Climate Change

Methodologies

The first studies of the welfare effects of climate change were done for the United States by Cline (1992), Nordhaus (1991), and Titus (1992; see also Smith, 1996). Although Nordhaus (1991; see also Ayres and Walter, 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 effects of climate change goes to Fankhauser (1994, 1995). Table 1 lists that study and a dozen other studies of the worldwide effects of climate change that have followed. The studies can be roughly divided into two groups: Nordhaus and Mendelsohn are colleagues and collaborators at Yale University; at University College of London, Fankhauser, Maddison, and I all worked with David Pearce and one another, while Rehdanz was a student of Maddison and mine.

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

[1] As one example, climate change affects human mortality and migration. The size of the population is therefore endogenous to the decision on emission abatement. See Blackorby and Donaldson (1984).

Table 1
Estimates of the Welfare Impact of Climate Change
(expressed as an equivalent income gain or loss in percent GDP)

			Worst-off region		*Best-off region*	
Study	*Warming (°C)*	*Impact (% of GDP)*	*(% of GDP)*	*(Name)*	*(% of GDP)*	*(Name)*
Nordhaus (1994a)	3.0	−1.3				
Nordhaus (1994b)	3.0	−4.8 (−30.0 to 0.0)				
Fankhauser (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
Plambeck 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, Schlesinger, and Williams (2000)[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 and Boyer (2000)	2.5	−1.5	−3.9	Africa	0.7	Russia
Tol (2002)	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)				

Note: Where available, estimates of the uncertainty are given in parentheses, either as standard deviations or as 95 percent confidence intervals.
[a] 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] Mendelsohn et al. only include market impacts.
[d] The national results were aggregated to regions by the current author for reasons of comparability.
[e] Maddison only considers market impacts on households.
[f] The numbers used by Hope (2006) are averages of previous estimates by Fankhauser and Tol; Stern et al. (2006) adopt the work of Hope (2006).

storminess. The studies must then translate from climate change to economic consequences. A range of methodological approaches is possible here.

Nordhaus (1994b) interviewed a limited number of experts.

The studies by Fankhauser (1994, 1995), Nordhaus (1994a), and me (Tol, 1995, 2002a, b) 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 agricultural products, an example of a traded good or service, agronomy papers are used to predict the effect of climate on crop yield, and then market prices or economic models are used to value the change in output. As another example, the effect of sea level rise is composed of additional coastal protection and land lost, estimates of which can be found in the engineering literature; the economic input in this case then includes not only the cost of dike-building and the value of land, but also the decisions about which properties to protect. For nonmarket goods and services, such as health, 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 monetization of nonmarket climate change effects 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 contexts other than climate change.

An alternative approach, exemplified in Mendelsohn's work (Mendelsohn, Morrison, Schlesinger, and Andronova, 2000; Mendelsohn, Schlesinger, and Williams, 2000) 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 effect of climate change. Mendelsohn's estimates are done per sector for selected countries, extrapolated to other countries, and then added up, but physical modeling is avoided. Studies by Nordhaus (2006) and Maddison (2003) 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 (2003) 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 in response to both market and nonmarket events.

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, modeled. 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 effects of sea level rise and carbon dioxide fertilization, do not have much spatial variation.

Findings and Implications

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 twenty-first century. However, the studies in Table 1 are comparative static—and thus they effectively 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 effect on welfare at that future time, usually expressed as a percentage of income. For instance, Nordhaus (1994a) estimates that the effect of 3°C global warming is as bad as losing 1.3 percent 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 do not report any estimate of the uncertainty. The rest of Table 1 illustrates differential effects around the world. The third column shows the percentage change 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 green-

house 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 twenty-first century. For comparison, the European Union calls for 20–30 percent emission reduction (relative to 2005) by 2020.

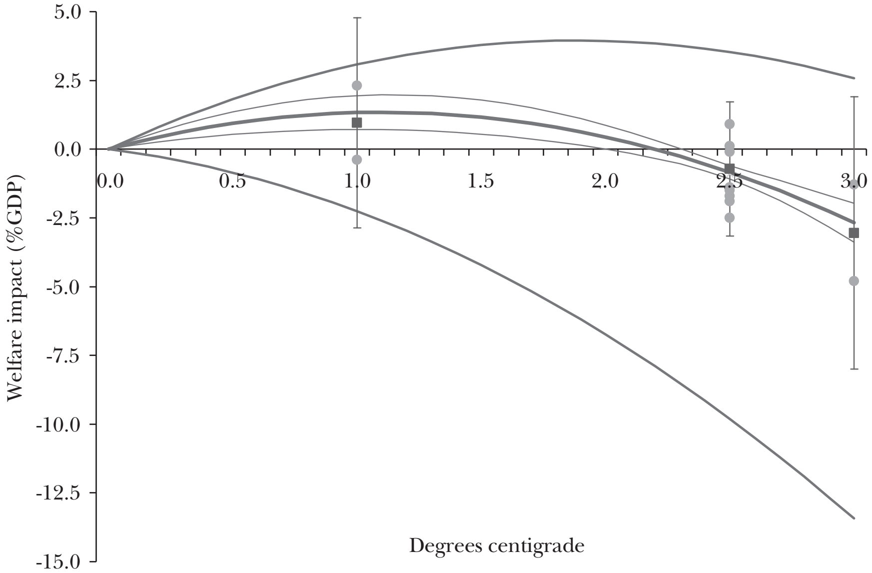
A second finding is that some estimates, by Hope (2006), Mendelsohn, Morrison, Schlesinger, and Andronov (2000), Mendelsohn, Schlesinger, and Williams (2000), and myself (Tol, 2002b), point to initial *benefits* of a modest increase in temperature, followed by losses as temperatures increase further. Figure 1 illustrates the pattern. There are no estimates for a warming above 3°C, although climate change may well go beyond that (as discussed 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.

The horizontal axis of Figure 1 shows the increase in average global temperature. The vertical index shows the central estimate of welfare impact. 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, Morrison, Schlesinger, and Andronova, 2000; Mendelsohn, Schlesinger, and Williams, 2000; Nordhaus and Boyer, 2000; Tol, 2002b; also, compare Figure 19-4 in Smith et al., 2001).

The initial benefits arise partly because more carbon dioxide in the atmosphere reduces "water stress" in plants and may make them grow faster (Long, Ainsworth, Leakey, Noesberger, and Ort, 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, 2002b; Tol, Fankhauser, Richels, and Smith, 2000). In short, even though total economic

Figure 1
Fourteen Estimates of the Global Economic Impact of Climate Change



Note: Figure 1 shows 14 estimates of the global economic impact of climate change, expressed as the welfare-equivalent income gain or loss, as a function of the increase in global mean temperature relative to today. The circular dots represent the estimates (from Table 1). The 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 heavier 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 inner two lines are the 95 percent confidence interval for the central line re-estimated with one observation dropped. The thick outer two lines are the 95 percent confidence interval, where the standard deviation is the least squares fit to the five reported standard deviations or half-confidence intervals (again, compare with 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.

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 (see also Yohe and Schlesinger, 2002). Indeed, impact estimates for sub-Saharan Africa go up to a welfare loss equivalent to a quarter of income (as shown in Table 1). The estimates for low-income countries 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, Chiabai, and Meuhlenbachs,

2006; Smit and Wandel, 2006; Tol, 2008b; 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 pattern holds 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 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, in Tol and Dowlatabadi (2001) and Tol and Yohe (2006), my coauthors and I argue that the economic growth foregone by stringent abatement of greenhouse gases would more than offset the avoided effects of climate change, at least in the case of malaria. Similarly, in Tol (2005), I show 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, Sygna, Haugen (2004) being one of the few exceptions—climate change effects would not be homogeneous within countries; certainly, particular economic sectors (like agriculture), regions (like coastal zones), and age groups (like 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 become less negative 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 effects 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, Nordhaus, and Shaw (1994)—include some provision for agents to alter their behavior 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 2.5°C. 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 for the 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 hints at a rough degree of 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. However, these 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 each time. 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 short, 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.

Improving Future Estimates

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.[2]

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 effect of climate change on agriculture by Mendelsohn, Nordhaus, and Shaw (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 effects may be large (as discussed below). The uncertainties of the estimates are largely unknown. These problems are gradually being addressed, but progress is slow. The list of warnings given here is similar to those in papers I've written with Fankhauser (Fankhauser and Tol, 1996, 1997).

A deeper conceptual issue arises with putting value on environmental services. Empirical studies have shown that the willingness to pay for improved environmental services may be substantially lower than the willingness to accept compensation for diminished environmental services (for example, Horowitz and McConnell, 2002). The difference between willingness to pay and willingness to accept compensation goes beyond income effects and may even hint at loss aversion and agency effects, particularly when involving issues of 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

[2] General equilibrium studies of the effect of climate change on agriculture have a long history (Kane, Reilly, and Tobey, 1992; Darwin, 2004). These papers show that markets matter, and may even reverse the sign of the initial impact estimate (Yates and Strzepek, 1998). In Bosello, Roson, and Tol (2007) and Darwin and Tol (2001), my coauthors and I 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, in Bosello, Rosen, and Tol (2006), we show that the direct costs are biased towards zero for health, that is, direct benefits and costs are smaller in absolute value than benefits and costs estimated by a general equilibrium model. This is because countries that would see their labor productivity fall (rise) because of climate change would also lose (gain) competitiveness, so that trade effects amplify the initial impact. In Berrittella, Bigano, Roson, and Tol (2006), my coauthors and I also emphasize the redistribution of impacts on tourism through markets.

pay as the basis for valuation of environmental services, as recommended by Arrow, Solow, Portney, Leamer, Radner, and Schuman (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 climate?" This question is a different one, and the answer would be different if future generations are loss averse or distinguish between self-imposed and other-imposed risks. The current generation does, and the willingness to accept compensation tends to be higher than the willingness to pay. Consequently, the marginal avoided compensation would be larger than the marginal benefit, so the tax on greenhouse gas emission would be higher.

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 includes 13 studies and 14 estimates; in contrast, in Tol (2008a), I report 47 studies with 211 estimates of the marginal damage cost, and more have been published since then, including Hope (2008a, b), Nordhaus (2008), and Stern and Taylor (2007). However, it is not always recognized that marginal damage cost estimates are derived from total cost estimates. Some of the total cost estimates—including Maddison (2003), Mendelsohn, Morrison, Schlesinger, and Andronova (2000), Mendelson, Schlesinger, and Williams (2000), Nordhaus (2006), and 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 effect 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 more than 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 are 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[3]; some more recent studies have also analyzed variants of hyperbolic discounting, where the rate of discount falls over time.

Moreover, 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 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, Nordhaus's (1991) estimate of the total welfare loss of a 3.0°C warming is 1.3 percent of GDP. To derive a marginal damage cost estimate from this, you would need to assume when, in the future, warming of 3.0°C would occur and whether damages are linear or quadratic or some other function of temperature (and precipitation and other factors). Then, the future stream of incremental damages due to today's emissions would need 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 monetized 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, Hepburn, and Tol, 2009; Fankhauser, Tol, and Pearce, 1997).

Table 2 shows some characteristics of a meta-analysis of the published estimates of the social cost of carbon. The first set of columns 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, forthcoming). Because there are many estimates of the social cost of carbon, a

[3] 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 (Ramsey) discount rate, 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. All climate policy analyses that I am aware of use the same numerical value for risk aversion, consumption smoothing over time, domestic inequity aversion, and international aversion, although these four issues are conceptually distinct (as discussed in Saelen, Atkinson, Dietz, Helgeson, and Hepburn, 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.

Table 2
The Social Cost of Carbon
(measured in $/tC)

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

Note: Numbers in the table show the social cost of carbon measured in 1995 dollars per metric ton of carbon ($/tC). Estimates are based on 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.

probability density function can be constructed in a reasonably objective way. (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 I used in Tol (2008a).[4] The results are shown in the second set of columns in Table 2, labeled "Fitted distribution."

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 ton 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

[4] 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, forthcoming). 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⟩.

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. For the sample and fitted distribution statistics (first and second set of columns in Table 2), the studies have been divided up into three subsamples based on the pure rate of time preference used in the study (0, 1, or 3 percent). 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 0 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.[5] Table 2 shows that the estimates for the whole sample are dominated by the estimates based on lower discount rates.

The sample and distribution characteristics of Table 2 also allow us to identify outliers. On the low side, my results (Tol, 2005) stand out with a social cost of carbon of −\$6.6/tC for a 3 percent pure rate of time preference and \$19.9/tC for a 0 percent rate. The reason is that my model was the first of those used for marginal cost estimation that showed initial benefits from climate change. In my later work, the early benefits are less pronounced. On the high side, the results of Ceronsky, Anthoff, Hepburn, and Tol (2006) stand out, with a social cost estimate of \$2400/tC for a 0 percent pure rate of time preference and \$120/tC for a 3 percent 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 percent pure rate of time preference, the \$815/tC estimate of Hope (2008a) 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 percent as well.

Although Table 2 reveals a large estimated uncertainty about the social cost of carbon, the actual uncertainty may well be 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

[5] Some readers may wonder why the estimates with a discount rate of 0 percent don't look all that substantially higher than the estimates with a discount rate of 1 percent. 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 0 percent discount rate would be more substantial. For the record, there is even one estimate (Hohmeyer and Gartner, 1992) based on a 0 percent consumption discount rate (as discussed in Davidson, 2006) and thus a *negative* pure rate of time preference.

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 ton 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 remain very expensive (Schaefer and Jacoby, 2005, 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.

Missing Effects

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 effects, 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, Buzas, and Clement, 1997). Redesigning urban water management systems, be it for more or less water, would be costly (Ashley, Balmford, Saul, and Blanksby, 2005), as would implementing safeguards against increased uncertainty about future circumstances. Extratropical storms may increase, leading to greater damage and higher building standards (Dorland, Tol, and Palutikof, 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, Bleaken, Cresswell, Pope, and Senior, 2005). Ocean acidification may harm fisheries (Kikkawa, Kita, and Ishimatsu, 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 harbors, 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, Falkingham, Melling, and de Abreu, 2004). Warmer weather would reduce expenditures on clothing and food, and traffic disruptions due to snow and ice (Carmicheal, Gallus, Temeyer, and Bryden, 2004).

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

These relatively 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 change could 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 and Spouge, 2002), which would lead to a 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 Huang, 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. In Nicholls, Tol, and Vafeidis (2008), my coauthors and I find that the effects of sea level rise would increase ten-fold should the West Antarctic Ice Sheet collapse. But the work of Olsthoorn, van der Werff, Bouwer, and Huitema (2008) suggests that this may be too optimistic; that we may have overestimated the speed with which coastal protection can be built up. In Link and Tol (2004), my coauthor and I estimate the effects of a shutdown of the thermohaline circulation. We 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 (as suggested by 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, or 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 effects grow faster than the discount rate—because of the large uncertainty, this outcome 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 these issues. 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, Boyle, and Brown, 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 the 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 (Gallup, Sachs, and Mellinger, 1999; Acemoglu, Johnson, and Robinson, 2001; Masters and McMillan, 2001; van Kooten, 2004; Nordhaus, 2006), although others would argue that institutions are more important than geography (Acemoglu, Johnson, and Robinson, 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. In Fankhauser and Tol (2005), my coauthor and I argue that only very extreme parameter choices would imply such a scenario. In contrast, Dell, Jones, and Olken (2008) find that climate change would slow the *annual* growth rate of poor countries by 0.6 to 2.9 percentage 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 diarrhea, in a way that affects long-term economic growth (for example, via a mechanism as in Galor and Weil, 1999); or in which climate-change-induced resource scarcity intensifies violent conflict (Zhang, Zhang, Lee, and He, 2007; Tol and Wagner, 2008) 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 effects, but Kjellstrom, Kovats, Lloyd, Holt, and Tol (2008) show that it may well be substantial.

The missing effects further emphasize that climate change may spring nasty surprises. Such risks justify greenhouse gas emission reduction beyond that recommended by a cost–benefit analysis under quantified risk. The size of the appropriate "uncertainty premium" is in some sense 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). More recent research has dispelled these fears.

Conclusion

The quantity and intensity of the research effort on the economic effects of climate change seems incommensurate with the perceived size of the climate problem, the expected costs of the solution, and the size of the existing research gaps. Politicians are proposing to spend hundreds of billions of dollars on greenhouse gas emission reduction, and at present, economists cannot say with confidence whether this investment is too much or too little.

The best available knowledge—which is not very good—is given in Table 2. A government that uses the same 3 percent discount rate for climate change as for other decisions should levy a carbon tax of $25 per metric ton of carbon (modal value) to $50/tC (mean value). A higher tax can be justified by an appeal to the high level of risk, especially of very negative outcomes, not captured in the standard estimates (Weitzman, forthcoming). The price of carbon dioxide emission permits in the European Union was $78/tC in January 2009. The United States has no federal policy specifically to reduce carbon emissions, although many utilities apparently factor in the likelihood of a carbon tax of $15/tC in their investment decisions (Richels, personal communication). This pattern suggests that the European Union may be placing too high a price on carbon emissions, while the United States is placing too low a price on such emissions. Outside the high-income countries of the world, essentially no climate policy exists—although these countries are most vulnerable to climate change, and some of them like China and India are major emitters of carbon. Many of these countries subsidize fossil fuel use, rather than taxing it.

There is a strong case for near-term action on climate change, although prudence may dictate phasing in a higher cost of carbon over time, both to ease the transition and to give analysts the ongoing ability to evaluate costs, benefits, and policy mechanisms.

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