PROGRESS IN ESTIMATING THE MARGINAL COSTS OF GREENHOUSE GAS EMISSIONS

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Abstract

The unjust distributional consequences of climate change, and its potentially negative aggregate effect on economic growth and welfare are two reasons to be concerned about climate change. Our knowledge of the impact of climate change is incomplete. Monetary valuation is difficult and controversial. The effect of other developments on the impacts of climate change is largely speculative. Nonetheless, it can be shown that poorer countries and people are more vulnerable than are richer countries and people. A modest global warming is likely to have a net negative effect on poor economics in hot climates, but may have a positive effect on rich economies in temperate climates. If one counts dollars, the world aggregate impact may be positive. If one counts people, the world aggregate effect is probably negative. For more substantial warming, negative effects become more negative, and positive effects turn negative. The marginal costs of carbon dioxide emissions are uncertain and sensitive to assumptions that partially reflect ethical and methodological positions, but are unlikely to exceed $50 per tonne of carbon. The marginal costs of methane emission are likely to be less than $250/tCH_4$; the marginal costs of nitrous oxide emissions are probably lower than $7000/tN_2O$. Global warming potentials, the official manner to trade-off the various greenhouse gases, do not reflect, conceptually or numerically, the real trade-offs in either a cost-benefit or a cost-effectiveness framework.

Keywords

Impacts of climate change, economic valuation, equity, marginal costs

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1. Introduction

Climate change continues to figure prominently as one of the major environmental concerns for the future. Some people argue climate change is a problem because it could cause unacceptable hardship for particularly vulnerable populations (e.g. those living on small island states). Others are concerned about the potential threat to certain unique and valuable systems (such as coral reefs). Still others worry that climate change will increase the probability of large-scale climate instabilities (e.g., a shutdown of the Gulf Stream), and will have costly impacts on economies through floods and storms. A fourth group wonders about the total (or aggregate) impacts of climate change. They argue that emission reduction is costly too, and that abatement costs should be balanced against the avoided costs of climate change. The subject of this paper – the marginal costs of climate change – provides useful information on all these reasons for concern (Smith *et al.*, 2001), but it particularly addresses the need for and problems in calculating aggregate costs of climate change .

A key challenge when assessing the impacts of climate change is synthesis, i.e., the need to reduce the complex pattern of local and individual impacts to a more tractable set of indicators. The challenge is to identify indicators that can summarize and make comparable the impacts in different regions, sectors or systems in a meaningful way. Various indicators have been advanced. Many models use 'physical' measures such as number of people affected (e.g., Hoozemans *et al.*, 1993), change total plant growth (White *et al.*, 1999), runoff (Arnell, 1999), number of systems undergoing change (e.g., Alcamo *et al.*, 1995), and so on. Such physical metrics are well suited to measure the impact on natural systems. Applied to systems under human management they suffer from being inadequately linked to human welfare, the ultimate indicator of concern. Other researchers recommend the use of different metrics for different types of impacts (e.g., impact on markets, mortality, ecosystems, quality of life and equity; see Schneider, 1997). Composite vulnerability profiles have been proposed but not fully implemented (e.g., Downing *et al.*, 2001). The final comparison or aggregation across different metrics is then left to policy makers, as is the trade-off between avoided impacts and the costs of emission reduction.

If the aim is to explicitly compare the impacts of climate change with mitigation costs, it is necessary to express the benefits of mitigated climate change in the same metric as the costs of emission reduction, that is money (Nordhaus, 1991, 1994a; Cline, 1992; Downing *et al.*, 1995, 1996; Hohmeyer and Gaertner, 1992; Fankhauser, 1995; Mendelsohn and Neumann, 1999; Titus, 1992; Tol, 1995).[1] This metric is particularly well suited to measure market impacts, that is impacts that are linked to market transactions and directly affect GDP (i.e. a country's national accounts). The costs of sea level rise can be expressed as the capital cost of protection plus the economic value of land and structures at loss or at risk; and agricultural impact can be expressed as costs or benefits to producers and consumers. Using a monetary metric to express non-market impacts, such as effects on ecosystems or human health, is more difficult, though it is possible in principle. There is a broad and established literature on valuation theory and its application, including studies (mostly in a non-climate change context) on the monetary value of lower mortality risk, ecosystems, quality of life, etc (e.g., Freeman, 1993). But economic valuation can be controversial, and requires sophisticated analysis that is still mostly lacking in a climate change context (e.g., Pearce *et al.*, 1996).

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[1] Multicriteria analyis would be an alternative, but has yet to be applied to climate change.

It should be noted, though, that difficulties in valuation are only one of many problems that plague impact assessments. Even greater challenges arise in relating climate change, whether impacts of policy effects, to issues of equity. What if climate change increases (or reduces) income disparities, especially between developed and developing countries? What if an entire region collapses, such as semi-arid Africa? Or we no longer expect to meet international development targets, such as the reduction of poverty? Such challenges to our 'moral economy' – world views of human concerns and the global village – are not part of the customary analysis of impacts and policy.

Even if it were easy and well-accepted, expressing total impacts in monetary terms is, in itself, not sufficient to allow a consistent comparison of the (avoided) impacts of climate change with mitigation costs, or to compare climate policy to other policies, e.g. on education, public health care, or urban air quality. To be able to do that one needs to gain an understanding of the impact of climate change at the margin, i.e. the effect that can be achieved by a small alteration in greenhouse gas emissions. This aspect of monetisation has not been pursued to a great extent in the literature.

The ExternE project, from which this paper and others in this special issue greatly benefited, is therefore a major step forward towards an internally consistent set of marginal costs estimates for a range of environmental problems caused by power generation and transport.

In the next section, we outline the main challenges and limitations of climate change impact research. In section 3 we discuss the literature on monetary estimates of the total (aggregate) impact of climate change and its distribution across population groups. Section 4 reviews the few estimates of the marginal damage costs of greenhouse gas emissions. Section 5 discusses the sensitivity of such estimates and key uncertainties, and section 6 concludes.

2. Limitations

Research into the economic impacts of climate change is still at a nascent stage.

A major difficulty in impact assessment is our still incomplete understanding of climate change itself, in particular the regional details of climate change (Mahlman, 1997). Impacts are local, and impacts are related to weather variability and extremes. Current climate change scenarios and current climate change impact studies use crude spatial and temporal resolutions, too crude to capture a number of essential details that determine the impacts. While there is a growing sense of the relative confidence in climate change (IPCC 2001), this has not been translated into robust risk assessments of impacts and their aggregate valuation.

Knowledge gaps continue at the level of impact analysis. Despite a growing number of country-level case studies (e.g., U.S. Country Studies Program, 1999), our knowledge of local impacts is still too uneven and incomplete for a careful, detailed comparison across regions. Furthermore, differences in assumptions often make it difficult to compare case studies across countries. Only a few studies try to provide a coherent global picture, based on a uniform set of assumptions. The basis of many such global impact assessments tend to be case studies with a more limited scope, often undertaken in the United States, which are then extrapolated to other regions . Such extrapolation is difficult and will be successful only if regional circumstances are carefully taken into account, including differences in geography, level of development, value systems and adaptive capacity. Not all analyses are equally careful in undertaking this task.

There are other shortcomings that affect the quality of analysis. While our understanding of the vulnerability of developed countries is improving – at least with respect to market impacts – good information about developing countries remains scarce. Non-market damages, indirect effects (e.g., the effect of changed agricultural output on the food processing industry), horizontal interlinkages (e.g., the interplay between water supply and agriculture; or how the loss of ecosystem functions will affect GDP), and the socio-political implications of change are also still poorly understood. Uncertainty, transient effects (the impact of a changing rather than a changed and static climate), and the influence of change in climate variability are other factors deserving more attention.

Another key problem is adaptation. There has been substantial progress in the treatment of adaptation in recent years. However, adaptation is hard to capture adequately in an impact assessment. Adaptation will entail complex behavioral, technological and institutional adjustments at all levels of society, and not all population groups will be equally adept at adapting. Some adaptations reduce impacts (e.g., crop choice). Others increase climate change (e.g., air conditioning), or increase indirect effects (e.g., irrigation creates water stresses that may increase climate impacts). The goals of adaptation are not always the same across studies. In some studies the (implicit) goal is to maintain current cropping patterns, others want to maintain current farmers' incomes, or adjust existing practices in the most efficient manner. Different goals lead to different adaptation costs and different residual impacts.

Various approaches are used to model adaptation (e.g., spatial analogues, micro-economic modeling), but they all either underestimate or overestimate its effectiveness and costs. The standard approach used in coastal impact assessment and in many agricultural models is to include in the analysis a limited number of 'prominent', but essentially arbitrarily chosen adaptations. This underestimates adaptive capacity because many powerful adaptations are excluded (Tol *et al*., 1998). Approaches based on analogues (Mendelsohn *et al*., 1994, Kumar and Parikh, 1998, Darwin, 1999) on the other hand, probably overestimate adaptive capacity because they neglect the cost of transition and learning, and impediments to adaptation. This is especially true for cases where adaptation in developed countries today is used as a proxy for worldwide adaptation to an uncertain future climate. A few studies model adaptation as an optimization process, in which agents trade off the costs and benefits of different adaptation options (Yohe *et al.*, 1995, 1996; Fankhauser, 1994). In this case, the assumed behavior may be too economically rational compared to real behavior. The goals of adaptation are not always the same across studies. In some studies the (implicit) goal is to maintain current cropping patterns, others want to maintain current farmers' incomes, or adjust existing practices in the most efficient manner? Different goals lead to different adaptation costs and different residual impacts.

Impact studies are largely confined to autonomous adaptation, that is, adaptations that occur without explicit policy intervention from the government. But in many cases governments too will embark on adaptation policies to avoid certain impacts of climate change, and may start those policies well before critical climatic change occurs – for example, by linking climate change adaptation to other development and global change actions, such as on drought and desertification or biodiversity.

The analysis is further complicated by the strong link between adaptation and other socio-economic trends. The world will substantially change in the future, and this will affect vulnerability to climate change. For example, a successful effort to roll back malaria could reduce the negative health effects on malaria risk. A less successful effort could introduce antibiotic-resistant parasites or pesticide-resistant mosquitoes, increasing vulnerability to climate change. The growing pressure on natural resources from unsustainable economic development is likely to exacerbate the impacts of climate change. However, if this pressure leads to improved management (e.g., water markets), vulnerability might decrease. Even without explicit adaptation, impact assessments therefore vary depending on the ‘type’ of socio-economic development expected in the future. The sensitivity of estimates to such baseline trends can in some cases be strong enough to reverse the sign, i.e., a potentially negative impact can become positive under a suitable development path or vice versa (Mendelsohn and Neumann, 1999).

The need for synthesis and aggregation poses challenges with respect to the spatial and temporal comparison of impacts. Aggregating impacts requires an understanding of (or assumptions about) the relative importance of impacts in different sectors, in different regions and at different times. Developing this understanding implicitly involves value judgments. The task is simplified if impacts can be expressed in a common metric, but even then aggregation is not possible without value judgments. The value judgments underlying regional aggregation are discussed and made explicit in Azar (1999), Azar and Sterner (1996) and Fankhauser *et al.* (1997, 1998). Aggregation across time, and the issue of discounting, is discussed Arrow *et al.* (1996) and Weyant and Portney (2000). Problems in aggregating across sectors are discussed in Rothman (2000).

Despite the limits in knowledge, a few general patterns emerge . They are derived from general principles, observations of past vulnerabilities, and limited modeling studies.

3. Total Impacts and Their Distribution

A number of studies have estimated the total impact of climate change (aggregated across sectors) in different regions of the world. Table 1 shows aggregate, monetized impact estimates for a doubling of atmospheric carbon dioxide on the current economy and population from the three main studies undertaken since the IPCC Second Assessment Report (Pearce *et al.*, 1996), and summarises the ‘first generation’ of studies already reviewed in the Second Assessment Report for comparison. The numerical results remain speculative, but they can provide insights on signs, orders of magnitude, and patterns of vulnerability. Results are difficult to compare because different studies assume different climate scenarios, make different assumptions about adaptation, use different regional disaggregation and include different impacts. The Nordhaus and Boyer (1999) estimates, for example, are more negative than others, partly because they factor in the possibility of catastrophic impact. The Mendelsohn *et al.* (1996) and Tol (1999a) estimates, on the other hand, are driven by optimistic assumptions about adaptive capacity and baseline development trends, which results in mostly beneficial impacts.

Table 1. Estimates of the regional impacts of climate change.[a]

	‚First Generation’	Mendelsohn *et al.*		Nordhaus / Boyer
	2.5°C	1.5°C	2.5°C	2.5°C
North America	-1.5			
USA	-1.0 to -1.5		0.3	-0.5

OECD Europe	-1.3			
EU	-1.4			-2.8
OECD Pacific	-1.4 to -2.8			
Japan			-0.1	-0.5
Eastern Europe & fUSSR	0.3			
Eastern Europe				-0.7
fUSSR	-0.7			
Russia			11.1	0.7
Middle East	-4.1			-2.0[c]
Latin America	-4.3			
Brazil			-1.4	
South & Southeast Asia	-8.6			
India			-2.0	-4.9
China	-4.7 to -5.2		1.8	-0.2
Africa	-8.7			-3.9
DCs		0.12	0.03	
LDCs		0.05	-0.17	
World				
output weighted	-1.5 to -2.0		0.1	-1.5
population weighted				-1.9
at world average prices				
equity weighted				

[a] Figures are expressed as impacts on a society with today's economic structure, population, laws etc. Mendelsohn *et al.*'s estimates denote impact on a future economy. Estimates are expressed as per cent of Gross Domestic Product. Positive numbers denote benefits, negative numbers denote costs.

[b] Figures in brackets denote standard deviations. They denote a lower bound to the real uncertainty

[c] high-income OPEC

[d] China, Laos, North Korea, Vietnam

Source: Pearce et al. (1996); Mendelsohn *et al*. (1996); Nordhaus and Boyer (2000); Tol (1999a).

Standard deviations are rarely reported, but likely amount to several times the 'best guess'. They are larger for developing countries, where results are generally derived through extrapolation rather than direct estimation. This is illustrated by the standard deviations estimated by Tol (1999a), reproduced in Table 1. Downing *et al*. (1996) provide a much higher range of uncertainty, from nearly 0 impact to almost 40% of world GDP, reflecting a much wider range of assumptions than are commonly included. The Tol estimates probably still underestimate the true uncertainty, for example because they exclude omitted impacts and severe climate change scenarios.

Overall, the current generation of aggregate estimates may understate the true cost of climate change because they tend to ignore extreme weather events; underestimate the compounding effect of multiple stresses; and ignore the costs of transition and learning. However, studies may also have overlooked positive impacts of climate change and not adequately accounted for how development could reduce impacts of climate change. Our current understanding of (future) adaptive capacity, particularly in developing countries, is too limited, and the inclusion of adaptation in current studies too varied to allow a firm conclusion about the direction of the estimation bias.

While our understanding of aggregate impacts remains limited, it is constantly improving. Some sectors and impacts have gained more analytical attention than others, and as a result are better understood. Agricultural and coastal impacts in particular are now well studied. Knowledge about the health impacts of climate change is also growing. Several attempts have been made to identify other non-market impacts, such as changes in aquatic and terrestrial ecological systems, and ecosystem services, but a clear and compatible quantification has not yet emerged. A few generic patterns and trends are nevertheless appearing:

- Market-impacts are lower than initially thought, and may be in some countries and sectors positive – at least in developed regions. The downward correction is largely due to the effect of adaptation, which is more fully (although far from perfectly) captured in the latest estimates. Efficient adaptation reduces the net costs of climate change because the cost of such measures is lower than the concomitant reduction in impacts. However, impact uncertainty and lack of capacity may make efficient and error-free adaptation difficult.

- Even so, market impacts could be significant in some conditions, such as a rapid increase in extreme events, which might lead to large losses and/or costly over-adaptation (for example sea walls to protect culturally important areas) (see Downing *et al.*, 1998).

- Non-market impacts will be more pronounced than early aggregate studies conveyed, as many (but not all) of the effects that have not yet been quantified could be negative. In particular, there is concern about the impact on human health and mortality. Although few studies have taken adequate account of adaptation or development, the literature suggests substantial negative health impacts in developing countries, mainly because of insufficient basic health care (e.g., Martens *et al.*, 1997; Tol and Dowlatabadi, forthcoming). There is also concern about the impact on water resources (e.g., Arnell, 1999) and ecosystems (e.g., White *et al.,* 1999, Markham, 1996).

- Developing countries are more vulnerable to climate change than developed countries because their economies rely more heavily on climate-sensitive activities (in particular agriculture), and many already operate close to environmental and climatic tolerance levels (e.g., with respect to coastal and water resources). Developing countries are poorly prepared to deal with the climate variability and natural hazards they already face today (World Bank 2000). If current development trends continue, few of them will have the financial, technical, and institutional capacity and knowledge base to deal with the additional stress of climate change.

- Differences in vulnerability will not only be observed between regions, but also within them. Some individuals, sectors, and systems will be less affected, or may even benefit, while other individuals, sectors, and systems may suffer significant losses. There are indications that poor people in general, wherever they live, may be more vulnerable to climate change than the better to do. Differences in adaptive capacity are again a key reason for this pattern.

- Estimates of global impact are sensitive to the way figures are aggregated. Because the most severe impacts are expected in developing countries, the more weight is assigned to developing countries, the more severe are aggregate impacts (see the next section). Using a simple adding of impacts, some studies estimate small net positive impacts at a few degrees of warming, while others estimate small net negative impacts.

- Net aggregate benefits do not preclude the possibility of a majority of people being negatively affected, and some population groups severely so. This is due to the fact that developed economies, many of which could have positive impacts, contribute the majority of global production but account for a smaller fraction of world population. However, there are no studies so far that have consistently estimated the total number of people negatively affected by climate change.

Most impact studies assess the consequences of climate change at a particular concentration level or a particular point in time, thus providing a static "snap shot" of an evolving, dynamic process. One of the main challenges of impact assessments is to move from this static analysis to a dynamic representation of impacts as a function of shifting climate characteristics, adaptation measures and exogenous trends like economic and population growth. Little progress has been made in this respect, and our understanding of the time path aggregate impacts will follow under different warming and development scenarios, is still extremely limited. Among the few explicitly dynamic analyses are Sohngren and Mendelsohn (1999), Tol and Dowlatabadi (forthcoming) and Yohe *et al.* (1996).

Dynamic studies remain highly speculative at this point, as the underlying models only provide a very rough reflection of real-world complexities. Figure 1 shows examples from three studies. While some analysts still work with relatively smooth impact functions (e.g. Nordhaus and Boyer 2000), there is growing recognition (e.g., Tol. 1999b; Mendelsohn and Schlesinger 1999) that the climate impact dynamics – the conjunction of climate change, societal change, impact, and adaptation – is certainly not linear, and might be quite complex.

Impacts in different sectors may unfold along fundamentally different paths. Coastal impacts, for example, are expected to grow continuously over time, more or less in proportion to the rise in sea level. The prospects for agriculture, in contrast, are more diverse. While some models predict aggregate damages already for moderate warming, many studies suggest that under some (but not all) scenarios the impact curve might be hump-shaped, with short-term (aggregate) benefits under modest climate change turning into losses under more substantial change (e.g., Mendelsohn and Schlesinger 1999).

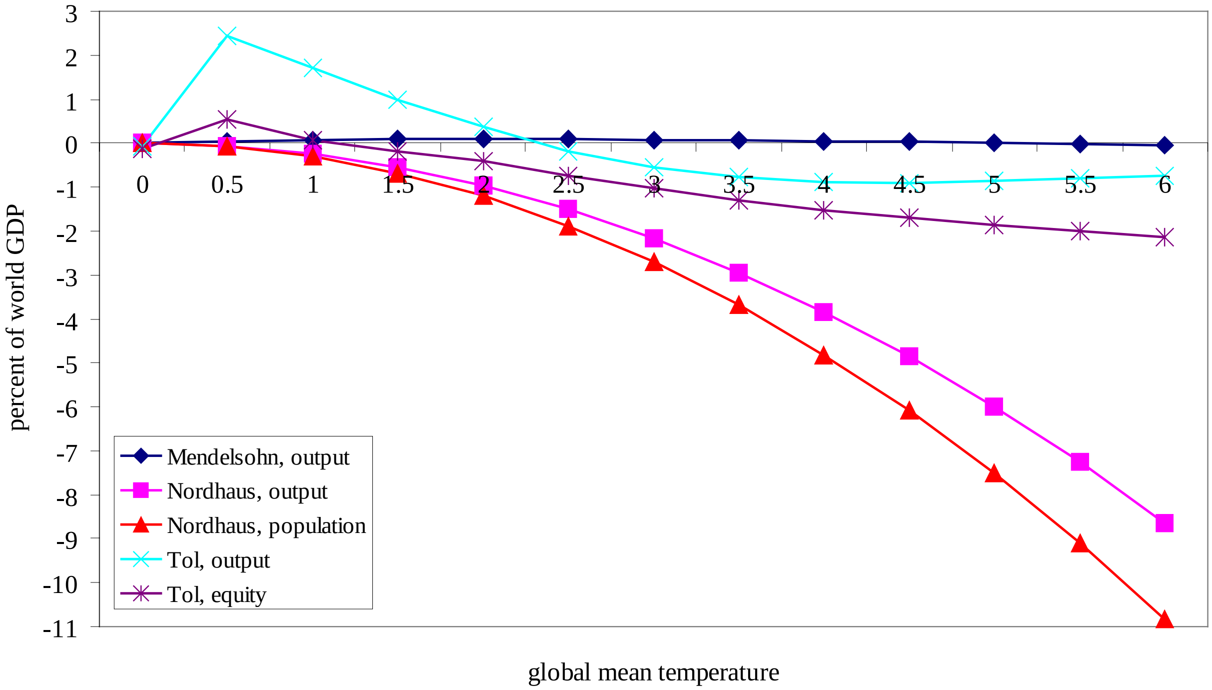

Figure 1. The impact of climate change as a function of the global mean temperature, according to Mendelsohn *et al.* (1996), Nordhaus and Boyer (2000), and Tol (1999a,b). Mendelsohn *et al.* aggregate impacts across different regions weighted by regional output. Nordhaus and Boyer aggregate either weighted by regional output or weighted by regional population. Tol aggregates either by regional output or by equity, that is, by the ratio of world per capita income to regional per capita income.

4. Marginal cost estimates

The marginal damages caused by a metric ton of carbon dioxide emissions in the near future were estimated in the Second Assessment Report at US$5 – 125 per tC. Most estimates are in the lower part of that range, and higher estimates only occur through the combination of a high vulnerability with a low discount rate (see Pearce *et al*., 1996). Plambeck and Hope (1996), Eyre *et al.* (1997), Tol (1999c) and Tol and Downing (2000) have since reassessed the marginal damage costs of greenhouse gas emissions. Performing extensive sensitivity and uncertainty analyses, they arrive at essentially the same range of numbers as do Pearce *et al.* (1996).

Table 2 reproduces some estimates. The first four studies were also reported in Pearce *et al.* (1996). Most estimates are in the range $5-20/tC, but higher estimates cannot be excluded. The uncertainty about the marginal damage costs is right-skewed, so the mean is higher than the best guess, and nasty surprises are more likely than pleasant surprises.

More recent studies reported by Eyre *et al.* (1999 – here represented by Tol, 1999c, and Downing's estimates in Tol and Downing, 2000) basically confirm the earlier numbers, but also point out that the marginal damage cost estimate is extremely sensitive to the discount rate.

The alternative estimate of Tol (1999c) uses equity weighting, an aggregation procedure that takes into account that a dollar is worth more to a poor person than to a rich one (see Fankhauser *et al.*, 1997, 1998). Equity weighting puts more emphasis on the impacts in developing countries, so the marginal damage cost estimate is considerably higher.

All the studies in Table 2 are based on what we called the 'first generation' of studies of total economic impacts , except the Tol estimate in Tol and Downing (2000). This last study uses more optimistic, estimates of the impact of climate change (cf. Table 1). Consequently, the marginal damage costs are low and, for a high discount rate, may even be negative (i.e. marginal benefits).

Table 2. Estimates of the marginal damage costs of carbon dioxide emissions (in $/tC)

Stud\PRTP[a]	0%	1%	3%
Nordhaus (1994a)			
- Best guess			5
- Expected value			12
Peck and Teisberg (1992)			10-12
Fankhauser (1994)[b]		20 (6-45)	
Cline (1992, 1993)		6-124	
Plambeck and Hope (1996)[c]	440	46	21
	(390-980)	(20-94)	(10-48)
Tol and	20	4	-7
Downing (2000)[d]	75	46	16
Tol (1999c)[e]			
- Best guess	73	23	9
- Equity weighted	171	60	26

[a] Pure rate of time preference, or utility discount rate. The more conventional consumption, or money discount rate equals the utility discount rate plus the growth rate of per capita income.

[b] Expected value, uncertainty about the discount rate included.

[c] Plambeck and Hope (1996) use pure rates of time preference of 0, 2% and 3%. The range is the 95% confidence interval (parametric uncertainty only).

[d] Tol and Downing (2000) report estimates from Tol's *FUND* model (top line) and from Downing's *Open Framework* model (bottom line).

[e] Tol uses consumption discount rates of 1%, 3% and 5%; the assumed per capita income growth is roughly 2%.

Estimates of the marginal costs of other greenhouse gases are fewer. Table 3 displays some estimates for methane (CH_4) and Table 4 for nitrous oxide (N_2O). Table 5 displays the ratio of the marginal costs of both gases to the marginal costs of carbon dioxide.

Table 3. Estimates of the marginal damage costs of methane emissions (in $/tCH_4$)

Study\PRTP[a]	0%	1%	3%
Fankhauser (1994)[b]	108 (48-205)		
Tol and	-90	-117	-119
Downing (2000)[c]	256	233	139
Tol (1999c)[d]			
- Best guess	141	89	52
- Equity weighted	517	295	170

[a] Pure rate of time preference, or utility discount rate. The more conventional consumption, or money discount rate equals the utility discount rate plus the growth rate of per capita income.

[b] Expected value, uncertainty about the discount rate included.

[c] Tol and Downing (2000) report estimates from Tol's *FUND* model (top line) and from Downing's *Open Framework* model (bottom line).

[d] Tol uses consumption discount rates of 1%, 3% and 5%; the assumed per capita income growth is roughly 2%.

Table 4. Estimates of the marginal damage costs of nitrous oxide emissions (in $/tN_2O$)

Study\PRTP[a]	0%	1%	3%
Fankhauser (1994)[b]	2895 (805-7235)		
Tol and	2351	782	-270
Downing (2000)[c]	11385	6636	2078
Tol (1999c)[d]			
- Best guess	7559	2201	817
- Equity weighted	16862	5459	2217

[a] Pure rate of time preference, or utility discount rate. The more conventional consumption, or money discount rate equals the utility discount rate plus the growth rate of per capita income.

[b] Expected value, uncertainty about the discount rate included.

[c] Tol and Downing (2000) report estimates from Tol's *FUND* model (top line) and from Downing's *Open Framework* model (bottom line).

[d] Tol uses consumption discount rates of 1%, 3% and 5%; the assumed per capita income growth is roughly 2%.

Table 5. Global damage potential, impact per tonne of CH_4 and N_2O relative to impact per tonne of CO_2.

	Tol[a]	Tol[b]	Downing[c]	Kandlikar[d]	Fankhauser[d]	Hammitt[f]	GWP[g]
CH_4	14	-122	19	12	20	11	25
N_2O	348	818	531	282	333	355	320

[a] Emissions between 1995 and 2004; time horizon: 2100; consumption discount rate: 3%; model: *FUND*1.6; scenario: IS92a; simple sum; no higher order effects.

[b] Emissions between 1995 and 2004; time horizon: 2100; utility discount rate: 1%; model: *FUND*2.0; scenario IS92a; simple sum; no higher order effects.

[c] Emissions between 1995 and 2004; time horizon: 2100; utility discount rate: 1%; model: *Open Framework*; scenario IS92a; simple sum; no higher order effects.

[d] Time horizon: 100 years; discount rate: 2%; scenario: IS92a; quadratic damages.

[e] Emissions between 1991 and 2000; time horizon: 2100; GDP is calculated as ratio of mean marginal damages.

[f] Emissions in 1995; time horizon: 2100; discount rate: 3%; scenario: IS92a; middle case.

[g] Gobal warming potential; time horizon: 100 years.

Sources: Tol (1999c), Tol and Downing (2000), Kandlikar (1995, 1996), Fankhauser (1995), Hammitt *et al.* (1996), Schimel *et al.* (1996).

Roughly, the ratio of the marginal cost of N_2O to CO_2 equals the Global Warming Potentials (GWP) of nitrous oxide. This is no real surprise, as the two gases have similar lifetimes so that discounting has the same effect on the nominator and the denominator. For the same reason, the ratio of marginal costs of short-lived methane to carbon dioxide differs from the GWP of methane, and according to some studies by a whole lot.

It should be noted that the marginal cost ratios (and to some extent the global warming potentials) reflect a cost-benefit perspective on climate policy. National and international climate policy apparently favours a cost-effectiveness approach, that is, an emission reduction strategy that meets a given target at the lowest possible cost. From a cost-effectiveness perspective, the appropriate trade-off between gases is the ratio of the marginal reduction costs, or the shadow prices of the respective constraints. Manne and Richels (2000) and Tol *et al.* (forthcoming) show that this ratio is also very different from the GPW, particularly in the case of methane. Methane is so short-lived in the atmosphere that near-term emission reduction hardly contributes to long-term goals of atmospheric stabilization.

5. Discussion: Sensitivity of marginal cost estimates to methodological assumptions

Estimates of the marginal costs of climate change are perhaps even more uncertain than those about total impacts. At a time when the quality of numerical results is still low, a key benefit of impact analysis lies in the insights it provides on the sensitivity of results. Sensitivity analysis offers critical information about the attributes of the damage function likely to be most influential to the choice of policy, and – by implication – where additional climate change impacts research is most needed.

Inclusion and metric

Most aggregate and marginal analyses are based on integrated assessment models. The impact functions used in integrated assessment models vary greatly with respect to the level of modeling sophistication, the degree of regional aggregation, the choice of indicator and other characteristics.

Many models have used monetary terms, e.g., dollars, to measure impacts. The spatially detailed models (e.g., Alcamo, 1994) pay some attention to unique ecosystems. Large-scale disruptive climate changes have received little attention, except for a survey of expert opinions (Nordhaus, 1994b) and analytical work (e.g., Gjerde *et al.*, 1998). Some climate change impact studies restrict themselves to sectors and countries that are relatively well-studied (e.g., Mendelsohn and Neumann, 1999). Others try to be comprehensive, despite the additional uncertainties (e.g., Hohmeyer and Gaertner, 1992). Most studies are somewhere in the middle (see Tol and Fankhauser, 1998). Some studies rely on an aggregate description of all climate change impacts for the world as a whole (e.g., Nordhaus, 1994a). Other studies disaggregate impacts with substantial spatial detail (e.g., Alcamo, 1994), but sacrifice the quality and amount of input data.

Aggregation

When results are aggregated, i.e., combining the winners (e.g., agriculture in northern Europe) with the losers (e.g., sea level rise in the Maldives), a mildly negative or mildly positive impact can result and geographic variation is typically lost. In a previous ExternE project (Eyre *et al.*, 1998), Downing and Tol investigated the effect of regional aggregation. At the country level, there are many more countries that are winners or losers, and by a larger amount, than implied by region-average calculations. For example, half of the OECD European countries have net benefits, and half have net costs. The total of the benefits for all countries with benefits is three times greater than the total of the benefits calculated at the regional level. Similarly, the total of the costs for countries with net costs is some 25% greater than the net costs calculated at the regional level. Thus, regional aggregation may hide some of the extreme impacts (both beneficial and adverse) and imply transfers of welfare between countries.

Equity and welfare

More detailed analyses stress the distributional consequences of climate change. The highly aggregated approaches tend to point out implications for efficiency, and in practice often ignore equity (see Tol, forthcoming, for an exception). The detailed approaches tend to identify issues regarding equity, although that justice interpretation is typically left to the reader. The equity-weighting scheme reported in Table 1 is fairly simple – and one could argue would be acceptable to most analysts. Similar estimates with and without weighting are some three-fold greater. Studies that would include macro-scale discontinuities, would stress precaution.

The comparison of impacts, i.e., the relative weight assigned to impacts in different regions and at different times, is one of the most sensitive aspects of aggregate analysis. With the exception of the discount rate, little explicit attention is paid to this aspect of climate change impacts, although studies differ considerably in their implicit assumptions. Fankhauser *et al.* (1997) and Azar (1999) are among the few studies to make their aggregation assumptions explicit. They find that, in general, the more weight one puts on the distribution of the impacts of climate change, the more severe are the aggregate impacts. Fankhauser's (1995) estimate of the annual global damage of 2xCO2, for instance, is based on the implicit assumption that people are neutral with respect to distribution (that is, losses to the poor can be compensated by equal gains to the rich) and risk (that is, a 1:1,000,000 change of losing $1 million is equivalent to losing $1 for certain). Replacing these assumptions with either standard risk-aversion or mild inequity-aversion, the global damage estimate increases by about a third (Fankhauser *et al.*, 1997). Marginal impacts are more sensitive. For the same changes in assumptions, Tol (1999c) finds a three-fold increase in the marginal damage estimate. See Table 2. The sensitivity of aggregate impact estimates is further illustrated in Figure 1.

Shape of the damage function

Most impact studies still look at the equilibrium effect of one particular level of greenhouse gas concentrations, usually $2xCO_2$. A full, transient analysis, however, requires impacts to be expressed as a function of change in greenhouse gas concentrations.[2] With so little information to estimate such functions, studies have to rely on sensitivity analyses. The policy implications can be profound. Compare, for example, the profile of impacts under a linear and a cubic damage function. Relative to the linear specification, a cubic function implies low near-term impacts, but rapidly increasing impacts further in the future. Using conventional discounting, this means that early emissions under a cubic damage function will cause less damage over their atmospheric lifetime, compared to a scenario with linear damages. The marginal damage caused by emissions further in the future, on the other hand, is much higher if we assume a cubic damage function (Peck and Teisberg, 1994).

Manne and Richels (1995) use a 'hockey-stick' function, with relatively small impacts before $2xCO_2$ and rapidly worsening impacts beyond $2xCO_2$. In this analysis, it is economically efficient to stabilize carbon dioxide concentrations. The stabilization level depends on the shape of the hockey stick. Other cost-benefit analyses, assuming lower climate change impact in the long run, have difficulty justifying concentration stabilization at any level.

The Rate of Change

Although most impact studies focus on the level of climate change, the rate of climate change is generally believed to be an important determinant in many instances because it affects the time available for adaptation. Again, the paucity of underlying impact studies forces integrated assessors to use exploratory modeling. Under most business as usual scenarios, the rate of climate change is larger in the short run than in the long run because emissions increase faster in the short run; this is even more pronounced in emission reduction policy scenarios. Indeed, if considering the rate of change, both tolerable window and safe corridor analyses (Toth *et al.*, 1997; Petschel-Held *et al.*, 1999; Alcamo and Kreileman, 1996) often find the rate of change to be the binding constraint in the next few decades.

Discount Rate and Time Horizon

Aggregate models suggest that the most severe impacts of climate change will occur further in the future. The chance of large-scale discontinuities (e.g., the collapse of the thermohaline circulation or the West-Antarctic ice sheet) is also higher in the future. The outcome of policy analysis is therefore sensitive to the weight afforded to events occurring in the remote future. In other words, estimates are sensitive to the choice of time horizon (Azar and Sterner, 1996; Cline, 1992 Hasselmann *et al.*, 1997) and the discount rate, i.e., the value of future consumption relative to today's. The literature on discounting is reviewed in Markandya *et al.* (2001 and Portney and Weyant (1999). Numerical analysis (e.g., Tol 1999c) has shown that estimates of marginal damage can vary by as much as a factor ten for different (and reasonable) assumptions about the discount rate. This makes the discount rate the second-most important determinant for the marginal damage (see Table 2), behind

[2] Impacts are, of course, also a function of social change. This is discussed above.

the question whether or not countries cooperate in reducing emissions; Nordhaus and Yang, 1996; Tol, 1999d).

6. Conclusion

The economic impact of climate change is a hard subject to study. Current methodologies are weak, and uncertainties remain large. Nonetheless, we draw four conclusions can be drawn with some confidence.

First, vulnerabilities differ considerably between regions. Poorer countries would face proportionally higher negative impacts than richer countries.

Second, (sustainable) development may reduce overall vulnerability to climate change, as richer societies tend to be better able to adapt and their economies are less dependent on climate. But it is not known whether development will be fast enough to reduce poorer countries' vulnerability in time. Delays in reducing climate impacts could affect achievement of sustainable development targets.

Third, the impacts of moderate global warming (say, up to 2-3°C in 2100) are mixed. Poorer countries are likely to be net losers, richer countries (especially in mid- to northern latitudes) may gain from moderate warming. The global picture depends on how one aggregates. If aggregation is on a dollar basis, the world as a whole may win a bit. If aggregation is based on people, the world as a whole may lose. In addition, impacts to natural ecosystems could be negative even at these levels of warming.

Fourth, the impacts of more substantial global warming (more than 2-3°C or sooner than 2100) are probably negative, and increasingly so for higher or faster warming. This holds for the majority of countries. Note that, because of the slow rate of change in the energy sector and the atmosphere, we are probably already committed to at least 2°C of warming.

It may be helpful to relate emerging relative confidence in climate change with our sense of progress in valuing climate change damages (see Figure XX). Some climatic changes can be predicted with relatively high confidence—global and regional warming, sea level rise and rising CO_2 concentrations. These changes will affect, among other things, agroclimatic suitability, heat stress and demand for water. Less confidence is ascribed to changes in storm- and water-related effects: precipitation, precipitation intensity, wind speeds, sunshine, etc. However, the range of scenarios generally fall within defined limits, leading to modest confidence in expected impacts on crop production, water systems and other resources. Low confidence is likely to continue for some time in our ability to project changes in the risk of extreme events (prolonged drought, intense cyclones, etc.) and large-scale changes such as collapse of major ice sheets. We have indicated above that confidence is higher in valuation of market impacts than non-market impacts, and equity and welfare effects are especially contentious.

What can we then conclude about the conjunction of confidence in climate change and the valuation of impacts (not ignoring uncertainties in GHG emissions and impacts science as well)? It does not take too much imagination to reach very large damages, but they require incorporating relatively uncertain climate changes and impacts, and the kinds of valuations of ecological and human systems that are not customary in present assessment models – that is the lower and right-hand cells in the table. On the other hand, we have relatively high confidence that the market-impacts of some trends in the climate system will have benefits in some regions and sectors (e.g., northern agriculture) and costs in others (e.g., coastal habitation in vulnerable deltas). In between these two poles, where climate futures are at best uncertain risks and valuation of non-market impacts is poorly understood, remains a fruitful research frontier.

Overall, there is a clear economic rationale for reducing greenhouse gas emissions. By how much, where and when cannot be answered without also considering the costs of emission reduction. One needs to compare the marginal damage costs of climate change to the marginal costs of emission reduction . The marginal damage costs of carbon dioxide emissions are uncertain, but the current literature suggests that estimates in excess of $50/tC require relatively unlikely scenarios of climate change, impact sensitivity and economic values.

This does not mean that emission reduction targets can be determined based on a simple cost-benefit test. The distribution of impacts, risks, and uncertainty also need to be factored into the analysis. While relatively little about climate change impacts is known with certainty, today's policy makers are not required to make once-for-all decisions binding their successors over the next century. There will be ample opportunities for mid-course adjustments. Climate negotiations are best viewed as an ongoing process of "act-then learn". Today's decisions makers must aim at evolving an acceptable hedging strategy -- one that balances the risks of premature actions against those of waiting too long.

The first step is to determine the sensitivity of *today's* decisions to major uncertainties in the greenhouse debate. How important is it to know what energy demands will be in thirty years? To identify the technologies that will be in place to meet those demands? Or to be able to predict damages for the second half of the next century. An exhaustive analysis of these questions has yet to me undertaken, but considerable insight can be gleaned from an Energy Modeling Forum Study conducted several years ago (EMF-14, 1997). In the study, seven modeling teams addressed a key consideration in climate policy making: concerns about low probability but high consequence events.

The study assumed that uncertainty would not be resolved until 2020. Two parameters were varied: the mean temperature sensitivity factor and the cost of damages associated with climate change and variability. The unfavorable high consequence scenario was defined as the top 5 percent of each of these two distributions. Two surveys of expert opinion were used for choosing the distribution of these variables.

The analysis showed that the degree of hedging is dependent on the stakes, the odds, society's attitude towards risk and the cost of greenhouse insurance. Also critical is the timing of the resolution of key uncertainties The longer it takes to resolve uncertainty, the greater the need for precautionary action. This underscores the importance of scientific research among the portfolio of options for dealing with climate change.

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