HOW MUCH DAMAGE WILL CLIMATE CHANGE DO? RECENT ESTIMATES

Richard S.J. Tol[a,*], Samuel Fankhauser[b], Richard G. Richels[c] and Joel B. Smith[d]

September 2000

Working Paper **SCG-2**

Research Unit Sustainability and Global Change

Centre for Marine and Climate Research, Hamburg University

Bundesstrasse 55, 20146 Hamburg, Germany

http://www.uni-hamburg.de/wiss/

Abstract

Two reasons to be concerned about climate change are its unjust distributional impact and its negative aggregate effect on economic growth and welfare. Although our knowledge of the impact of climate change is incomplete and uncertain, economic valuation is difficult and controversial, and the effect of other developments on the impacts of climate change is largely speculative, we find 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 countries in hot climates, but may have a net positive effect on rich countries in temperate climates. If one counts dollars, the world aggregate may be positive. If one counts people, the world aggregate is probably negative. Negative impacts would become more negative, and positive impacts would turn negative for more substantial warming. The marginal costs of carbon dioxide emissions are uncertain and sensitive to assumptions that partially reflect ethical positions, but unlikely to be larger that $50/tC.

Keywords

climate change, impacts, valuation, marginal cost

[a,*] Hamburg, Vrije and Carnegie Mellon Universities. Corresponding author: ZMK, Hamburg University, Bundesstrasse 55, 20146 Hamburg, Germany, +49 40 42838 7007 (voice), +49 40 42838 7009 (fax), tol@dkrz.de
[b] European Bank for Reconstruction and Development
[c] Electric Power Research Institute
[d] Stratus Consulting Inc.

1. Introduction

Climate change continues to figure prominently on the environmental policy agenda, both nationally and internationally. With the fate of the Kyoto Protocol still in the balance, and as it has become clear that climate is changing, partly because of human activities, and impacts are becoming more evident (e.g., Wuethrich, 2000), many are asking what appropriate emission targets should be. Some people argue for emission controls because climate change 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 climate instabilities (e.g., a shutdown of the gulf stream). A fourth group argues that emission reduction is costly too, and that these costs should be balanced against the avoided costs of climate change. The subject of this paper – the economic, or monetary, costs of climate change – provides useful information on all these 'reasons for concern' (Smith *et al.*, 2001), but it is particularly relevant for the first and forth concern (distribution of impact; and the 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 individual impacts to a more tractable set of regional or sectoral indicators. The challenge is to identify a set of 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), 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). 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 and consistently compare the avoided impacts of climate change with mitigation costs, it is meaningful, indeed necessary to express the benefits of mitigated climate change in the same metric as the costs of emission reduction, that is money (Nordhaus, 1991, 1994; Cline, 1992; Downing *et al.*, 1995, 1996; Hohmeyer and Gaertner, 1992; Fankhauser, 1995; Mendelsohn and Neumann, 1999; Titus, 1992; Tol, 1995). 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). Thus, 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). It should be noted, though, that difficulties in valuation are only one of many problems that plague impact assessments. The next section outlines the main issues limitations of economic impact assessment.

A further advantage of expressing (avoided) impacts of climate change in money is that climate policy can be compared to other policies. One would like to avoid spending so much on greenhouse gas emission reduction that other worthwhile goals – education, public health care, urban air quality to name a few – would suffer a lack of resources as a consequence. This aim of monetisation has not been pursued to a great extent in the literature.

2. Limitations

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

Perhaps the main difficulty in impact assessment is our still incomplete understanding of climate change itself. Both distributional and aggregate analysis make heavy demands about the regional details of climate change, one of the major uncertainties in climate change models (Mahlman, 1997). Impacts are local, and impacts are due to weather variability. 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.

Uncertainties 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 studies undertaken in developed countries, often 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), the link between market and non-market effects (e.g., 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 climate variability are other factors deserving more attention. Because of these knowledge gaps, distributional analysis has to rely on (difficult) expert judgment and extrapolation if it is to provide a comprehensive picture.

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. 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, Mendelsohn and Dinar, 1998, Darwin, 1999) on the other hand, probably overestimate adaptive capacity because they neglect the cost of transition and learning. 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 smart compared to real behavior. The goals of adaptation are not always the same across studies. Do we want to maintain current cropping patterns, do we want to maintain current farmers’ incomes, or do we want to produce food? 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. Governments may want to embark on adaptation policies to avoid certain impacts of climate change. Governments may even want to start those policies well before critical climatic change will occur. Governments may want to do this as an alternative to greenhouse gas emission reduction. Unfortunately, our current understanding of impact and adaptation costs does not permit us to make a well-informed trade-off between emission abatement policies and proactive adaptation policies.

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 of climate change. 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 fall. 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).

“Horizontal” interlinkages, such as the interplay between different impact categories (e.g., water supply and agriculture), the effect of non-climate related stress factors, adaptation and exogenous development trends are crucial determinants of impact but have not been fully considered in many studies.

Despite the limits in knowledge, a few general patterns emerge with regard to the distribution of climate change impacts. These patterns are derived from general principles, observations of past vulnerabilities, and limited modeling studies. These patterns are discussed in Section 3. Section 4 reviews the few estimates of the world aggregate impact and, more importantly, the marginal damage costs of emissions. Marginal damage cost is the damage avoided by a small reduction in current greenhouse gas emissions.

3. Distribution

A number of studies have estimated the total impact (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. For comparison, the table also shows the range of estimates found in the 'first generation' studies surveyed in the Second Assessment Report (Pearce *et al.*, 1996). Clearly, in all these studies there are substantial uncertainties about the total impacts to regions and whether some regions will have net benefits or net damages at certain changes in global climate. But these and other studies clearly suggest that:

- developing countries are, on the whole, more vulnerable to climate change than developed countries;
- at low magnitudes of climate change, damages are more likely to be mixed across regions, but higher magnitudes virtually all regions have net damages;
- the distribution of risk may change at different changes in climate.

Developing countries tend to be more vulnerable to climate change 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). And if current development trends continue, few developing countries will have the financial, technical, and institutional capacity and knowledge base for efficient adaptation (a key reason for the higher health impacts)..

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

	‚First Generation'	Mendelsohn et al.		Nordhaus / Boyer	Tol[b]
	2.5°C	1.5°C	2.5°C	2.5°C	1.0°C
North America	-1.5				3.4(1.2)
- USA	-1.0 to -1.5		0.3	-0.5	
OECD Europe	-1.3				3.7 (2.2)
- EU	-1.4			-2.8	
OECD Pacific	-1.4 to -2.8				1.0 (1.1)
- Japan			-0.1	-0.5	
Eastern Europe & fUSSR	0.3				2.0 (3.8)
- Eastern Europe				-0.7	
- fUSSR	-0.7				

- Russia			11.1	0.7	
Middle East	-4.1			-2.0[c]	1.1 (2.2)
Latin America	-4.3				-0.1 (0.6)
- Brazil			-1.4		
South & Southeast Asia	-8.6				-1.7 (1.1)
- India			-2.0	-4.9	
China	-4.7 to -5.2		1.8	-0.2	2.1 (5.0)
Africa	-8.7			-3.9	-4.1 (2.2)
DCs		0.12	0.03		
LDCs		0.05	-0.17		
World					
- output weighted	-1.5 to -2.0		0.1	-1.5	2.3 (1.0)
- population weighted				-1.9	
- at world average prices					-2.7 (0.8)
- equity weighted					0.2 (1.3)

[a] Estimates are incomplete and our confidence in individual numbers is very low. There is a considerable range of uncertainty around estimates. Tol's estimated standard deviations are lower bounds to the real uncertainty. Figures are expressed as impacts on a society with today's economic structure, population, laws etc. Mendelsohn'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

[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).

Table 1 shows that the impacts of climate change will not be distributed equally. This does not only hold for regions. 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 a number of reasons for this.

Susceptibility to climate change differs. A clear example is sea level rise, which mostly affects coastal zones. People living in the coastal zone will generally be negatively affected by sea level rise, but the numbers of people differ by region. For example, Nicholls *et al.* (1999) found that under a sea level rise of about 40 cm by the 2080s and assuming increased coastal protection, 55 million people would be flooded annually in South Asia, 21 million in Southeast Asia, the Philippines, Indonesia, and New Guinea, 14 million in Africa, and 3 million people in the rest of the world. The relative impacts in small island regions are also significant. In addition, the Atlantic coast of North and Central America, the Mediterranean, and the Baltic are projected to have the greatest loss of wetlands. Inland areas only face secondary effects, which unlike the negative primary effects, may be either negative or positive (Darwin and Tol, in press; Yohe *et al.*, 1996).

Another example is agriculture, which is a major economic sector in some countries and a small one in others. Agriculture is one of the sectors most susceptible to climate change, so countries with a large portion of the economy in agriculture are more vulnerable than countries with a lower share. And these shares vary widely. While OECD countries have about 2-3% of their gross domestic product (GDP) from agriculture, African countries have 5 to 58% (World Resources Institute, 1998). Those with high shares of economic output coming from agriculture tend to be located in the lower latitudes.

Activities at their margin of climatic suitability have the most to lose from climate change, should local conditions worsen, and have the most to win, should conditions improve. One example is subsistence farming under severe water stress, for instance, in the semi-arid regions of Africa or South Asia. A decrease of precipitation, an increase in evapotranspiration, or higher interannual variability (particularly, longer droughts) could tip the balance from a meager livelihood to no livelihood at all. An increase of precipitation (and so on) could have the reverse effect. Whether climatic conditions improve or deteriorate, the unique cultures often found in marginal areas could be lost.

Numerous modeling studies of shifts in production of global agriculture, including Kane et al., (1992), Rosenzweig and Parry (1994), Darwin *et al.*, (1995), Parry *et al.*, (1999), and Darwin (1999), found that while changes to total global output of agriculture are estimated to be small, production in high latitude countries is estimated to increase and production in low latitude countries are estimated to decrease. (Results in the temperate zone are mixed.) Low latitude countries tend to be least developed and depend heavily on subsistence farming. On current development trends they will continue to have a relatively high share of their GDP in agriculture. So, the impacts of declines in agricultural output on low latitude countries will likely be proportionately greater than any gains in high latitude countries.

Vulnerability to health effects of climate change also differs across regions and within countries. Wealthier countries will be better able to cope with risks to human health than less wealthy countries. For example, adjacent countries sharing the same climate zone, but with differing socioeconomic conditions can have very different health risks. There are approximately a thousand times more cases of dengue fever on the Mexican side of the U.S.-Mexico border than there are in Texas (U.S. National Assessment, 2000). Within countries, risks also vary. In a country such as the United States, the very young and the very old are most vulnerable to heat waves and cold spells, so regions with a rapidly growing or rapidly aging population would have relatively large health impacts. In addition, poor people in wealthy countries may also be more vulnerable to health impacts than those with average incomes in the same countries. For example, Kalkstein and Greene

(1997) found that residents of inner cities in the United States are at greater risk of heat stress mortality than others.

Adaptive capacity differs considerably between sectors and systems. The ability to adapt and cope with climate change impacts is a function of wealth, technology, information, skills, infrastructure, institutions, equity, empowerment, and ability to spread risk. The poorest in societies are most vulnerable to climate change. Poverty determines vulnerability through a number of mechanisms, principally in the access to resources to allow coping with extreme weather events, and through the marginalization from decision making and social security (Kelly and Adger, in press). Vulnerability is likely to be differentiated by gender, for example, through the 'feminisation of poverty' brought about through differential gender roles in natural resource management (Agarwal, 1991). If climate change increases water scarcity, it is women who are likely to bear the labour and nutritional impacts.

Groups and regions with limited adaptive capacity along any of the above dimensions are more vulnerable to climate change just as they are more vulnerable to other stresses. Indeed, concern about climate change may be dwarfed by concerns about other components of sustainable development. The capacity to adapt to climate change and climate variability depends, as well, on an ability to monitor and detect signals of change with sufficient precision to sustain appropriate responses.

The suggested distribution of vulnerability to climate change can be clearly observed in the pattern of vulnerability to natural disasters. The poor are more vulnerable than the rich (e.g., Burton *et al.*, 1993). The poor live in more hazardous places, have less protection, and have less reserves, insurance and alternatives. For example, Adger (1999) shows that the marginalized people within coastal communities in northern Vietnam are more susceptible to the impacts of present day weather hazards and that, importantly, the wider policy context can exacerbate this vulnerability. In the Vietnamese case, the transition to market based agriculture has decrease the access of the poor to social safety nets and facilitated rich households to overexploit mangroves which previously provided protection from storms. Similarly, Mustafa (1998) demonstrates the differentiation of flood hazards in lowland Pakistan by social group: Insecure tenure leads to greater impacts on poorer communities.

The natural disaster literature also provides a number of major qualifications. Even if the rich are less vulnerable, they are not invulnerable. Being shielded from ordinary weather extremes and hence unprepared, if things go wrong, they may go wrong badly (although not as dramatically as in developing countries). Further, affluence has also brought new exposure, such as electric power lines. This literature also concludes that organization, information and preparation can help mitigate large damages at a moderate cost, for the less well to do as well as the affluent (e.g., Burton *et al.*, 1993). This underlines the need for adaptation particularly in poor countries, should the threat of extreme weather events increase.

Differences among people in developed countries with respect to adapting to smooth climate change are probably not so severe as they are in developing and transition countries because of the elaborate safety nets that these countries have constructed in response to other non-climate stresses. When it comes to sudden change, though, the ability to adapt will fall more fully on individuals as even the relatively well-off tend to their own problems; and so differences across regions and socio-economic groups will be critical. Differences across countries that support this conclusion with very high confidence even with smooth change would, for the same reason, be exacerbated by sudden change.

4. Aggregate Impacts

Estimating the aggregate impact of climate change is an intricate task that requires careful professional judgment and skills. Aggregate analysis is based on the same tools as most distributional analysis, and uses regional data as inputs. Consequently, it shares with distributional analysis the methodological difficulties and shortcomings discussed above. In fact, many of these problems are even more pronounced for aggregate analysis:

- choice of an appropriate (set of) indicator(s) in which to express impacts
- need to overcome knowledge gaps and scientific uncertainties to provide a comprehensive picture
- difficulties in modeling the effects of adaptation
- difficulties in forecasting baseline developments (such as economic and population growth, technical progress)

In addition, analysts have to grapple with some issues that are generic to aggregate analysis. The most important of them is 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 judgements. The task is simplified if impacts can be expressed in a common metric, but even then aggregation is not possible without value judgements. The value judgements 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).

All these factors make aggregate analysis difficult to carry out, and reduce our overall confidence in aggregate results. Nevertheless, aggregate studies provide important and policy relevant information.

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. Pearce *et al.* (1996) suggested that the aggregate impact of $2xCO_2$ – if expressed in monetary terms – might be equivalent to perhaps 1.5 to 2.0% of world GDP. Estimated damages are slightly lower (relative to GDP) in developed countries but significantly higher in developing countries – particularly in small island states and other highly vulnerable countries, where impacts could well be catastrophic. Pearce *et al.* (1996) pointed out the low quality of these numbers and the many shortcomings of the underlying studies.

Since then, our understanding of aggregate impacts has improved, but it remains limited. 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 much better 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. Most studies and assessments have only demonstrated the potential impact at one point in time (e.g., at $2xCO_2$), while neglecting transient responses and adaptation.

Table 1 contains a summary of results from aggregate studies that use money as their metric. The numerical results as such 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 estimates, for example, are lower than others because they factor in the possibility of catastrophic impact. The Mendelsohn estimates, on the other hand, are driven by optimistic assumptions about adaptive capacity and baseline development trends, which results in mostly beneficial impacts.

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), also reproduced in Table 1. The Tol estimates probably still underestimate the true uncertainty, for example because they exclude omitted impacts and severe climate change scenarios.

An alternative indicator of climate change impact (excluding ecosystems) is number of people affected. Few studies directly calculate this figure, but it is possible to compare the population of regions experiencing negative impacts with that of positively affected regions. Such calculations suggest that a majority of people may be negatively affected already under moderate climate change . This may be true even if the net aggregate monetary impact is positive, since developed economies, many of which could have positive impacts, contribute the majority of global production but account for a smaller fraction of world population. The quality of affected-population estimates is still poor, however. They are essentially back-of-the envelope extensions of monetary models, and the qualifications outlined in that context also apply here.

On the whole, our confidence in the numerical results of aggregate studies remains low. A few generic patterns and trends are nevertheless emerging in which we have more confidence:

- Market-impacts will be lower than initially thought, and may in some cases be positive – at least in developed countries. 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.
- 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, the literature suggests substantial negative health impacts in developing countries, mainly because of insufficient basic health care (e.g., Martens *et al.*, 1997). There is also concern about the impact on water resources (e.g., Arnell, 1999) and ecosystems (e.g., White *et al.*, 1999, Markham, 1996).
-
- Estimates of global impact are sensitive to the way figures are aggregated. Because the most severe impacts are expected in developing countries, aggregate impacts are more severe, the more weight is assigned to developing countries. 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.

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.

One of the main challenges of impact assessments is to move from the static analysis of certain benchmarks or "snap shots" 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).

Lacking dynamic analyses, it is at present impossible to say whether certain impacts are best mitigated through greenhouse gas emission reduction or through other policies. For example, Rosenzweig and Parry (1994) estimate that the number of hungry people may increase by about 10% because of climate change. Emission reduction may reduce that number, but a reform of the world's agricultural markets may be more effective. Tol and Dowlatabadi (forthcoming) argue that the additional cases of malaria due to the costs of emission reduction may be larger than the avoided cases of malaria through reduced climate change. This study, and similar ones, are currently too speculative to attach too much weight to the specific conclusions.

Some information about impacts over time is available for individual sectors. Scenarios derived from integrated assessment models can provide comprehensive emissions, concentrations, and climate change estimates that can be linked to impact models.

An important analytic question is how aggregate impacts are related to increased climate change. Do impacts increase monotonically or may they be positive (i.e., net benefits) and then negative beyond some threshold?

Little is known about the shape of the aggregate impact function. Dynamic functions 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 1997) that the climate change dynamics might in fact be more complex, and may not follow a monotonic path. Generic patterns that are emerging include:

- Moderate climate change may have both positive and negative effects, with most positive effects occurring in the market sector of developed countries. For higher levels of warming, impacts will become predominantly negative. But the overall pattern is complex, estimates remain uncertain, and the possibility of highly deleterious outcomes cannot be excluded.

- 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).

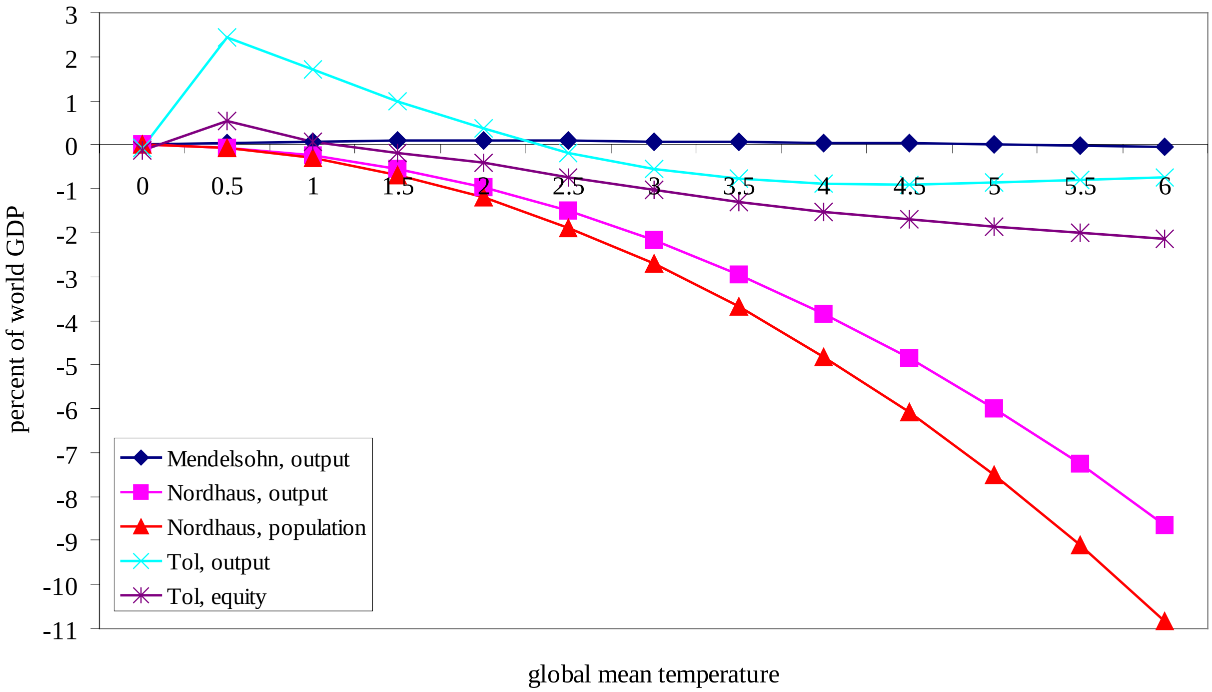

Figure 1. The impact of climate change as a function of the global mean temperature, according to Mendelsohn *et al.* (1996), Nordhaus and Boyer (2000), and Tol (1999a,b). Mendelsohn *et al.* aggregate impacts across different regions weighted by regional output. Nordhaus and Boyer aggregate either weighted 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.

Aggregating intertemporal impacts into a single indicator is extremely difficult, perhaps elusive. 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 earliernumbers, 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 man 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 the earlier studies of total economic impacts (Pearce et al., 1996), except the Tol estimate in Tol and Downing (2000). This last study uses more optimistic, perhaps too optimistic, estimates of the impact of climate change (cf. Table 1). Consequently, the marginal damage costs are and, for a high discount rate, may even be marginal benefits.

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

Study\PRTP[a]	0%	1%	3%
Nordhaus (1994)			
- 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)	75	46	16
Tol (1999c)[d]			
- Best guess	73	23	9
- Equity weighted	171	60	26

[a] Pure rate of time preference.

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

5. Sensitivity

At a time when the quality of numerical results is still low, a key benefit of aggregate impact analysis lies in the insights it provides on the sensitivity of impacts. 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 – on where additional climate change impacts research is most needed.

Inclusion and metric

Most aggregate 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. Disruptive climate changes have received little attention, except for a survey of expert opinions (Nordhaus, 1994b) and analytical work (e.g., Gjerde *et al.*, 1999). 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).

When results are aggregated, i.e., combining the winners (e.g., agriculture in Finland) 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. More detailed analyses, on the other hand, stress the distributional consequences of climate change. The aggregate 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. Studies that would include macro-scale discontinuities, would stress precaution.

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 analysis, however, requires impacts to be expressed as a function of change in greenhouse gas concentrations. With so little information to estimate this function, studies have to rely on sensitivity analyses. The policy implications can be profound. For example, if impact is a linear (but bounded) function of climate change, near-term impacts are relatively high and long-term impacts are relatively low. With a cubic function, the situation is reversed, and long-term impacts increase rapidly. Using conventional discounting, a linear (but bounded) impact function would imply a higher marginal damage (i.e., the net present value of a small change in carbon dioxide emissions) in the near-term, whereas a cubic impact function would imply a lower but more rapidly increasing marginal damage (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 first half of the 21st century.

The Time Horizon

Aggregate models suggest that aggregate impacts of climate change may be positive on the short run when climate change is still relatively modest, but turn negative for more severe climate change. Also, uncertainties increase rapidly, including the chance of large-scale discontinuities (thermohaline circulation, West-Antarctic Ice Sheet). Thus, the outcomes of a policy analysis are sensitive to its time horizon, that is, whether the hazards of the remote future are considered or not (Azar and Sterner, 1996; Cline, 1992; Hasselmann *et al.*, 1997).

The Discount Rate

A dollar today is not the same as a dollar next year, because today's dollar could have earned a year's worth of interest. Besides, people are often impatient. Essentially, the discount rate measures the value of future consumption relative to today's. As most of the impacts of climate change take place in the (far) future, the used discount rate is of utmost importance. Arrow *et al.* (1996) and Portney and Weyant (1999) review the literature on this subject. Tol (1999c), for instance, shows that the marginal damage is an order of magnitude larger at the bottom of the range of exponential discount rates that most people find reasonable than the marginal damage at the top of that range. This makes the discount rate the second-most important determinant for the marginal damage. See Table 2. (The first-most is whether or not countries cooperate in reducing emissions; Nordhaus and Yang, 1996; Tol, 1999d.)

The Welfare Criteria

Most of the discussions about critical elements of an impact assessment amount to the question what one finds important and what not. 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 about what matters (cf. 'composition of the damage function' above). Fankhauser *et al.* (1997) and Azar (1999) are amongst the few exceptions. They find that, in general, the more weight one puts on the distribution of the impacts of climate change, the more severe the aggregate impacts are. For instance, Fankhauser's (1995) initial estimate of the annual global damage of 2xCO_2 is based on the implicit assumptions that distribution is irrelevant (that is, losses to the poor are compensated by equal gains to the rich) and people are risk-neutral (that is, a one-in-a-million 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 (1999e) 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.

6. Conclusion

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

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

Third, the impacts of moderate global warming (say, up to 2-3°C) are mixed. Poorer countries are likely to be net losers, richer countries may gain from moderate warming. The global picture depends on how one aggregates. If one counts dollars, the world as a whole may win a bit. If one counts 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) are probably negative, and increasingly so for higher warming. This holds for the majority of countries. Note that, because of the slow workings of the energy sector and the atmosphere, we are committed to at least 2°C of warming.

Thus, there is an economic rationale for reducing greenhouse gas emissions. By how much, where and when cannot be answered without considering the costs of emission reduction. Obviously, 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 is questionable to assume that the marginal damage costs exceed $50/tC.

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 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 (for climate sensitivity, see Morgan and Keith (1995), for damages, see Nordhaus, 1994).

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.

Acknowledgements

This paper draws heavily on the IPCC Third Assessment Report of Working Group II, Chapter 19 (Smith *et al.* forthcoming). We are grateful to all the authors, reviewers and review editors of that chapter. David Pearce gave helpful comments on an earlier version of this paper. The US National Science Foundation through the Center for Integrated Study of the Human Dimensions of Global Change (SBR-9521914) and the Michael Otto Foundation provided welcome financial support. The interpretations and any errors in this paper are, however, ours. The views expressed in this paper are our own and do not necessarily reflect those of any of the institutions with which we are affiliated.

References

Adger, W.N. (1999), 'Social Vulnerability to Climate Change and Extremes in Coastal Vietnam', *World Development*, **27**, 249-269.

Agarwal, B. (1991), *A Field of her Own*, Oxford University Press, Oxford.

Alcamo, J., (Ed.) 1994) *IMAGE 2.0 - Integrated Modeling of Global Climate Change*, Dordrecht: Kluwer Academic Publishers.

Alcamo, J., Krol, M. and Leemans, R. (1995) Stabilizing Greenhouse Gases: Global and Regional Consequences -- Results from the IMAGE 2.0 Model. pp.1-10. Bilthoven: RIVM.

Arnell, N.W. (1999), 'Climate Change and Global Water Resources', *Global Environmental Change*, **9**, S31-S50.

Arrow, K.J., Cline, W.R., Maeler, K.-G., Munasinghe, M., Squitieri, R. and Stiglitz, J.E. (1996) Intertemporal Equity, Discounting, and Economic Efficiency. In: Bruce, J.P., Lee, H. and Haites, E.F., (Eds.) *Climate Change 1995: Economic and Social Dimensions -- Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 125-144. Cambridge: Cambridge University Press.

Azar, C. and Sterner, T. (1996) Discounting and Distributional Considerations in the Context of Global Warming. *Ecological Economics* **19** 169-184.

Azar, C. (1999) Weight Factors in Cost-Benefit Analysis of Climate Change. *Environmental and Resource Economics* **13** 249-268.

Burton, I., Kates, R.W. and White, G.F. 1993) *The Environment as Hazard*, 2 edn. New York: The Guilford Press.

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

Darwin, R.F. (1999) A FARMer's View of the Ricardian Approach to Measuring Agricultural Effects of Climatic Change. *Climatic Change* **41** (3-4):371-411.

Darwin, R.F., Tsigas, M., Lewandrowski, J. and Raneses, A. (1995) World Agriculture and Climate Change - Economic Adaptations. 703, pp.1-86. Washington, D.C.: U.S. Department of Agriculture.

Downing, T.E., Eyre, N., Greener, R. and Blackwell, D. (1996) Projected Costs of Climate Change for Two Reference Scenarios and Fossil Fuel Cycles. Oxford: Environmental Change Unit.

Downing, T.E., Greener, R.A. and Eyre, N. (1995) The Economic Impacts of Climate Change: Assessment of Fossil Fuel Cycles for the ExternE Project. pp.1-48. Environmental Change Unit and Eyre Energy Environment: Oxford and Lonsdale.

Eyre, N., Downing, T.E., Rennings, K. and Tol, R.S.J. (1999) Assessment of Global Warming Damages. In: Holland, M.R., Berry, J. and Forster, D., (Eds.) *Externalities of Energy, Vol. 7: Metholodogy and 1998 Update*, pp. 101-112. Luxembourg: Office for Official Publications of the European Communities.

Eyre, N., Downing, T.E., Hoekstra, R. and Rennings, K. (1999) Externalities of Energy, Vol 8: Global Warming. pp.1-50. Luxembourg: Office for Official Publications of the European Communities.

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

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

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

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

Freeman, A.M., III 1993) *The Measurement of Environmental and Resource Values*, Washington,D.C.: Resources for the Future.

Gjerde, J., Grepperud, S. and Kverndokk, S. (1998) Optimal Climate Policy under the Possibility of a Catastrophe. pp.1-37. Milan: Fondazione Eni Enrico Mattei.

Hasselmann, K., Hasselmann, S., Giering, R., Ocana, V. and von Stoch, H. (1997) Sensitivity Study of Optimal CO_2 Emission Paths Using a Simplified Structural Integrated Assessment Model (SIAM). *Climatic Change* **37** 345-386.

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

Hoozemans, F.M.J., Marchand, M. and Pennekamp, H.A. (1993) A Global Vulnerability Analysis: Vulnerability Assessment for Population, Coastal Wetlands and Rice Production and a Global Scale (second, revised edition). Delft: Delft Hydraulics.

Kalkstein, L.S. and Greene, J.S. (1997), ‘An Evaluation of Climate/Mortality Relationships in Large U.S. Cities and the Possible Impacts of a Climate Change’, *Environmental Health Perspectives*, **105** (1), 2-11.

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

Kelly, P.M. and Adger, W.N. (1999) Social Equity in Adaptation as a Key Constraint in Integrating Climate Policies.

Mahlman, J.D. 1997. "Uncertainties in Projections of Human-Caused Climate Warming." *Science* 278: 1416-1417.

Manne, A.S. and Richels, R.G. (1995) The Greenhouse Debate: Economic Efficiency, Burden Sharing and Hedging Strategies. *Energy Journal* **16** (4):1-37.

Markham, A. (1996) Potential Impacts of Climate Change on Ecosystems: A Review of Implications for Policymakers and Conservation Biologists. *Climate Research* **6** (2):179-191.

Martens, W.J.M., Jetten, T.H. and Focks, D.A. (1997) Sensitivity of Malaria, Schistosomiasis and Dengue to Global Warming. *Climatic Change* **35** 145-156.

Mendelsohn, R.O., Morrison, W.N., Schlesinger, M.E. and Andronova, N.G. (1996) A Global Impact Model for Climate Change. Anonymous

Mendelsohn, R. O. and Neumann, J. E., (Eds.) 1999) *The Impact of Climate Change on the United States Economy*, Cambridge: Cambridge University Press.

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

Mendelsohn, R.O. and Schlesinger, M.E. (1999) Climate-Response Functions. *Ambio*

Morgan, M.G. and Keith, D.W. (1995) Subjective Judgments by Climate Experts. *Environmental Science and Technology* **29** (10):468A-476A.

Mustafa, D. (1998), 'Structural Causes of Vulnerability to Flood Hazards in Pakistan', *Economic Geography*, **74**, 289-305.

Nicholls, R.J., Hoozemans, F.M.J. and Marchand, M. (1999) Increasing Flood Risk and Wetland Loss due to Global Sea-Level Rise: Regional and Global Analyses. *Global Environmental Change* (forthcoming):

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

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

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

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

Nordhaus, W.D. and Boyer, J.G. (1999) Warming the World: Economic Models of Global Warming. Anonymous

Pearce, D.W., Cline, W.R., Achanta, A.N., Fankhauser, S., Pachauri, R.K., Tol, R.S.J. and Vellinga, P. (1996) The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control. In: Bruce, J.P., Lee, H. and Haites, E.F., (Eds.) *Climate Change 1995: Economic and Social Dimensions -- Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 179-224. Cambridge: Cambridge University Press.

Peck, S.C. and Teisberg, T.J. (1992) CETA: A Model for Carbon Emissions Trajectory Assessment. *Energy Journal* **13** (1):55-77.

Peck, S.C. and Teisberg, T.J. (1994) Optimal Carbon Emissions Trajectories When Damages Depend on the Rate or Level of Global Warming. *Climatic Change* **28** 289-314.

Portney, P. R. and Weyant, J. P., (Eds.) (1999) *Discounting and Intergenerational Equity*, Washington, D.C.: Resources for the Future.

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

Rothman, D.S. 2000. "Measuring Environmental Values and Environmental Impacts: Going from the Local to the Global." *Climatic Change* 44: 351-376.

Schneider, S.H. (1997) Integrated Assessment Modeling of Global Climate Change: Transparent Rational Tool for Policy Making or Opaque Screen Hiding Value-Laden Assumptions? *Environmental Modeling and Assessment* **2** 229-249.

Smith, J.B., Schellnhuber, H.-J., Mirza, M.Q., Lin, E., Fankhauser, S., Leemans, R., Ogallo, L., Richels, R.G., Safriel, U., Tol, R.S.J., Weyant, J.P., Yohe, G.W., (forthcoming), 'Synthesis', IPCC Working 2 Third Assessment Report, Cambrigde: Cambridge University Press.

Sohngen, B.L. and Mendelsohn, R.O. (1999) The Timber Market Impacts of Climate Change on the US Timber Market. In: Mendelsohn, R.O. and Neumann, J.E., (Eds.) *The Impact of Climate Change on the US Economy*, pp. 94-132. Cambridge: Cambridge University Press.

Titus, J.G. (1992) The Costs of Climate Change to the United States. In: Majumdar, S.K., Kalkstein, L.S., Yarnal, B.M., Miller, E.W. and Rosenfeld, L.M., (Eds.) *Global Climate Change: Implications, Challenges and Mitigation Measures*, pp. 384-409. Easton: Pennsylvania Academy of Science.

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

Tol, R.S.J. (1999) New Estimates of the Damage Costs of Climate Change, Part II: Dynamic Estimates. D99/02, pp.1-31. Amsterdam: Institute for Environmental Studies, Vrije Universiteit.

Tol, R.S.J. (1999) New Estimates of the Damage Costs of Climate Change, Part I: Benchmark Estimates. D99/01, pp.1-32. Amsterdam: Institute for Environmental Studies, Vrije Universiteit.

Tol, R.S.J. (1999), 'The Marginal damage costs of Greenhouse Gas Emissions', *The Energy Journal*, **20** (1), 61-81.

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

Tol, R.S.J., 'Equitable Cost-Benefit Analysis of Climate Change', *Ecological Economics* (forthcoming).

Tol, R.S.J. and H. Dowlatabadi, 'Vector-borne Diseases, Climate Change, and Economic Growth', *Integrated Assessment* (forthcoming).

Tol, R.S.J. and T.E. Downing (2000), *The Marginal damage costs of Climate Changing Gases*, Institute for Environmental Studies **D00/08**, Vrije Universiteit, Amsterdam.

Tol, R.S.J. and S. Fankhauser, 'On the Representation of Impact in Integrated Assessment Models of Climate Change', *Environmental Modelling and Assessment*, **3**, 63-74.

Tol, R.S.J., Fankhauser, S. and Smith, J.B. (1998) The Scope for Adaptation to Climate Change: What Can We Learn from the Impact Literature? *Global Environmental Change* **8** (2):109-123.

U.S. Country Studies Program. 1999. *Climate Change: Mitigation, Vulnerability, and Adaptation in Developing Countries.* Washington, DC: U.S. Country Studies Program.

White, D.J., Running, S.W., Thornton, P.E., Keane, R.E., Ryan, K.C., Fagre, D.B. and Key, C.H. (1998), 'Assessing Simulated Ecosystem Processes for Climate Variability Research at Glacier National Park', *Ecological Applications*, **8**, 805-823.

Wuetrich, B. 2000. "How Climate Change Alters Rhythms of the Wild." *Science* 287: 793-795.

Yohe, G.W., Neumann, J.E. and Ameden, H. (1995) Assessing the Economic Cost of Greenhouse-Induced Sea Level Rise: Methods and Applications in Support of a National Survey. *Journal of Environmental Economics and Management* **29** S-78-S-97

Yohe, G.W., Neumann, J.E., Marshall, P. and Ameden, H. (1996) The Economics Costs of Sea Level Rise on US Coastal Properties. *Climatic Change* **32** 387-410.