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# Why Worry About Climate Change? A Research Agenda

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## ABSTRACT

Estimates of the marginal damage costs of carbon dioxide emissions suggest that, although climate change is a problem and some emission reduction is justified, very stringent abatement does not pass the cost-benefit test. However, current estimates of the economic impact of climate change are incomplete. Some of the missing impacts are likely to be positive and others negative, but overall the uncertainty seems to concentrate on the downside risks and current estimates of the damage costs may have a negative bias. The research effort on the economic impacts of climate change is minute and lacks diversity. This field of study should be strengthened, with a particular focus on the quantification of uncertainties; estimating missing impacts, estimating impacts in developing countries; interactions between impacts and higher-order effects; the valuation of biodiversity loss; the implications of extreme climate scenarios and violent conflict; and climate change in the very long term. I discuss these particular gaps in research, and speculate on possible sign and size of the impacts of climate change.

## KEYWORDS

Climate change, impacts, valuation, cost-benefit analysis

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## 1. INTRODUCTION

Politicians, the media, the public, and many scientists call for a substantial reduction of greenhouse gas emissions. However, cost-benefit analyses of climate policy recommend much more modest action. Yet, many economists are uneasy about applying cost-benefit analysis to climate change, and argue that prudent action would go beyond their models' advice. This paper explores this quandary, focussing on the impacts of climate change.

Tol (2005a) reviews the literature on estimates of the marginal damage costs of carbon dioxide emissions, the main cause of climate change. He finds that the Pigou tax, an indirect tax on carbon dioxide emissions, is estimated to be relatively small: for a 3% utility discount rate, the median estimate in the literature is $7/tC. This estimate is higher than the actual price of carbon in most countries. However, only the most optimistic studies of the costs of emission reduction suggest that $7/tC would buy substantial abatement (Weyant, 1993; 2004). I am not aware of any serious study that suggests that this carbon tax would buy atmospheric stabilisation. Indeed, cost-benefit analyses of climate change show only modest emission reduction (Nordhaus, 1991; Nordhaus and Yang, 1996; Tol, 1999),[1] so that climate policy consists almost entirely of adaptation. Do economists such as Tol (2005a) therefore conclude that we should not worry about climate change? This paper argues not.

Tol (2005a) is a literature review and meta-analysis of the marginal damage costs. The *quantified* part of the climate change impacts literature suggests that we should not worry too much: the recommended Pigou tax is too low to induce much emission reduction (see Pearce et al., 1996 and Smith et al., 2001, for a survey). However, before reaching a conclusion from an estimate, one needs to consider the completeness of that estimate. Damage cost estimates are incomplete. There are reasons to assume that some of the omitted impacts are substantial and negative, but other omitted impacts may be positive. This paper does not argue 'we don't know and therefore …'. Rather, it surveys the missing climate change impact estimates, speculates why we should worry about them, and sketches what research will need to be done to quantify these impacts.

I do not adopt a more risk averse, or prudent, or precautionary standpoint to the unquantified impacts of climate change, because there is a long history of worrying that proved unfounded on closer inspection.[2] Initially, people were worried about widespread starvation (Hohmeyer and Gaertner, 1992), about extreme sea level rise (Schneider and Chen, 1980), or about infectious diseases killing millions (Haines and Fuchs, 1991). Later studies showed the initial worries to be exceedingly pessimistic (Darwin et al., 1995; Nicholls and Tol, 2006; McMichael et al., 2003). At the moment, there is concern about water resources (Arnell, 2004; Lehner et al., 2006), the thermohaline circulation (Rahmstorff, 1994), and melting ice caps (Oppenheimer and Alley, 2004; 2005) but here as well the concern may be overstated (Mendelsohn and Bennett, 1997; Link and Tol, 2004; Nicholls et al., 2005).

Another argument against a precautionary approach is that climate change is a two-sided risk, not a one-sided one. Gradual emission reduction is probably cheap, but stringent, rapid emission reduction may well be expensive, even if implemented in a cost-effective manner (Weyant, 2004). Governments may not adopt cost-effective abatement policies, which would increase costs substantially. For most of 2006, the price of carbon permits in Europe was higher than economic models suggest it should be (e.g., Viguier et al., 2003), another reason for caution on the abatement side.

Nonetheless, the policy suggested by cost-benefit analysis – emission reduction, but not enough to stabilise emissions let alone concentrations – is intuitively wrong. It cannot be the case that the best policy is to let the world get warmer and warmer and warmer still. An obvious reason is that the human body fails if it gets too hot (Parker, 2000, suggests a limit of 43ºC), and if the ambient concentration of carbon dioxide is too high (the US Occupational Safety and Health Administration has a provisional exposure limit of 10,000 ppm; see NIOSH, 2001). But common sense suggests that climate change should be stopped at a lower level. Our best estimates challenge the common sense, but it is as yet unclear whether our research findings are superior to our gut feelings.

There are two other reasons to challenge the recommendations of cost-benefit analyses of climate change. The first is uncertainty. Uncertainties are vast, and negative surprises are more likely than positive surprises. Qualitatively, such uncertainty almost always calls for more stringent action.[3] However, quantitatively, the uncertainties are unknown (CBO, 2005) but perhaps very large: Tol (2003; cf. Tol and Yohe, 2007b) and Weitzman (2007) argue that the standard deviation or even the mean of crucial decision variables may be unbounded. The second reason is equity. The largest (smallest) emitters of greenhouse gases are least (most) vulnerable to climate change (e.g., Toman, 2006; Gardiner, 2006). Cost-benefit analysis of climate change with inequity aversion typically recommends higher emission abatement (Tol, 2001; 2002a).[4] However, in other arenas, equity is not an important argument, so why would it be in climate change?

This paper is written from a utilitarian/welfarist perspective. If one can make a case for greenhouse gas emission reduction on the basis of hard-nosed neo-classical economics, then one can make a case for emission abatement from other ethical perspectives too. This is not generally the case. However, the moral problems with unchecked climate change are much larger than the ethical issues with climate policy – regardless of whether one considers the relations of the present rich with the present poor, with future humans, or with other species. In this paper, I largely ignore these issues. A climate policy that works if people are selfish would also work if people are altruistic.

This paper is structured as follows. In Section 2, I review estimates of the economic impacts of climate change. I discuss direct costs, both total and marginal, and indirect costs. I particularly emphasise the quality and completeness of the assumptions. In Section 3, I survey four reasons why the economic impact would be higher than currently estimated. These are biodiversity loss, extreme climate scenarios, violent conflict, and the very long term. Section 4 concludes the discussion.

## 2. A REVIEW OF THE ECONOMIC IMPACTS OF CLIMATE CHANGE

### *2.1. Total costs*

The first studies of the welfare impacts of climate change were done for the USA (Cline, 1992; Nordhaus, 1991; Titus, 1992; Smith, 1996). Although Nordhaus (1991; see also Ayres and Walter, 1991) extrapolated his US estimate to the world, the credit for the first serious study of the global welfare impacts goes to Fankhauser (1994; 1995).[5] Other global estimates include those by Nordhaus (1994a; 1994b), Tol (1995), Nordhaus and Yang (1996), Plambeck and Hope (1996), Nordhaus and Boyer (2000), Mendelsohn, Morrisson et al. (2000), Mendelsohn, Schlesinger and Williams (2000), Tol (2002b), Maddison (2003), Hope (2006),[6] Rehdanz and Maddison (2005) and Nordhaus (2006).

This is a rather short list of studies, and an even shorter list of authors.[7] Although most fields are dominated by a few people, dominance is here for want of challengers. The effect of this is hard to gauge. The reasons are lack of funding (this work is too applied for academic sources, while applied agencies do not like the typical results and pre-empt this by not funding it), lack of daring (this research requires making many assumptions, and taking on well-entrenched incumbents), and lack of reward (the economics profession frowns on the required interdisciplinarity). In addition, many people, including many economists, would argue that climate change is beyond cost-benefit analysis and that monetary valuation is unethical.

Table 1 shows some characteristics of these studies. 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, impacts are not more than a few percent of GDP. The estimates of Hope (2006), Mendelsohn, Morrisson et al. (2000), Mendelsohn, Schlesinger and Williams (2000) even point to initial benefits of climate change.[8] With such estimates, it is 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 per cent, one of the more contentious findings of the climate economics literature.

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

Third, climate change may initially have positive impacts. This is partly because the higher ambient concentration of carbon dioxide would reduce water

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<br>0.1 | -3.6<br>-0.5 | Africa | 4.0<br>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.

stress in plants and may make them grow faster – although this effect is now believed to be weaker (Long et al., 2006). Another reason is that the global economy is concentrated in the temperate zone, where a bit of warming may well be welcomed because of reductions in 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 though initial *economic* impacts are positive, it does not necessarily follow that greenhouse gas emissions should be subsidised. The climate responds rather slowly to changes in emissions, so the initial impacts cannot be avoided. Impacts starts falling – that is, additional climate change reduces global welfare – roughly at the same time as climate change can be influenced by present and future emission reduction (Hitz and Smith, 2004; Tol, 2002c; Tol et al., 2000).

The fourth insight is that relative impacts are higher in poorer countries (see also Yohe and Schlesinger, 2002).[9] This is because poorer countries have a lower adaptive capacity (Adger, 2006; Alberini et al., 2006; Smit and Wandel, 2006; Tol and Yohe, 2007a; Yohe and Tol, 2002), particularly in health (Tol, 2005b; Tol et al., 2007), and have a greater exposure to climate change, particularly in agriculture and water resources. Furthermore, poorer countries tend be hotter and therefore closer to temperature limits and short on spatial analogues should it get warmer still. At the same time, there are fewer studies on the impacts of climate change on developing countries than on developed countries. Although research is scarce (O'Brien et al., 2004), there is little 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. This has two policy implications. Firstly, recall that 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, 1992; 1995). While this makes for wonderful rhetoric and fascinating research (e.g., Tol, 2001), reality shows little compassion for the poor by the rich. 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 (2005b) 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 and financial, but would more likely take the shape of technical and financial assistance with adaptation (cf. Paavola and Adger, 2006).

The agreement between the studies is remarkable if one considers the diversity in methods. The studies of Fankhauser, Hope, Nordhaus, and Tol all use the enumerative method: 'physical' impact estimates are obtained one by one, from 'natural science' papers based on 'process-based' models or 'laboratory experiments'. These physical impacts are multiplied with their respective prices, and added up. The 'prices' are obtained by benefit transfer. In contrast, Mendelsohn's work[10] is based on direct, empirical estimates of the welfare impacts, using observed variations 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, but they assume that all climate effects are aggregated by the economy into incomes and expenditures. Rehdanz and Maddison (2005) also empirically estimate the aggregate impact, but use self-reported happiness as an indicator; their approach is similar to that of Nordhaus and Maddison, but the indicator is subjective rather than objective. The enumerative studies of Fankhauser etc. 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 of Mendelsohn etc. rely on uncontrolled experiments. This has the advantage that everything varies as in reality, but the disadvantages are that the assessment is limited to observed variations (which may be small compared to projected changes, particularly in the case of carbon dioxide concentration) and that effects may be spuriously attributed to climate. Therefore, the variety of methods enhances confidence, not in the individual estimates, but in the average.

The shortcomings of the estimates are at least as interesting. 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. 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 4 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).

### 2.2. *Marginal costs*

Although the number of studies of the *total* costs of climate change is small, a larger number of studies estimate the *marginal* costs. The marginal damage cost of carbon dioxide is defined as the net present value of the incremental damage due to an infinitesimally small increase in carbon dioxide emissions. If this is computed along the optimal trajectory of emissions, the marginal damage cost equals the Pigou tax. Marginal damage cost estimates derive from total cost estimates – the fact that there are more estimates available, does not imply that we know more about the marginal costs than we do about the total costs. In fact, some of the total cost estimates (Maddison, 2003; Mendelsohn, Morrisson et al., 2000; Mendelsohn, Schlesinger and Williams, 2000; Nordhaus, 2006; Rehdanz and Maddison, 2005) have yet to be used for marginal cost estimation, so that the empirical basis is actually smaller.

Tol (2005a) reviews 103 estimates from 28 studies. A number of new studies have appeared since (Ceronsky et al., 2005; Downing et al., 2005; Guo et al., 2006; Hope, 2006; Wahba and Hope, 2006) – all in response to a *faux pas* of HM Treasury (Clarkson and Deyes, 2002).[11] Tol (2005a) also overlooked the older studies of Nordhaus (1982) and Haraden (1992; 1993), and the papers of Cline (2004), Hohmeyer (2004), Hope (2003; 2005), Link and Tol (2004), Manne (2004), Stern et al. (2006), Uzawa (2003) have since appeared or only recently came to my attention. There are now 211 estimates from 50 studies.

Tol (2005a) combines the estimates to a joint probability density function (PDF), assuming that all estimates that do not report some measure of uncertainty have the same coefficient of variation. This assumption emphasises lower estimates at the expense of higher ones. Therefore, Figure 1 shows the PDF of the best guesses, weighted by the quality of the study[12] and the importance that the authors attach to a particular estimate;[13] cf. Tol (2005a) for details.

According to Figure 1, there is a 2% chance that the marginal damage cost is less than $0/tC, a 53% change that it is less than $25/tC, a 66% chance that it is less than $50/tC, an 81% chance that it is less than $100/tC, and a 95% chance that it is less than $250/tC. If only those estimates are included that use a pure rate of time preference of 3%, then the estimate lies below $100/tC with virtual certainty (99.98%), and it lies below $15/tC with a 50% chance. If the pure rate of time preference is 0%, there is a 17% chance that the estimate lies below $50/tC, and a 26% chance that it is greater than $250/tC. There is no chance that the marginal cost is negative with even a 1% pure rate of time preference. Partly, this demonstrates the power of discounting.[14] However, a high discount rate also discounts the uncertainty about future populations, incomes, emissions and climate. It may be that authors who advocate lower discount rates would also use higher estimates of the impact of climate change.

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;

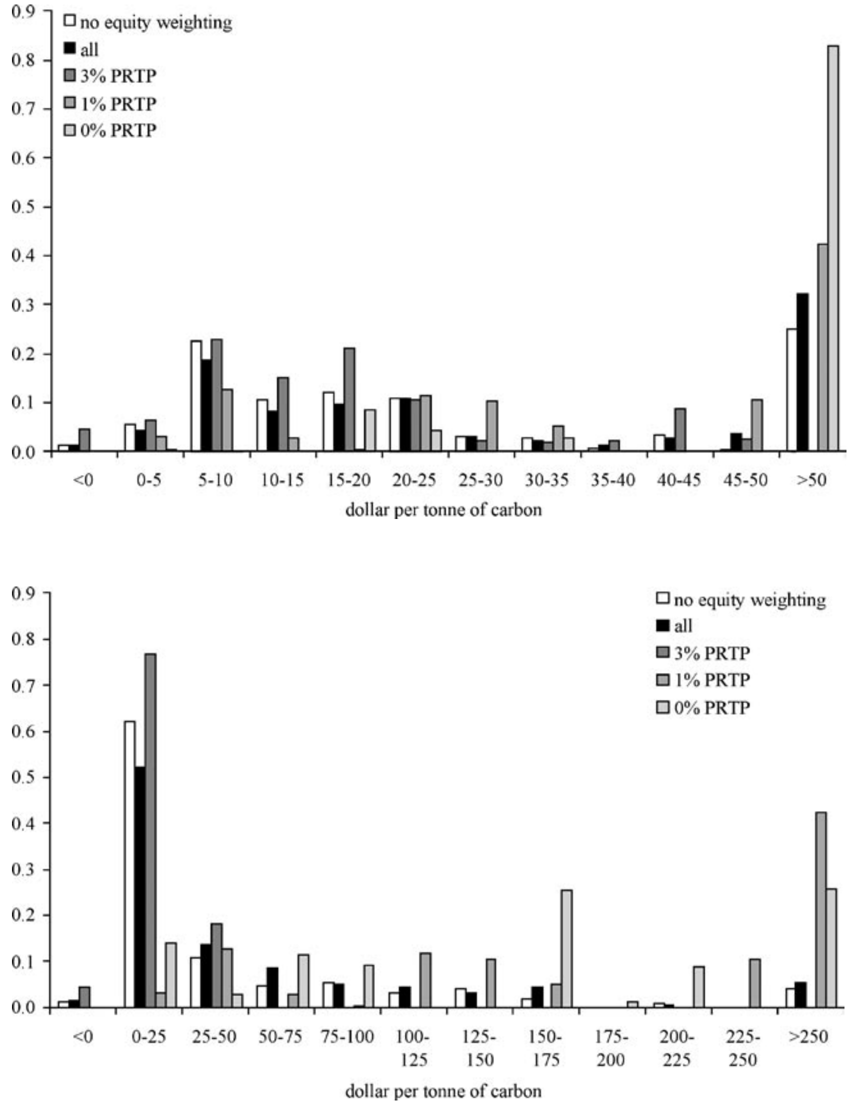

FIGURE 1. Histogram of the best estimates of the marginal damage costs of carbon dioxide emissions, in bins of \$5/tC (top panel) and \$25/tC (bottom panel), for the entire sample and various subsamples.

2006). Substantial emission reduction requires a carbon tax of at least \$50/tC, and cannot be justified with a pure rate of time preference of 3%.

Figure 1 also shows the difference between all studies and the studies that do not use equity weighting (cf. Azar and Sterner, 1996; Fankhauser et al., 1997; 1998).[15] Equity weighting tends to increase the marginal damage cost estimate, as the impacts on poorer, more vulnerable regions attain greater weight. The chance that the marginal damage cost is less than \$25/tC (\$50/tC) rises to 64% (75%) if equity-weighted estimates are excluded.

This highlights that climate change is an ethical issue. Emissions of one generation cause problems for the next generations, and richer countries emit more while poorer countries suffer more damage. In an academic study, the analyst can freely experiment with lower discount rates and equity weights. In reality, decision makers do not necessarily show that much care about other generations and faraway lands (cf. Schelling, 1992; 1995; Gardiner, 2006; MacCracken, 2006; Singer, 2006; Toman, 2006). A lower discount rate for climate change implies a lower discount rate for other decisions too, and hence greater expenditures on, say, education and pensions. Equity weights for climate change would need to be applied to other decisions as well, about say agricultural subsidies or import tariffs.

### *2.3. Indirect effects*

The literature reviewed above is largely limited to estimates of the direct costs. The direct cost equals price times quantity; prices are assumed to be constant; climate change affects quantities only. This is a reasonable, but crude approximation of the welfare impact of small changes. However, if climate change were to have a larger effect on quantities, then one would expect the price to change as well. Put differently, if climate change has a substantial impact on supply (demand), then it also impacts demand (supply). A partial equilibrium model is needed to estimate these effects. Furthermore, the impact on one market would spill over to others markets, as producers compete for inputs, and consumers change their consumption patters. A general equilibrium model is needed to estimate these effects, and the total welfare impact of climate change. Studies about the general equilibrium effects of climate change are now emerging. In addition, climate change may have an effect on development as well.

General equilibrium studies of the effect of climate change on agriculture have a long history (Kane et al., 1992; Fischer et al., 1993; 1996; Darwin et al., 1995; Tsigas et al., 1996). Studies show that market adaptation matters, and may even reverse the sign of the initial impact estimate. General equilibrium models have now entered other areas as well. 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) emphasise the redistribution of impacts on tourism through markets.

### *2.4. Higher order effects*

Generally, richer countries are less vulnerable to climate change than are poorer countries (see above). 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; see below for further discussion). This would, wrongly, suggest that warming would 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.

Tol (2003) finds that the utility equivalent of the impacts of climate change may be infinitely negative (see also Yohe, 2003). The mechanism is that climate change slows economic growth, which increases impacts; this negative feedback eventually reverses economic growth and drives the economy to subsistence level. The welfare loss may be infinite. However, as shown in Fankhauser and Tol (2005) and Tol (2008), only very extreme parameter choices would imply such a scenario.[16] An extreme scenario would dominate other, less extreme scenarios only under particular assumptions about utility and welfare (Tol, 2003) and about international aid (Tol and Yohe, 2007b). While these assumptions are defensible from an academic perspective, they do not seem to be applicable in the real world.

Furthermore, one should not over-interpret cross-sectional analyses of dynamic processes. The work by Nordhaus (2006) and van Kooten (2004) explicitly relates to climate change, but other papers investigate the relationship between geography and development (Gallup et al., 1999; Masters and McMillan, 2001). Easterly and Levine (2003) shows convincingly that the conclusions of Gallup et al. (1999) 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) 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.

The demo-economic models that follow Galor and Weil (1999) also put mortality[17] 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.

### *2.5. 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 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. Diarrhoea impacts have been quantified recently (Link and Tol, 2004). Like malaria, diarrhoea is a disease that is driven by poverty but sensitive to climate. Including diarrhoea tightens the link between development and climate policy. Increasing water temperatures would increase the costs of cooling power plants (Szolnoky et al., 1997). Redesigning urban water management systems, be it for more or less water, would be costly (Ashley et al., 2005), as would implementing the safeguards against the increased uncertainty about future circumstances. Roads and bridges would suffer from weather conditions for which they were not designed; this would imply either disruption of traffic or expensive retrofits. Extratropical storms may well increase, leading to greater damage and higher building standards (Dorland et al., 1999). Expenditures on these things are relatively small. Even if climate change would double or triple the cost, the impact would be small. Ocean acidification were to reduce marine biodiversity, and may well harm fisheries (Kikkawa et al., 2004). Ocean fisheries are only a small, and declining fraction of GDP, while there are ready substitutes for wild fish protein (notably fish farming). The value of biodiversity is unclear (see below).

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; Harrison and Wallace, 2005). 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 positive in some places, and negative in others. Tourism is an example. Climate change may well drive summer tourists towards the poles and up the mountains (Hamilton et al., 2005a; 2005b; Bigano et al., 2007). People, however, are unlikely to change the time and money spent on holiday making. The effect is a redistribution of tourist revenue (Berrittella et al., 2006). The global impact is close to zero, but regional impacts are measured in tens of billions of dollars – positive in temperate, rich countries, and negative in tropical, poor countries. This exacerbates the already skewed distribution of climate impacts. Some ski resorts may go out of business, and others would need expensive snowmaking equipment (Elsasser and Buerki, 2002; Scott et al., 2003). Other ski resorts would profit from the reduced competition. Although regional impacts may be substantial, at the global scale positives and negatives cancel.

Other impacts are simply not known. Some rivers may see an increase in flooding, and others a decrease (Kundzewicz et al., 2005). At the moment, only a limited number of rivers have been studied in detail, and it is unclear how to extrapolate to other rivers. It is clear though, that land use and water management may greatly increase or reduce impacts. Although river floods wreak substantial havoc and damages of a single event can reach substantial numbers, average flood damage is in fact small relative to the economy (Tol et al., 2003). Tropical storms do more damage, although a substantial share of the impact is due to bad planning rather than bad weather (Burton et al., 1993). Nonetheless, tropical storms may prevent capital accumulation and the plantation of lucrative tree crops such as banana (Ennos, 1997; Mulcahy, 2004). Unfortunately, it is not known how climate change would alter the frequency, intensity, and spread of tropical storms (McDonald et al., 2005; Pielke et al., 2005).

Although the sign of the aggregate unknown impacts is not known, risk aversion would lead one to conclude that greenhouse gas emission reduction should be more stringent than suggested by a cost-benefit analysis based on the quantified impacts only. However, the size of the bias is unknown too – so the main policy implication is that more research is needed.

## 3. REASONS FOR CONCERN / GAPS IN KNOWLEDGE

Section 2.4 above lists a number of 'small' gaps in knowledge. There are also 'big' gaps, discussed below.

### *3.1. Biodiversity loss*

Climate change would have a profound impact on nature. The distribution of plants and animals is partly determined by temperature and precipitation; while organisms that are relatively robust to climate change may be affected through competitors, parasites, pests, preys, and predators that are more sensitive to climate change. Most species would shift their distribution and change their abundance; this implies local extinctions and new introductions. Some species would be unable to adapt fast enough and would go extinct, globally (Gitay et al., 2001). From an economic policy perspective, there are three major problems.

First, there are few quantitative studies of the impacts of climate change on ecosystems and biodiversity. Large-scale dynamic vegetation models were build to study the carbon cycle, and have a very crude resolution for plant species (20 types at most) while ignoring animals altogether (Sitch et al., 2003). Studies which are rich in species detail are few in number, and confined to small groups of species and at best continental in scale (Burkett et al., 2005; Harrison et al., 2003; Termansen et al., 2006). The reasons are that quantitative ecology is still in its infancy, and that there are very many species to be modelled. Although ecosystem impacts may be important, there is little hard material to go by.

Second, climate is not the only thing that is changing. Changes in land use, changes in the nutrient cycles, alien invasions and acidification all have large-scale and profound effects on nature. These effects are synergistic rather than additive. This hampers interpretation of past observations (and hence model building), complicates making projections of the future, and muddles the attribution of impacts to causes (Parmesan and Yohe, 2003; Root et al., 2003).

Third, valuation of ecosystem change is difficult. Great strides have been made in the valuation literature, but methods and applications have grown more specific, focusing on a single issue in a particular locality (e.g., Champ et al., 2003). The benefit transfer literature reinforces this, demonstrating that values are heterogeneous and contextual (Ready et al., 2004). Wide-spread change that is hard to detect and to attribute is beyond current valuation methods. Furthermore, climate-change-induced ecosystem change is unlikely to be marginal – a challenge for economic methods in general.

Although the challenges are daunting, 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 were to be worth as much as 1% of GDP, this would not fundamentally change the conclusion of the cost-benefit analysis discussed above.

### *3.2. Extreme climate scenarios*

Extreme climate scenarios are widely considered to be a main reason for concern about climate change. 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, but there has been little research. This is partly because output data are few and not readily available from climate models on extreme climate change. Another reason is that impact models have been designed for more gradual climate change. Nicholls et al. (2005), for instance, had to go back and reformulate their models of erosion and coastal protection and redo the input before considering sea level rise faster than 1 metre per century. That study reports an order of magnitude increase in the impacts of sea level rise should the West-Antarctic Ice Sheet collapse in less than 200 years. If adaptation is more difficult than assumed in the model (as suggested by Olsthoorn et al., 2005), impacts may be even be worse. Link and Tol (2004) estimate the impacts of a shutdown of the thermohaline circulation. In their scenario, a THC shutdown slows global warming, at least over land. Unsurprisingly, they report *benefits* of a THC shutdown. Working with a finer spatial resolution and a most drastic scenario, Link and Tol (2006) find a small negative effect on the global scale, but much larger negative effects in some countries. Ceronsky et al. (2005) also run more drastic scenarios than do Link and Tol (2004), also finding negative impacts of abrupt climate change.

The policy implications are unclear. In a decision analysis, what matters is impact times probability. It is hard to estimate probabilities because the mechanisms are still unclear, and measurements are difficult. The thermohaline circulation, for instance, depends on the vertical transport of water to great depth, which is hard to observe (Baehr et al., forthcoming; Keller et al., 2007). The fate of the West-Antarctic Ice is determined at the interface of the ice and the bedrock on which it rests (Vaughan and Spouge, 2002), that is, far below the surface. The uncertainties about the mechanisms also hamper policy analysis in another way: it is not clear whether greenhouse gas emission abatement would reduce the probability of a WAIS collapse or a THC shutdown. It may be that these things would happen anyway, or that the threshold has been crossed already, and even that climate change would reduce the probability of collapse. These questions are firmly in the realm of the natural science, and firm policy conclusions cannot be drawn before these questions are answered. The few available policy analyses (Baranzini et al., 2003; Gjerde et al., 1999; Guillerminet and Tol, 2005; Keller et al., 2004) therefore focus on methodological issues, using speculative parameterisations to illustrate their points.

### *3.3. Violent conflict*

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; 2005; Homer-Dixon, 1991; 1994; Homer-Dixon et al., 1993; Maxwell and Reuveny, 2000). The study by Zhang et al. (2006) is one of the few to look explicitly at climate change. They conclude that conflict was more prevalent during cold periods of Chinese history, and speculate that food scarcity is the reason.

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). Constructing scenarios of conflict would be hard, but not impossible; such scenarios would necessarily be stochastic, with climate affecting the probability of conflict (Geller and Singer, 1998).

Clearly, an intensification of conflict would be something to worry about. Carefully correcting for endogeneity (Nafziger and Auvinen, 2002), Butkiewicz and Yanikkaya (2005) find that political instability (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. Barnett (2006) argues that conflict directly increases vulnerability – conflict also indirectly increases vulnerability through its adverse impact on development.

Despite the conclusions of studies quoted above, it is possible to imagine a scenario in which climate change does cause violent conflict. One example may be prolonged drought, perhaps in the Horn of Africa (Held et al., 2006), followed by mass migration. There are three reasons to assume that this is unlikely. First, migration results from a complex of push and pull factors, not from a single push factor (McGregor, 1994; McLeman and Smit, 2006). Second, drought is only a real problem for the poor; a scenario like this would happen only if warming and drying are faster than development. If not, food imports (Reilly and Schimmelpfennig, 1999) or desalination (Zhou and Tol, 2005) may be the preferred options. Third, drought is a slow-onset disaster. It may exhaust people before they move. Poor and exhausted people are unlikely to take up arms, and if they do, they are probably not very effective. The human suffering would be substantial nonetheless.

A potentially more serious example is rapid sea level rise in the major deltas of Asia and Africa. Coastal plains are often fertile and hence densely populated (Nicholls and Small, 2002). Without coastal protection, inundation, erosion and saltwater intrusion would drive many people to higher grounds (Nicholls and Tol, 2006). They may resettle peacefully, or start quarrelling with their new neighbours. One can speculate about the consequences of large-scale migrations today. In West Africa, for instance, the situation is already so tense that additional refugees are unlikely to do any good – note that the coasts of Cameroon, Gabon and Nigeria are most vulnerable to sea level rise. Similarly, forced migration of large numbers of Bengali from the coastal plain to the hills of northern Indian and Bangladesh would not be without problems either, and may even escalate to nuclear war.

However, these impacts will not be on today's world. Sixty-three years ago, Western Europe was at war. In 2070, South Asia and West Africa may be stable and prosperous. The climate change signal is dominated by the development signal.

Terrorism is another unknown. Sea level rise will lead to the evacuation of a number of islands (Nicholls and Tol, 2006). Forcibly moved populations may harbour resentment. Sometimes, this is very strong, and a small minority may turn violent (e.g., van Amersfoort, 2004). It may well be that a Maldivian terrorist will try and blow up the headquarters of ExxonAramco. As with the other scenarios above, one can think of the plot and make it sound plausible. With the current state of conflict research, however, it is impossible to compute, even bound probabilities and intensities.

As a further complication, although climate change may contribute to violent conflict and terrorism, it does not follow that slowing climate change is the best response. Addressing the other roots of violence may be easier or cheaper, at least in some case, and would certainly have substantial co-benefits.

### *3.4. The very long term*

During this century, the world will probably run out of conventional oil and gas, the two most important energy sources of today (Moomaw et al., 2001). If conventional oil and gas is replaced by renewable and nuclear energy sources, there will not be much of a climate problem. If unconventional oil and gas take over, climate change will continue. If coal takes over, climate change will be substantial (Nakicenovic and Swart, 2001). Energy is an essential input to the economy, so the resource problem will have to be solved. This requires a complete overhaul of the energy sector. Solving the climate problem also requires a complete overhaul of the energy sector (Richels and Edmonds, 1995). Given the scale of the energy sector and the longevity of its capital stock, it would make sense to overhaul the energy sector only once, and solve the resource problem and the climate problem at the same time.[18]

Put differently, the energy system is heading towards to a bifurcation. There are various solutions to the resource problem: coal; unconventional oil and gas; or renewables and nuclear. If climate change is enough of a concern, the future of energy is renewable and nuclear. From this perspective, we do not want to know the marginal costs of carbon dioxide emissions. Instead, we want to know the difference in impacts between three radically different futures, and compare it to the difference in energy costs between the alternative futures and their non-climate-related externalities (Mendelsohn, 2006). Unfortunately, we do not know the difference in impacts.

The first problem is that most of the tools of economics are designed for analysis at the margin, that is, small change. That is adequate for most problems, where policy makers indeed tinker at the margin. It may not be adequate for climate change.

The second problem is that most static impact analyses are for $2xCO_2$ only, while most dynamic impact studies stop at 2100. The choice between a renewable and nuclear future and a coal future is the choice between $2xCO_2$ on the hand and 4x, 6x, perhaps $8xCO_2$ on the other. Current estimates have that there is not enough fossil fuel to drive the atmospheric concentration of carbon dioxide much above 2200 ppm or $8xCO_2$, while combusting all conventional oil and gas will not push the atmosphere beyond 550 ppm or $2xCO_2$; unconventional oil and gas may add another 250 ppm of carbon (Moomaw et al., 2001). Because of the inertia in the energy and climate systems, the alternative scenarios about the eventual replacement of conventional oil and gas will be still be relatively close to one another in 2100, but the gap would widen after 2100.

We have not even begun to study the impacts of climate change in the very long term.[19] Radiative forcing is logarithmic in $CO_2$ concentrations, and equilibrium warming is proportional to radiative forcing. If $2xCO_2$ leads to an equilibrium warming of 2.5°C, then $4xCO_2$ implies 5.0°C, and $8xCO_2$ would imply 7.5°C warming. For $8xCO_2$, all coal reserves would need to be burned. Sea level rise would not stop at 2-3 m, but may be to 10 m or more – by the end of the millennium. Using Nordhaus's (1994a) quadratic damage function, 2.5°C warming would lead to a welfare loss equivalent to a 1.3% income loss; 7.5°C warming would lead to a damage of 11.7% of world income – but only in a distant future: even if the $CO_2$ concentration were to continually grow at its historic maximum rate of 3 ppm per year, it would take 650 years to reach $8xCO_2$. The SRES A2 scenario (Nakicenovic and Swart, 2001) has $CO_2$ concentrations go up by 6 ppm per year at the end of the twenty-first century, but even then $8xCO_2$ would not occur until well after the year 2300.

Does the difference in climate change impacts justify the extra costs of renewables, nuclear, and carbon capture and storage? $2xCO_2$ may be the best we can get, and $8xCO_2$ may be the worst –the difference may be worth 10% of GDP, 300 years or more into the future. Answering that question requires redoing this back-of-the-envelope calculation with proper carbon cycle, climate and impact models, based on proper scenarios of development in the long run, and of course with extensive sensitivity and uncertainty analyses, particularly on the shape of the damage function. However, 10% of GDP in 300 years time is not worth a lot today with a positive pure rate of time preference – one would have to make the case that there is a severe downside risk, for example because the climate sensitivity is much larger or the damage curve much steeper than commonly believed.

## 7. DISCUSSION AND CONCLUSION

This paper reviews what is known and what is not known about the economic impacts of climate change. What is known suggests that climate change is a problem that requires a serious effort to reduce greenhouse gas emissions. However, the impact estimates do not support drastic mitigation; instead, climate policy should emphasise adaptation. The marginal damage costs of carbon dioxide lies probably below \$50/tC – a tax like this would stimulate energy efficiency improvements but only minor fuel switching. Higher estimates require that the discount rate is lowered below what is common, or that an uncharacteristic weight is placed on the plight of developing countries.

There are three policy implications. Firstly, short-term emission reduction is justified in economic terms, but to a limited extent only. Secondly, in the long-term, deep emission cuts are not justified economically. The policy response to climate change should be dominated by adaptation, not by mitigation. Thirdly, deep emission cuts may be justified in terms of equity and justice (Broome, 1992; Lumer, 2002) – but this would have a dramatic effect on other policies (pensions, education, trade, development aid) as well.

What is known is only a small part of what matters. Many climate change impacts have been identified but not estimated, and there are undoubtedly yet to be identified impacts too. Some of these impacts are clearly negative, and some clearly positive. It is impossible to say with any kind of certainty whether current impact estimates have a positive or a negative bias. Yet, countries like Canada, Finland, Iceland, Norway and Sweden are cold but prosperous. Warming would reduce costs and lift constraints and thus accelerate economic growth, but it is hard to imagine that warming would unleash very rapid growth. At the same time, tropical countries clearly suffer from violent storms, prolonged droughts, and the presence of tropical diseases. Further warming would not be good, and subjecting more places to such conditions cannot be positive either. Although not quantified, one can more easily imagine a scenario in which warming has dramatic consequences than a scenario in which warming has large positive effects. So, at the least, the great many unknowns imply that the uncertainty is skewed to the negative; and that, if anything, current impacts estimates are positively biased. This suggests that greenhouse gas emission reduction should be more stringent than suggested by cost-benefit analysis.

The policy implications are twofold. Firstly, in the short-term, more emission reduction may be economically justified than suggested by a cost-benefit analysis. Secondly and more importantly, we need to build up the technological and institutional ability to rapidly respond to climate change – be it in the form of greenhouse gas emission reduction, adaptation (including international adaptation assistance), or geoengineering.

Policy should not fly blind, however. If the above diagnosis of the state of knowledge is correct, it would most of all call for a vigorous research programme.

Although some countries propose to spend billions of dollars on emission reduction, and other countries pretend that climate change is a problem that can safely be ignored, little effort is spent on supporting these courses of action by research into whether climate change is a serious problem or not. Climate science is well-funded, but climate impact research much less so. Furthermore, the climate change impact research community is focused on incremental improvements on what is known, ignoring the big unknowns. The number of senior economists who do serious research on the impacts of climate change can be counted on two hands. This is in no proportion to the alleged seriousness of the climate change problem. Worldwide carbon dioxide emissions amounted to some 8 billion tonnes of carbon in 2007. The difference between a carbon tax of $25/tC and $50/tC is worth $200 billion – and spending a small fraction of that money would improve estimates of the social cost of carbon.

Future research should focus on:

- the quantification of uncertainties;
- the estimation of missing impacts;
- the estimation of impacts in developing countries;
- the interactions between impacts of climate change;
- the higher-order economic effects of the impacts of climate change;
- ecosystem change and biodiversity loss and their welfare implications;
- the impact of extreme climate scenarios;
- violent conflict; and
- the impact of climate change in the very long term.

This research agenda is not limited to the discipline of economics, but economists can and should contribute to every single point. Only after answering these questions can we state with some confidence that climate change is not a dramatic problem, or justify the drastic emission reductions proposed by some policy makers.

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## NOTES

[1] Occasionally, a cost-benefit analysis appears that seems to justify stringent emission reduction. Stern et al. (2006) is a recent example. In the Stern Review, as in Azar (1999) and Hasselmann et al. (1997), the result rests largely on assuming a discount rate that is well below the rate that OECD countries are observed to use for long term decisions (Evans and Sezer, 2004).

[2] The precautionary principle is sometimes interpreted as 'uncertainty is no excuse' for inaction, and sometimes as 'better safe than sorry', meaning more stringent action than the facts suggest. I here tend to the latter interpretation.

[3] Note that the uncertainty is right-skewed even for a risk-neutral decision maker. Risk-averse decision makers would put even more emphasis on negative surprises. However, more risk-averse decision makers would also use a higher discount rate. Higher risk aversion therefore does not automatically imply more stringent emission reduction.

[4] Note that a high aversion to inequity often coincides with a high risk aversion and a high discount rate.

[5] Hohmeyer and Gaertner (1992) earlier published some low quality estimates.

[6] Note that Stern et al. (2006) is based on Hope (2006); see note 6.

[7] This problem is worse if one considers that Nordhaus and Mendelsohn are colleagues; that Fankhauser, Maddison and Tol all worked with David Pearce; and that Rehdanz works with Maddison and Tol. Hope's estimates are averages of Fankhauser's and Tol's.

[8] Studies published after 1995 all have regions with net gains and net losses due to global warming, whereas earlier studies only find net losses.

[9] Emissions are higher in richer countries. This hampers an international agreement on emission reduction.

[10] Originally, Mendelsohn's work was confined to the USA (e.g., Mendelsohn et al., 1994), but it has now been replicated for other countries (Dinar et al., 1998; Kumar and Parikh, 2001; Kurukulasuriya et al., 2006; Lang, 2001; Maddison, 2000; Niggol Seo et al., 2005; Reinsborough, 2003), and the methods have been refined (Darwin, 1999; Helms et al., 1996; Mendelsohn et al., 1996; Schlenker et al., 2005; Timmins, 2006).

[11] Clarkson and Deyes (2002) present an excellent literature review of the economic impact of climate change. The entire report works towards the conclusion that the social cost of carbon would be around £7/tC. Unfortunately, the summary has £70/tC. See Pearce (2003).

[12] Quality criteria include whether the study was peer-reviewed, was based on a new estimate of the total impact of climate, used a reasonable method for estimating marginal costs, used a dynamic impact model, and used reasonable scenarios of climate change; as well as the age of the study.

[13] For example, whether estimates are presented as central estimates or as sensitivity analysis; whether estimates are included to demonstrate that previous work can be replicated; and whether estimates are highlighted in abstract and conclusions.

[14] Some recent studies (Nordhaus and Boyer, 2000; Newell and Pizer, 2003, 2004; Guo et al., 2006) use declining discount rates, as advocated by Gollier (2002a,b) and Weitzman

(2001). Declining discount rates lead to higher (lower) marginal damage costs estimates than if the discount rate is held constant at its initial high (eventual low) level.

[15] In the absence of equity weighting, regional estimates of the monetary value of the impacts of climate change are added up. With equity weighting, the utility equivalents of the monetary values are added up. This corrects the global impact estimate for income differences between countries. Most cost-benefit analyses are within a single country, and impacts are assessed for the person with the average income.

[16] Kemfert (2002; see also Roson and Tol, 2006, and Kemfert, 2006) finds large dynamic impacts, but she assumes that climate change impacts crowd out investment; this assumption is questionable for market impacts, and indefensible for non-market impacts.

[17] Albeit of infants, not of grown settlers from distant places

[18] Perhaps this solves the energy security problem too, although a different geographic concentration of energy sources may lead to different conflicts.

[19] Indeed, only a few climate change scenarios have been published (e.g., Lenton et al., 2006).

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