Open access • Journal Article • DOI:10.1111/J.1468-2516.2010.00326.X

The Economic Impact of Climate Change — Source link

Richard S.J. Tol

Institutions: Economic and Social Research Institute

Published on: 01 May 2010 - Perspektiven Der Wirtschaftspolitik (Economic and Social Research Institute)

Topics: Climate change, Economic impact analysis and Greenhouse gas

Tol, Richard S. J.

Working Paper

The economic impact of climate change

ESRI Working Paper, No. 255

Provided in Cooperation with:
The Economic and Social Research Institute (ESRI), Dublin

Working Paper No. 255

September 2008

The Economic Impact of Climate Change

Richard S.J. Tol[a,b,c,d]

Abstract: I review the literature on the economic impacts of climate change, an externality that is unprecedentedly large, complex, and uncertain. Only 14 estimates of the total damage cost of climate change have been published, a research effort that is in sharp contrast to the urgency of the public debate and the proposed expenditure on greenhouse gas emission reduction. These estimates show that climate change initially improves economic welfare. However, these benefits are sunk. Impacts would be predominantly negative later in the century. Global average impacts would be comparable to the welfare loss of a few percent of income, but substantially higher in poor countries. There are over 200 estimates of the marginal damage cost of carbon dioxide emissions. The uncertainty about the social cost of carbon is large and right-skewed. For a standard discount rate, the expected value $50/tC, which is much lower than the price of carbon in the European Union but much higher than the price of carbon elsewhere. Current estimates of the damage costs of climate change are incomplete, with positive and negative biases. Most important among the missing impacts are the indirect effects of climate change on economic development, large scale biodiversity loss, low probability – high impact scenarios, the impact of climate change on violent conflict, and the impacts of climate change beyond 2100. From a welfare perspective, the impact of climate change is problematic because population is endogenous, and because policy analyses should separate impatience, risk aversion, and inequity aversion between and within countries.

Key words: Impacts of climate change; social cost of carbon

JEL Classification: Q54

[a] Economic and Social Research Institute, Dublin, Ireland
[b] Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands
[c] Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands
[d] Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA

The Economic Impact of Climate Change

1. Introduction

Climate change is one of the defining issues of the early 21st century. The research effort is enormous, and media attention is intense. **Climate** change is an election issue, and it has won people an Oscar and a Nobel Peace Prize. Economic research is centred on three questions: What if? So what? What should we do? This paper assesses the first two questions. What are the implications of climate change? And how serious is this problem? The paper also touches on the third question. What are the elements of an optimal climate policy? The paper does not answer these questions. Two decades of economic research yielded valuable insights, but only now the scope of the problem has become clear. This paper surveys what we know and what we still need to learn about the economic impacts of climate change – and what this implies for climate policy.

Climate change is the mother of all externalities, larger, more complex, and more uncertain than any other environmental problem. Sulphur dioxide emissions, one of the main causes of acidification, arise from impurities in fossil fuels. Sulphur is a nuisance as well as an externality. However, thermal energy is generated by breaking the chemical bonds in carbohydrates (e.g., oil) and oxidising the components to CO_2 and H_2O. That is, CO_2 is intrinsic to fossil fuel combustion. Similarly, methane (CH_4) emissions are necessary to prevent the build-up of hydrogen in anaerobic digestion. One cannot have beef, dairy, or rice without methane emissions. Greenhouse gas emissions are therefore fundamental to our food production and our energy system. There are no easy solutions. The sources of greenhouse gas emissions are also more diffuse than that of any other environmental problem. Every company, every farm, every household emits some greenhouse gases. The impacts are similarly pervasive. Agriculture, energy use, health, and nature are directly affected by the weather, and this in turn affects everything and everyone. Indeed, it cannot be excluded that poor countries are poor partly because they are hot. The depletion of the ozone layer is another global externality, but its causes (substances used in a small number of industrial processes and residential applications) and consequences (human health, ecosystems) are rather confined. The causes and consequences of climate change are very diverse, and those who contribute least are most vulnerable. Climate change is therefore not just an efficiency problem, but also an equity problem. As the status quo is an unjust externality, the Coasian separation of equity and efficiency has little practical value. Climate change is also a long-term problem. Some greenhouse gases have an atmospheric life-time of tens of thousands of years, and a small part of carbon dioxide will stay in the atmosphere practically forever. Greenhouse gas emissions are in this sense comparable to nuclear waste, but the quantities are too large to permit the containment approach that is used to store radioactive material. 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. As all these issues come together in the emission of greenhouse gases, climate change truly is one of the greatest intellectual challenges of our times.

Therefore this paper cannot possibly cover all economic aspects of climate change. I focus on the impacts of climate change, and sketch the implications for policy. Section 2 reviews the estimates of the total economic impacts. Section 3 surveys the marginal cost estimates. Section 4 discusses the many and large research gaps. Section 5 concludes.

2. Estimates of the total impact of climate change

The first studies of the welfare impacts of climate change were done for the USA (Cline, 1992; Nordhaus, 1991; Titus, 1992; cf. Smith, 1996). Although Nordhaus (1991; cf. Ayres and Walter, 1991) extrapolated his US estimate to the world, and Hohmeyer and Gaertner (1992) published some estimates, the credit for the first serious study of the global welfare impacts goes to Fankhauser (1994, 1995). Other global estimates were published by Nordhaus (1994a,b), Tol (1995), Nordhaus and Yang (1996), Plambeck and

Hope (1996), Nordhaus and Boyer (2000), Mendelsohn *et al.* (2000a,b), Tol (2002a,b), Maddison (2003), Rehdanz and Maddison (2005) and Nordhaus (2006).[1]

There are a dozen studies. The number of authors is lower, and can be grouped into a UCL group and a Yale one.[2] Most fields are dominated by a few people and fewer schools, but dominance in this field is for want of challengers. The impact of this is unknown, but this insider argues below that the field suffers from tunnel-vision. This situation is worrying. Politicians proclaim that climate change is the greatest challenge of this century. Billions of dollars have been spent on studying the problem and its solutions, and hundreds of billions may be spent on emission reduction (e.g., Weyant *et al.*, 2006). Yet, the economics profession has essentially closed its eyes to the question whether this expenditure is justified.[3]

The reasons for the dearth of research are:

- lack of funding – this work is too applied for funding by academic sources, while applied agencies dislike the typical results and pre-empt embarrassment by not funding economic impact estimates;
- lack of daring – this research requires making many, often questionable assumptions, and taking on well-entrenched incumbents; and
- lack of reward – the economics profession frowns on applied research in general and interdisciplinarity in particular.

In addition, many people, including many economists, would argue that climate change is beyond cost-benefit analysis (e.g., van den Bergh, 2004) and that monetary valuation is unethical (e.g., Spash, 2007; Ackerman, 2008).

[1] 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).

[2] Nordhaus and Mendelsohn are colleagues and collaborators; Fankhauser, Maddison and Tol all worked with David Pearce and one another; Rehdanz was a student of Maddison and Tol.

[3] There is a large literature on the economics of climate change, but it is focussed on international agreements, policy instruments for emission reduction, and impacts of emission reduction.

Table 1 shows selected characteristics of the published estimates. Figure 1 displays these estimates against the global mean temperature. A few insights emerge. First, the welfare impact of a doubling of the atmospheric concentration on the current economy is relatively small. Although the estimates differ, welfare losses are a few percent of GDP or less. It is therefore no surprise that cost-benefit analyses of climate change recommend only limited greenhouse gas emission reduction – for instance, Nordhaus (1993) argues that the optimal rate of emission reduction is 10-15%.[4]

Second, although the impact is relatively small, is not negligible. A damage of a few per cent of GDP per year is a real concern.

Third, some estimates (Hope, 2006; Mendelsohn *et al.*, 2000a,b; Tol, 2002b) point to initial benefits of climate change.[5] This is more clearly seen in Figure 1. The initial benefits are partly because more carbon dioxide in the atmosphere reduces water stress in plants and may make them grow faster (Long *et al.*, 2006). Another reason is that the global economy is concentrated in the temperate zone, where warming reduces heating costs and cold-related health problems. At the same time, the world population is concentrated in the tropics, where the impacts of initial climate change are probably negative.

Even if, initially, *economic* impacts may well be positive, it does not follow that greenhouse gas emissions should be subsidized as the climate responds rather slowly to changes in emissions. The initial impacts cannot be avoided; they are sunk benefits. Impacts start falling at roughly the same time emission control affects climate change (Hitz and Smith, 2004; Tol, 2002b; Tol *et al.*, 2000). The fitted line in Figure 1 suggests that the turning point is at 1.1ºC warming, with a standard deviation of 0.6 ºC. Even though total impacts of 1-2ºC warming may be positive compared to today, incremental impacts are negative.

[4] This is one of the more contentious findings of the climate economics literature. It is rejected by most natural scientists and many economists, despite the impeccable pedigree of the estimate and its author.
[5] Studies published after 1995 all have regions with net gains and net losses due to global warming; earlier studies only find net losses.

The fourth insight is that relative impacts are higher in poorer countries (see also Yohe and Schlesinger, 2002).[6] This is because poorer countries are less able to adapt to climate change (Adger, 2006; Alberini *et al.*, 2006; Smit and Wandel, 2006; Yohe and Tol, 2002), particularly in health (Tol, 2005). Poor countries are more exposed to climate change, particularly in agriculture and water resources. Furthermore, poorer countries tend be hotter and therefore closer to biophysical temperature limits and short on spatial analogues should it get warmer still. However, there are fewer studies on the impacts of climate change on developing countries than on developed countries.[7] This has two policy implications. Firstly, greenhouse gases mix uniformly in the atmosphere. It does not matter where they are emitted or by whom, the effect on climate change is the same. Therefore, any justification of stringent emission abatement is an appeal to consider the plight of the poor and the impacts imposed on them by the rich (Schelling, 2000). Secondly, if poverty is the root cause for vulnerability to climate change, one may wonder whether stimulating economic growth or emission abatement is the better way to reduce impacts. Indeed, Tol and Dowlatabadi (2001) and Tol and Yohe (2006) argue that the economic growth foregone by stringent abatement more than offsets the avoided impacts of climate change, at least for malaria, while Tol (2005) shows that development is a cheaper way of reducing climate-change-induced malaria than is emission reduction. Moreover, richer countries may find it easier and cheaper to compensate poorer countries for the climate change damages caused, than to reduce greenhouse gas emissions. Such compensation may be explicit, but would more likely take the shape of technical and financial assistance with adaptation (cf. Paavola and Adger, 2006).

A fifth insight from Table 1 is that impact estimates have become less pessimistic over time. The trend is that estimates increase by 0.23% of GDP per year, with a standard deviation of 0.10%/yr. There are three reasons for this. Firstly, the projections of future emissions and future climate change have become less severe over time – even though the public discourse has become shriller. Secondly, the earlier impact studies focused on the negative impacts of climate change, whereas later studies considered the balance of

[6] Emissions are higher in richer countries. This hampers an international agreement on emission reduction.
[7] Note that some studies (e.g., Rosenzweig and Parry, 1994) assume rather than conclude that poorer countries are more vulnerable.

positives and negatives. Thirdly, earlier studies tended to ignore adaptation. That is, climate changes, but agents continue to do the same thing. Large and negative impacts are the result. More recent studies – triggered by Mendelsohn *et al*. (1994) – include adaptation. Climate changes, and agents change their behaviour to minimize losses and make the best of the new opportunities. However, agents are typically assumed to have perfect foresight, and to be flexible and properly incentivized. Although climate change is slow relative to economic and social change, these assumptions may be optimistic. Forecasts are imperfect, agents are constrained in many ways, and markets are often distorted – particularly in the areas that matter most for the impacts of climate change, viz. water, food, energy, and health. Therefore, recent studies may be too optimistic on adaptation and thus on the impacts of climate change. The observed trend cannot be extrapolated.

The broad agreement between the studies in Table 1 is remarkable as they used different methods. The studies by Fankhauser, Nordhaus (1994), and Tol use the enumerative method. That is, 'physical' impact estimates are obtained one by one, from 'natural science' papers based on 'process-based' models or 'laboratory experiments'. Physical impacts are multiplied with their respective prices, and added up. The 'prices' are obtained by benefit transfer (see below). In contrast, Mendelsohn's work is based on direct estimates of the welfare impacts, using observed variations (across space) in prices and expenditures to discern the effect of climate. Mendelsohn estimates are done per sector and then added up, but physical modelling and benefit transfer are avoided. Nordhaus (2006) uses empirical estimates of the *aggregate* climate impact on income, while Maddison (2003) looks at patterns of *aggregate* household consumption. Like Mendelsohn, Nordhaus and Maddison rely exclusively on observations, assuming that "climate" is reflected in incomes and expenditures. Rehdanz and Maddison (2005) also empirically estimate the aggregate impact using self-reported happiness. The difference with Nordhaus and Maddison is that their indicator is subjective rather than objective. The enumerative studies rely on controlled experiments (albeit with detailed, process-based models in most cases). This has the advantages of ease of interpretation and physical realism, but the main disadvantage is that certain things are kept constant that would change in reality. Adaptation is probably the key element. The statistical studies rely on uncontrolled experiments. This has the advantage that everything varies as it does in reality, but the disadvantages are that the assessment is constrained by observed variations[8] and that effects may be spuriously attributed to climate. The broad agreement of the estimates from such different methods enhances confidence.

The shortcomings of the estimates in Table 1 are interesting too. Welfare losses are approximated with direct costs, ignoring general equilibrium and even partial equilibrium effects (see below). In the enumerative studies, impacts are assessed independently of one another, even if there is an obvious overlap as between water resources and agriculture. 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 (Mendelsohn *et al*., 1994) were in stark contrast to earlier results (e.g., Parry, 1990). Valuation is based on benefit transfer, driven only by difference in per capita income. Realistic modelling of adaptation is problematic, and studies either assume no adaptation or perfect adaptation. Many impacts are unquantified, and some of these may be large (see below). The uncertainties are unknown – only 5 of the 14 estimates in Table 1 have some estimate of uncertainty. These problems are gradually solved, but progress is slow. Indeed, the above list of caveats is similar to those in Fankhauser and Tol (1996, 1997).

The enumerative method for estimating total impacts uses the inner product of a vector of quantities and prices. For traded goods and services, market prices are used. For non-traded goods and services, other methods are needed. As primary valuation studies are expensive, time-consuming, and situation-specific, monetisation of climate change impacts relies on benefit transfer. That is, values estimated for other issues are applied to climate change concerns. Furthermore, values estimated for a limited number of locations are extrapolated to the world, and values estimated for a given period are extrapolated to

[8] This particularly limits estimates of the direct impact of higher ambient concentrations of carbon dioxide.

the future. This is unavoidable. However, tests of benefit transfer methods have shown time and again that extrapolation errors are substantial (Brouwer and Spaninks, 1999).
There is also a conceptual issue with valuation. Empirical studies have shown that values can differ up to an order of magnitude depending on whether one estimates the willingness to pay (WTP) for improved environmental services, or whether one estimates the willingness to accept compensation (WTAC) for diminished services. There is a substantial literature on this matter (cf. Horowitz and McConnell, 2002), and it is now clear that this is more than a measurement error. People seem to be averse to risks imposed on them by others, and this would drive a wedge between WTP and WTAC. The impact studies listed in Table 1 all use WTP as the basis for valuation, as recommended by Arrow *et al*. (1993). Implicitly, the policy problem is phrased as "how much are we willing to pay to buy a better climate for our children?" Alternatively, the policy problem could be phrased as "how much compensation should we pay our children for deteriorating their climate?" Because of the deviation between WTP and WTAC, these two questions have different answers. Reducing emissions is more practical than setting up an intergenerational compensation fund, and this argues for WTP. However, the WTP formulation takes "no emission reduction" as the default, while the WTAC formulation takes "no climate change" as the default – WTP thus violates the "do no harm" principle that is paramount in ethics and law (Tol and Verheyen, 2004).

Table 1 and Figure 1 make clear that the uncertainty about the impact of climate change is vast – just how vast will become clear when the marginal impacts are discussed below. The studies that are based on a benchmark warming of 2.5ºC have an average impact of -0.7% of GDP, and a standard deviation of 1.2% of GDP – note that this is the uncertainty about the best estimate of the impacts, rather than the uncertainty about the impacts. Only 5 of the 14 studies in Table 1 report some measure of uncertainty. Two of these report a standard deviation, suggesting symmetry in the distribution. Three studies report a confidence interval – of these, two studies find the uncertainty is right-skewed, but one study finds a left-skewed distribution. Although there is little and contradictory evidence, negative surprises should be more likely than positive surprises. While it is relatively easy to imagine a disaster scenario – involving massive sea level rise, mass migration and violent conflict – it is not at all easy to argue that climate change will be a huge boost to economic growth. Even though there are no reliable estimates of the uncertainty, it should be large and right-skewed. The policy implication is that emission reduction should err on the ambitious side.

3. Estimates of the marginal damage cost of greenhouse gas emissions

Although the number of studies of the *total* costs of climate change is small (Table 1 has 13 studies and 14 estimates), a larger number of studies estimate the *marginal* costs: Tol (2008) reports 47 studies with 211 estimates, and a few more have been published since (Hope, 2008a,b; Nordhaus, 2008; Stern and Taylor, 2007). 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 an infinitesimally small increase in carbon dioxide emissions. The marginal damage cost equals the Pigou tax if it is computed along the optimal trajectory of emissions. Marginal damage cost estimates thus derive from total cost estimates. Note that some of the total cost estimates (Maddison, 2003; Mendelsohn *et al.*, 2000a,b; Nordhaus, 2006; Rehdanz and Maddison, 2005) have yet to be used for marginal cost estimation. Therefore, the 211 estimates of the social cost of carbon are based on 9 estimates of the total impact of climate change. The empirical basis for the optimal carbon tax is much smaller than is suggested by the number of estimates.

There is only one way to take a first derivative, so how can it be that 9 totals yield 211 marginals? The total impact of climate change is typically estimated as the difference between today's economy with today's climate and today's economy with some future climate. The same comparative static estimate of total impact implies different marginal costs along different projections of emissions and climate change. Alternative population and economic scenarios also yield different estimates, particularly if vulnerability to climate change is assumed to change with development. Marginal cost estimates further vary with the way in which uncertainty is treated (if at all). Estimates also differ with regional aggregation of impacts. Most studies add monetary impacts for world regions, which roughly reflects the assumption that emitters of greenhouse gases will compensate the victims of climate change. Other studies add utility-equivalent impacts, assuming a social planner and a global welfare function. Different assumptions about the shape of the welfare function imply widely different estimates of the social cost of carbon. However, the discount rate is the most important source of variation in the estimates of the social cost of carbon. This is not surprising as the bulk of the avoidable impact of climate change is in the distant future. Besides combinatorial sensitivity analyses with the three components of the Ramsey rule for geometric discounting, more recent studies have also analyzed numerous variants of hyperbolic discounting.

Table 2 shows some characteristics of the published estimates of the social cost of carbon. Following Tol (2008), 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 parsimonious (two-parameter), fat-tailed distribution that is defined on the real line. A few published estimates are negative, and fat-tails seem appropriate (cf. 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.

Table 2 reaffirms that the uncertainty about climate change is very large. If all estimates are included, this is partly explained by the use of different pure rates of time preference. However, as is shown by the estimates for three subsamples of the data using the same pure rate of time preference, time discounting is only part of the uncertainty. For a 3% pure rate of time preference, the mean social cost of carbon is $50/tC, and the median is $37/tC. However, the 99%ile is $271/tC. That is, the uncertainty is large and right-skewed. For a 1% pure rate of time preference, these numbers are more than twice as high. If the pure rate of time preference is lowered further, to 0%, estimates increase further – but by less than one might have expected, because most estimates are (inappropriately) based on a finite time horizon.[9] Table 2 shows that the estimates for the

[9] With an infinite time horizon, the social cost of carbon would still be finite as fossil fuel reserve are finite and the economy would eventually equilibrate with the new climate.

whole sample are dominated by the estimates based on lower discount rates. Note that there is one estimate (Hohmeyer and Gartner, 1992) based on a zero consumption discount rate (cf. Davidson, 2006) and thus a *negative* pure rate of time preference.

To place these numbers in their context, new power plants would be carbon-free for a carbon tax of $50-100/tC (Weyant *et al.*, 2006) while transport would decarbonise only at a much higher carbon tax (Schaefer and Jacoby, 2005, 2006). Substantial emission reduction requires a carbon tax of at least $50/tC, and can barely be justified with a pure rate of time preference of 3%. Note that the social cost of carbon is a global estimate – the contribution of each country to the damages is smaller.

4. Research needs

4.1. Higher order impacts

The literature reviewed above is largely limited to estimates of the direct costs, that is price times quantity, with constant prices. This is a crude approximation of the welfare impact. General equilibrium studies of the effect of climate change on agriculture have a long history (Kane *et al.*, 1992; Darwin, 2004). 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. Ignoring the general equilibrium effects leads to small negative bias in the global welfare loss, but differences in regional welfare losses are much greater and may be negative as well as positive. Similarly, Bosello *et al.* (2006) show that the direct costs are biased towards zero for health, while Berrittella *et al.* (2006) emphasize the redistribution of impacts on tourism through markets. More research alone these lines is needed.

A cross-sectional analysis of per capita income and temperature may suggest that people are poor because of the climate (Nordhaus, 2006; van Kooten, 2004). This would, wrongly, suggest that warming could cause economies to shrink or grow slower. This would increase the damages of climate change. As poverty implies higher impacts, this would drag the economy down further. However, as shown in Fankhauser and Tol (2005), only very extreme parameter choices would imply such a scenario. This is in sharp contrast to the econometric results of Dell *et al*. (2008), who find conclude 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 impact estimates. Unfortunately, Dell *et al*. (2008) have only few explanatory variables in their regression, so their climate effect may suffer from missing variable bias. Gallup *et al.* (1999) and Masters and McMillan (2001) find a relationship between geography and development, but Easterly and Levine (2003) show that the results are not robust, and that institutions are a better explanation of income difference than is geography and climate. Acemoglu *et al.* (2002) reach the same conclusion. However, Acemoglu *et al.* (2001; cf. Albouy, 2008) argue for climate as a root cause of development, via the route of the mortality of European settlers. Future climate change will not affect history, though. Demo-economic models (Galor and Weil, 1999) also put mortality[10] centre stage. In their models, the difference between Malthusian stagnation and exponential growth is determined by the quality-quantity trade-off for children, which is partly driven by infant mortality. A risk-averse parent would opt for more children, so as to increase the chance of old-age care; a large number of inadvertently surviving children would reduce the money spent on their education. These children would become poor adults, unable to afford health care for their offspring. Should climate change increase the prevalence of malaria and diarrhoea, then the poverty trap would widen. This mechanism has not been studied for climate change, but the impact of climate change on economic growth may dominate the static impacts shown in Table 1.

4.2. Missing impacts

The impacts of climate change that have been quantified and monetised include the impacts on agriculture and forestry, water resources, coastal zones, energy consumption, air quality, and human health. Obviously, this list is incomplete. Also within each impact

[10] albeit of infants, not of grown settlers from distant places

category, the assessment is incomplete. Studies of the impacts of sea level rise on coastal zones, for instance, typically omit saltwater intrusion in groundwater (Nicholls and Tol, 2006). Furthermore, studies typically compare the situations before and after climate change, but ignore that there will be substantial period during which adaptation is suboptimal – the costs of this are not know.

Some of the missing impacts are most likely negative. 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 the safeguards against the increased uncertainty about future circumstances. This is true for other infrastructure as well. 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 well harm fisheries (Kikkawa *et al.*, 2004). These matters are relatively small compared to overall economic activity. Even if climate change would double or triple the cost, the impact would be small.

Other missing impacts 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 may 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 (Carmicheal *et al.*, 2004). Also in these cases, the impact of climate change is likely to be small relative to the economy.

Some missing impacts 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 impacts are simply not known. Some rivers may see an increase in flooding, and others a decrease (Kundzewicz *et al.*, 2005).

These are the small unknowns. There may also be big unknowns: biodiversity loss, extreme climate scenarios, violent conflict, and the very long term. The impact of climate change on economic development, discussed above, may also be included among the "big unknowns".

Climate change would have a profound impact on nature. Plants and animals are directly affected temperature and precipitation, and indirectly through interactions with other organisms. Climate change implies changes in distribution and abundance, invasions, and local and global extinctions (Gitay *et al.*, 2001). Economists have problems with this. First, there are few quantitative studies of the impacts of climate change on ecosystems and biodiversity because quantitative ecology is still in its infancy, and there are many species to be modelled. Second, changes in land use and nutrient cycles, alien invasions and acidification also have large-scale and profound effects on nature. This hampers interpretation of past observations, complicates projections of the future, and muddles the attribution of impacts to causes (Parmesan and Yohe, 2003). Third, valuation of ecosystem change is difficult. Over the years, methods and applications have grown more specific (e.g., Champ *et al.*, 2003) while benefit transfer remains difficult (Brouwer and Spaninks, 1999). Wide-spread change that is hard to detect and to attribute is beyond current valuation methods. Nevertheless, valuation studies have consistently shown that, although people are willing to pay something to preserve or improve nature, they are not prepared to pay a large amount. Most studies put the total willingness to pay for nature conservation at substantially less than 1% of income (Pearce and Moran, 1994). Even if climate-change-induced biodiversity loss would be worth as much as 1% of GDP, this would not fundamentally change the total impact estimates of climate change.

Extreme climate scenarios are another big unknown. Examples are a shutdown of the thermohaline circulation (e.g., Marotzke, 2000), a collapse of the West-Antarctic Ice Sheet (Vaughan and Spouge, 2002), and massive releases of methane from the permafrost (e.g., Harvey and Huang, 1995). These scenarios have a number of things in common. First, they would lead to rapid changes in the natural system. Second, impacts have hardly been studied. Third, the mechanism is only partially understood. Fourth, the probability is unknown but probably low. Rapid climate change would be a problem, as there would be little time to adapt. This suggests that impacts would be large. Impact models, however, have been designed for more gradual climate change. Nicholls *et al.* (forthcoming) find that the impacts of sea level rise sharply increase should the West-Antarctic Ice Sheet collapse, but they may have overestimated adaptation and hence underestimated impacts (Olsthoorn *et al.*, forthcoming). Link and Tol (2004) estimate the impacts of a shutdown of the thermohaline circulation which slows global warming, at least over land. Unsurprisingly, they report *benefits* of a THC shutdown.

Research into the determinants of violent conflict has concluded that resource scarcity is at best a contributing factor to, but never a cause of war (Alesina and Spolaore, 2005; Collier and Hoeffler, 1998; Homer-Dixon, 1994). The corollary is that climate-change-induced resource scarcity would not lead to war either, although it may intensify pre-existing conflicts. It is therefore impossible to estimate the impact of climate change on violent conflict without a scenario with background conflicts. Such scenarios do not exist; all future scenarios for climate change are nice and peaceful (Nakicenovic and Swart, 2001). Clearly, an intensification of conflict would be something to worry about. Butkiewicz and Hanakkaya (2005) find that political instability (i.e., the chance of war) may decrease per capita economic growth in the poorest countries by 2% per year – although actual war has no significant effect. Conflict may thus dominate climate change impacts, but, as said, it is not clear whether climate change would lead to conflict.

The fourth big unknown is the impact in the very long term. Most static impact analyses are for $2xCO_2$ only, while most dynamic impact studies stop at 2100. Climate change will not stop there, but most estimates for 2100 suggest that climate change has a negative impact, that the impact is growing, and that the growth rate is accelerating – see Figure 1. Obviously, what happens after 2100 is important for climate policy, but we have not even started to study this – this is true for emissions, for climate change, for impacts, and for the monetary value of those impacts.

4.3. Welfare

The information gaps described above require research that combines economics with other disciplines. There are two issues that are pure economics. Both have to do with the specification of the welfare function.

The impacts of climate change are uncertain, but will likely fall heaviest on poorer countries (cf. Table 1). In textbook economics, attitudes towards uncertainty are measured by the rate of risk aversion, or the elasticity of marginal utility with respect to consumption. The same parameter 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.[11] The consumption elasticity of marginal utility thus plays four roles. Although conceptually distinct, all climate policy analyses that I am aware of use a single numerical value (cf. Saelen *et al*., 2008). The reason for this is simple. It is well known that consumption smoothing over time and risk aversion are different things, and different again from inequity aversion – and that attitudes towards income gaps are different within and between jurisdictions (e.g., Amiel *et al*., 1999). Despite considerable research, welfare theorists have yet to find welfare and utility functions that make the necessary distinctions and can be used in applied work. Climate change adds urgency to solving the theoretical problems.

There is a similar problem with population. Standard welfare functions work fine if population growth is exogenous, but produce peculiar and undesirable results if population is endogenous (Blackorby and Donaldson, 1984). As climate change affects

[11] The differences in impacts between countries are described above. Although research is scarce (O'Brien *et al.*, 2004), there is no reason to assume that climate change impacts would 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.

mortality and migration, population is endogenous to climate policy. A standard welfare function such as $W = P\ln(C/P)$, with W welfare, P population and C total consumption, would put a premium on migration from poor to rich countries and would thus encourage sea level rise and discourage coastal protection. As above, this problem is well recognised in welfare theory, but a practical solution has yet to be found.

5. Discussion and conclusion

Research into the economic impacts of climate change began in earnest with the publication of Nordhaus (1991). The tone of the survey of Pearce *et al.* (1995) suggest that the authors (including the present one) thought that everything was roughly known, and that research would be complete within a few years. This view was entirely mistaken. After 17 years of research, I am reasonably confident that we know the scope of the research agenda. As argued above, there are a number of impacts for which we have reasonable estimates, and a number of impacts for which we know the 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. There are also a number of issues for which we are aware of our ignorance. I believe that the result of 17 years of research is that there are no more unknown unknowns, at least no sizeable ones.

This is a sobering conclusion, and I would not be the first expert to suffer from overconfidence (Morgan and Henrion, 1990). It is worrying conclusion if one considers the amounts of money politicians are proposing to spend on greenhouse gas emission reduction. At present, we do not know whether this investment is too much or too little. The number of published studies fit on a single page (see Table 1), and none of the researchers listed work full-time on this issue. This level of research effort is incommensurate with the perceived size of the climate problem, the expected costs of the solution, and the size of the research gaps.

Nonetheless, decisions should be made with the best available knowledge – even if the best available knowledge is not very good. The main advice to policy is given in Table 2. A government that plays a cooperative game on climate policy, and uses the same discount rate for climate change as for other decisions, should levy a carbon tax of $26/tC (mode) to $50/tC (mean). A higher tax can be justified by an appeal to risk (Weitzman, forthcoming), but not necessarily by an appeal for a lower discount rate (Nordhaus, 2008, Ch 9) or international equity (Schelling, 2000). The price of carbon dioxide emission permits in the European Union is $134/tC.[12] In the USA, there is no federal emission reduction policy, although utilities apparently factor in a carbon tax of $15/tC in their investment decisions (Richels, personal communication). This suggests that neither EU nor US policy is optimal, and that the preferred policy lies somewhere in between. Outside the OECD, there is no climate policy – although these countries are most vulnerable to climate change, and their share of the social cost of carbon is positive even at high discount rate. Many of these countries subsidise fossil fuel use, rather than taxing it. Weak as the current knowledge on the economic impacts may be, the direction of policy adjustments are clear. While this does not constitute "a case for strong action on climate change" (Heal, 2008), it does constitute a strong case for action on climate change.

Acknowledgements

Discussions with David Anthoff, Sam Fankhauser, Bill Nordhaus, David Maddison, Robert Mendelsohn, Steve Pacala, Katrin Rehdanz, Rich Richels, Joel Smith, Rob Socolow, John Weyant, Bob Williams, and Gary Yohe have shaped my thinking on the issues discussed in this paper. David Pearce stands out for his early encouragement and for emphasizing intellectual honesty over political correctness. Rob Stavins also deserves special mention. Financial support by the ESRI Energy Policy Research Centre and CEC FP7 Climate Cost project is gratefully acknowledged.

[12] Permit price and exchange rate at August 29, 2008.

References

Acemoglu, D., S.Johnson, and J.A.Robinson (2001), 'The Colonial Origins of Comparative Development: An Empirical Investigation', *American Economic Review*, **91**, 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), pp. 1231-1294.

Ackerman, F. (2008), 'Climate economics in four easy pieces', *Development*, **51**, (3), pp. 325-331.

Adger, W.N. (2006), 'Vulnerability', *Global Environmental Change*, **16**, 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**, 123-144.

Alesina, A. and E.Spolaore (2005), 'War, Peace, and the Size of Countries', *Journal of Public Economics*, **89**, 1333-1354.

Amiel, Y., J.Creedy, and S.Hurn (1999), 'Measuring attitudes towards inequality', *Scandinavian Journal of Economics*, **101**, (1), pp. 83-96.

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

Ashley, R. M., Balmfort, D. J., Saul, A. J., & Blanskby, J. D. Flooding in the future - Predicting climate change, risks and responses in urban areas. 52[5], 265-273. 2005. Ref Type: Serial (Book,Monograph)

Ayres, R.U. and J.Walter (1991), 'The Greenhouse Effect: Damages, Costs and Abatement', *Environmental and Resource Economics* , **1**, 237-270.

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**, 913-924.

Blackorby, C. and D.Donaldson (1984), 'Social Criteria for Evaluating Population Change', *Journal of Public Economics*, **25**, 13-33.

Bosello, F., R.Roson, and R.S.J.Tol (2006), 'Economy-wide estimates of the implications of climate change: Human health', *Ecological Economics*, **58**, 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**, 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**, 585-598.

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

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., J.Gallus, 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.

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

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

Collier, P. and A.Hoeffler (1998), 'On Economic Causes of Civil War', *Oxford Economic Papers*, **50**, 563-573.

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

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

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

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.

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**, 513-535.

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

Fankhauser, S. (1994), '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** , 385-403.

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

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.

Gitay, H., S.Brown, W.E.Easterling, III, B.P.Jallow, J.M.Antle, M.Apps, R.Beamish, T.Chapin, W.Cramer, J.Frangi, J.Laine, E.Lin, J.J.Magnuson, I.Noble, J.Price, T.D.Prowse, T.L.Root, E.-D.Schulze, O.Sitotenko, 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.

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), pp. 2905-2926.

Heal, G.M. (2008), *Climate Economics: A Meta-Review and Some Suggestions*, Working Paper **13927**, National Bureau of Economic Research, Cambridge.

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

Homer-Dixon, T.F. (1994), 'Environmental Scarcities and Violent Conflict: Evidence from Cases', *International Security*, **19**, (1), 5-40.

Hope, C.W. (2006), 'The Marginal Impacts of CO2, CH4 and SF6 Emissions', *Climate Policy*, **6**, (5), 537-544.

Hope, C.W. (2008a), 'Discount rates, equity weights and the social cost of carbon', *Energy Economics*, **30**, (3), 1011-1019.

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

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

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**, 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.

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

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**, 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**, 1918-1921.

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

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

Masters, W.A. and M.S.McMillan (2001), 'Climate and Scale in Economic Growth', *Journal of Economic Growth*, **6**, 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.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., W.N.Morrison, M.E.Schlesinger, and N.G.Andronova (2000), 'Country-specific market impacts of climate change', *Climatic Change*, **45**, 553-569.

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

Morgan, M.G. and M.Henrion (1990), *Uncertainty - A Guide to Dealing with Uncertainty in Quantative Risk and Policy Analysis*, 1 edn, Cambridge University Press, Cambridge.

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

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**, 1073-1095.

Nicholls, R.J., R.S.J. Tol and A.T. Vafeidis (forthcoming), 'Global Estimates of the Impact of a Collapse of the West-Antarctic Ice Sheet: An Application of *FUND*', *Climatic Change*.

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

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

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

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

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.

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. (2006), 'Geography and Macroeconomics: New Data and New Findings', *Proceedings of the National Academy of Science* (www.pnas.org/cgi/doi/10.1073/pnas.0509842103).

Nordhaus, W.D. (2008), *A Question of Balance -- Weighing the Options on Global Warming Policies* Yale University Press, New Haven.

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**, 193-225.

Olsthoorn, A.A., P.E. van der Werff, L.M. Bouwer and D. Huitema (forthcoming), 'Neo-Atlantis: Dutch Responses to Five Meter Sea Level Rise', *Climatic Change*.

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

Parmesan, C. and G.W.Yohe (2003), 'A globally coherent fingerprint of climate change impacts across natural systems', *Nature* , **421**, 37-41.

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.

Pearce, D.W., W.R.Cline, A.N.Achanta, S.Fankhauser, R.K.Pachauri, R.S.J.Tol, and P.Vellinga (1996), 'The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control', 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. 179-224.

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

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

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

Saelen, H., G.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**, 1-24.

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

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

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

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

Spash, C.L. (2007), 'The Economics of Climate Change Impacts a la Stern: Novel and Nuanced to Rhetorically Restricted?', *Ecological Economics*, **63**, 706-713.

Stern, N.H., S.Peters, V.Bakhshi, A.Bowen, C.Cameron, S.Catovsky, D.Crane, S.Cruickshank, S.Dietz, N.Edmonson, S.-L.Garbett, L.Hamid, G.Hoffman, D.Ingram, B.Jones, N.Patmore, H.Radcliffe, R.Sathiyarajah, M.Stock, C.Taylor, T.Vernon, H.Wanjie, and D.Zenghelis (2006), *Stern Review: The Economics of Climate Change* Cambridge University Press, Cambridge.

Stern, N.H. and C.Taylor (2007), 'Climate Change: Risks, Ethics and the Stern Review', *Science*, **317**, 203-204.

Szolnoky, C., K.Buza?s, 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. (1995), 'The Damage Costs of Climate Change Toward More Comprehensive Calculations', *Environmental and Resource Economics*, **5**, 353-374.

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 H.Dowlatabadi (2001), 'Vector-borne diseases, development & climate change', *Integrated Assessment*, **2**, 173-181.

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

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

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

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

Tol, R.S.J. (2008), '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. and R.Verheyen (2004), 'State responsibility and compensation for climate change damages - a legal and economic assessment', *Energy Policy*, **32**, 1109-1130.

Tol, R.S.J. and G.W. Yohe (2006), 'Of Dangerous Climate Change and Dangerous Emission Reduction' in H.J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G.

Yohe (eds.), *Avoiding Dangerous Climate Change*, Cambridge University Press, Cambridge, Chapter 30, pp. 291-298.

van den Bergh, J.C.J.M. (2004), 'Optimal climate policy is a utopia: from quantitative to qualitative cost-benefit analysis', *Ecological Economics*, **48**, 385-393.

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

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

Weitzman, M.L. (forthcoming), 'On Modelling and Interpreting the Economics of Catastrophic Climate Change', *Review of Economics and Statistics.*

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.

Wilson, K. J., Falkingham, J., Melling, H., & De Abreu, R. "Shipping in the Canadian Arctic : Other possible climate change scenarios", pp. 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**, 261-287.

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** , 25-40.

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

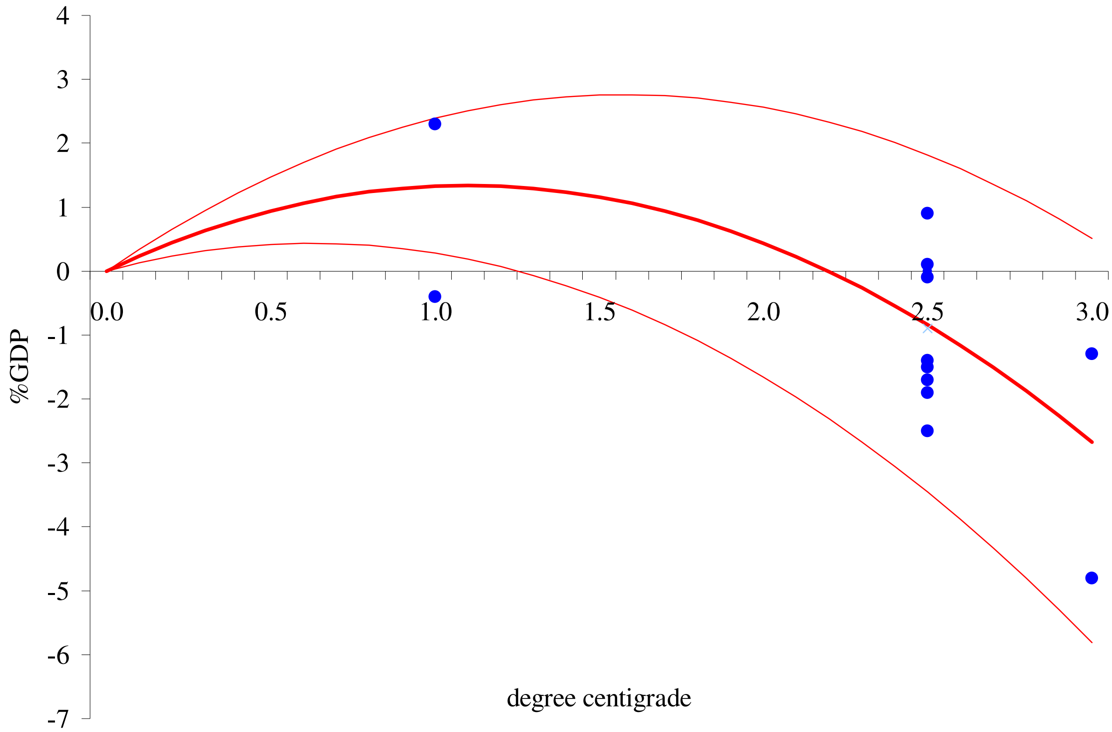

Figure 1. The 14 estimates of the global economic impact of climate change, expressed as the welfare-equivalent income loss with income measured by Gross Domestic Product, as a functions of the increase in global mean temperature relative to today. The dots represent the estimates. The central line is 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 other two lines are the 95% confidence interval, where the standard deviation is the least squares fit to the 5 reported standard deviations: $S = 0.43\ (0.18)\ T$, $R^2 = 0.58$, where S is the standard deviation.

Table 2. The social cost of carbon ($/tC); 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.

	all	Pure rate of time preference		
		0%	1%	3%
Mean	152	148	122	50
StDev	271	156	149	61
Mode	41	82	52	26
33%	38	68	46	20
Median	88	117	92	37
67%	149	175	144	56
90%	347	343	267	114
95%	539	489	418	204
99%	1688	669	677	271

Table 1. Impact estimates of climate change; numbers in brackets are either standard deviations or confidence intervals.

Study	Warming	Impact	Minimum		Maximum	
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 *et al.* (2000)[a,b,c]	2.5	0.0 0.1	-3.6 -0.5	Africa	4.0 1.7	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]	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.

Year	Number	Title/Author(s) ESRI Authors/Co-authors *Italicised*
2008		
	254	Measuring International Inequity Aversion *Richard S.J. Tol*
	253	Using a Census to Assess the Reliability of a National Household Survey for Migration Research: The Case of Ireland *Alan Barrett* and *Elish Kelly*
	252	Risk Aversion, Time Preference, and the Social Cost of Carbon David Anthoff*, Richard S.J. Tol* and Gary W. Yohe
	251	The Impact of a Carbon Tax on Economic Growth and Carbon Dioxide Emissions in Ireland *Thomas Conefrey, John D. Fitz Gerald, Laura Malaguzzi Valeri* and *Richard S.J. Tol*
	250	The Distributional Implications of a Carbon Tax in Ireland *Tim Callan, Sean Lyons, Susan Scott, Richard S.J. Tol and Stefano Verde*
	249	Measuring Material Deprivation in the Enlarged EU *Christopher T. Whelan, Brian Nolan* and *Bertrand Maître*
	248	Marginal Abatement Costs on Carbon-Dioxide Emissions: A Meta-Analysis Onno Kuik, Luke Brander and *Richard S.J. Tol*
	247	Incorporating GHG Emission Costs in the Economic Appraisal of Projects Supported by State Development Agencies *Richard S.J. Tol* and *Seán Lyons*
	246	A Carton Tax for Ireland *Richard S.J. Tol, Tim Callan, Thomas Conefrey, John D. Fitz Gerald, Seán Lyons, Laura Malaguzzi Valeri and Susan Scott*
	245	Non-cash Benefits and the Distribution of Economic Welfare *Tim Callan and Claire Keane*

244 Scenarios of Carbon Dioxide Emissions from Aviation
Karen Mayor and *Richard S.J. Tol*

243 The Effect of the Euro on Export Patterns: Empirical Evidence from Industry Data
Gavin Murphy and *Iulia Siedschlag*

242 The Economic Returns to Field of Study and Competencies Among Higher Education Graduates in Ireland
Elish Kelly, Philip O'Connell and *Emer Smyth*

241 European Climate Policy and Aviation Emissions
Karen Mayor and *Richard S.J. Tol*

240 Aviation and the Environment in the Context of the EU-US Open Skies Agreement
Karen Mayor and *Richard S.J. Tol*

239 Yuppie Kvetch? Work-life Conflict and Social Class in Western Europe
Frances McGinnity and *Emma Calvert*

238 Immigrants and Welfare Programmes: Exploring the Interactions between Immigrant Characteristics, Immigrant Welfare Dependence and Welfare Policy
Alan Barrett and Yvonne McCarthy

237 How Local is Hospital Treatment? An Exploratory Analysis of Public/Private Variation in Location of Treatment in Irish Acute Public Hospitals
Jacqueline O'Reilly and *Miriam M. Wiley*

236 The Immigrant Earnings Disadvantage Across the Earnings and Skills Distributions: The Case of Immigrants from the EU's New Member States in Ireland
Alan Barrett, *Seamus McGuinness* and *Martin O'Brien*

235 Europeanisation of Inequality and European Reference Groups
Christopher T. Whelan and *Bertrand Maître*

234	Managing Capital Flows: Experiences from Central and Eastern Europe Jürgen von Hagen and *Iulia Siedschlag*
233	ICT Diffusion, Innovation Systems, Globalisation and Regional Economic Dynamics: Theory and Empirical Evidence Charlie Karlsson, Gunther Maier, Michaela Trippl, *Iulia Siedschlag,* Robert Owen and *Gavin Murphy*
232	Welfare and Competition Effects of Electricity Interconnection between Great Britain and Ireland *Laura Malaguzzi Valeri*
231	Is FDI into China Crowding Out the FDI into the European Union? Laura Resmini and *Iulia Siedschlag*
230	Estimating the Economic Cost of Disability in Ireland John Cullinan, Brenda Gannon and *Seán Lyons*
229	Controlling the Cost of Controlling the Climate: The Irish Government's Climate Change Strategy Colm McCarthy, *Sue Scott*
228	The Impact of Climate Change on the Balanced-Growth-Equivalent: An Application of *FUND* David Anthoff, *Richard S.J. Tol*
227	Changing Returns to Education During a Boom? The Case of Ireland *Seamus McGuinness*, *Frances McGinnity, Philip O'Connell*
226	'New' and 'Old' Social Risks: Life Cycle and Social Class Perspectives on Social Exclusion in Ireland *Christopher T. Whelan* and *Bertrand Maître*
225	The Climate Preferences of Irish Tourists by Purpose of Travel *Seán Lyons, Karen Mayor* and *Richard S.J. Tol*
224	A Hirsch Measure for the Quality of Research Supervision, and an Illustration with Trade Economists *Frances P. Ruane* and *Richard S.J. Tol*

	223	Environmental Accounts for the Republic of Ireland: 1990-2005 *Seán Lyons, Karen Mayor* and *Richard S.J. Tol*
2007	222	Assessing Vulnerability of Selected Sectors under Environmental Tax Reform: The issue of pricing power *J. Fitz Gerald*, M. Keeney and *S. Scott*
	221	Climate Policy Versus Development Aid *Richard S.J. Tol*
	220	Exports and Productivity – Comparable Evidence for 14 Countries *The International Study Group on Exports and Productivity*
	219	Energy-Using Appliances and Energy-Saving Features: Determinants of Ownership in Ireland Joe O'Doherty, *Seán Lyons* and *Richard S.J. Tol*
	218	The Public/Private Mix in Irish Acute Public Hospitals: Trends and Implications *Jacqueline O'Reilly* and *Miriam M. Wiley*
	217	Regret About the Timing of First Sexual Intercourse: The Role of Age and Context *Richard Layte*, Hannah McGee
	216	Determinants of Water Connection Type and Ownership of Water-Using Appliances in Ireland Joe O'Doherty, *Seán Lyons* and *Richard S.J. Tol*
	215	Unemployment – Stage or Stigma? Being Unemployed During an Economic Boom *Emer Smyth*
	214	The Value of Lost Load *Richard S.J. Tol*
	213	Adolescents' Educational Attainment and School Experiences in Contemporary Ireland *Merike Darmody, Selina McCoy, Emer Smyth*
	212	Acting Up or Opting Out? Truancy in Irish Secondary Schools *Merike Darmody, Emer Smyth* and *Selina McCoy*

211	Where do MNEs Expand Production: Location Choices of the Pharmaceutical Industry in Europe after 1992 *Frances P. Ruane*, Xiaoheng Zhang
210	Holiday Destinations: Understanding the Travel Choices of Irish Tourists *Seán Lyons, Karen Mayor* and *Richard S.J. Tol*
209	The Effectiveness of Competition Policy and the Price-Cost Margin: Evidence from Panel Data Patrick McCloughan, *Seán Lyons* and William Batt
208	Tax Structure and Female Labour Market Participation: Evidence from Ireland *Tim Callan*, A. Van Soest, *J.R. Walsh*
207	Distributional Effects of Public Education Transfers in Seven European Countries *Tim Callan,* Tim Smeeding and Panos Tsakloglou