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Climate change costs

Recent advancements in the economic assessment

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Climate change is unique among the consequences of fossil fuel burning in its far reaching impact, both spatially and temporally. Earlier studies estimate the aggregated monetized damage due to climate change at 1.5 to 2.0% of world GDP (for 2 × CO_2); the OECD would lose 1.0 to 1.5% of GDP; the developing countries 2.0 to 9.0%, according to these estimates. These figures are not comprehensive and highly uncertain. Newer studies increasingly emphasize adaptation, variability, extreme events, other (non-climate change) stress factors and the need for integrated assessment of damages. As a result, differences in impacts between regions and sectors have increased, the market impacts in developed countries tended to fall, and non-market impacts have become increasingly important. Marginal damages are more interesting from a policy point of view. Earlier estimates range from about US$5 to US$125 per tonne of carbon, with most estimates at the lower end of this range. These figures are based on polynomial functions in the level of climate change, but the rate of change may be equally important, as are the speed of adaptation, restoration and value adjustment. Furthermore, future vulnerability to climate change will be different from current vulnerability. On the whole, the market impacts fall (relatively) with economic growth while the non-market impacts rise (relatively) with growth. Copyright © 1996 Published by Elsevier Science Ltd.

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Anthropogenic climate change is by and large caused by a similar set of activities as many other air pollution problems: the burning of fossil fuels, for energy production and in the transport sector, is by far the most important source of greenhouse gas emissions, although land use change and some agricultural practices can also be important contributors, particularly in developing countries. There is little consensus, though, about the exact magnitude, and even direction, of climate change impacts. What is clear is that compared to other air pollution damages, climate change impacts will be much wider reaching, both spatially and temporally.

Most air pollution problems are local or perhaps regional, that is adverse effects are predominantly felt in the neighbourhood of the emitting source. Climate change, on the other hand, is a global problem which will affect the whole world, although different regions will be affected in different ways and to different degrees. While most air pollution impacts become manifest without much delay, climate change impacts will not be felt for another 50 years or so. That is, impacts will affect a different generation of people from those causing the problem.

This wide spatial and temporal scope makes the assessment of global warming impacts rather difficult, even when abstracting from the large uncertainty about their exact magnitude. The global nature of the problem demands the analysis of impacts on a worldwide level, without, however, neglecting regional variation. The task thus requires the accumulation of detailed information on regional and sectoral impacts and their aggregation into a meaningful overall assessment. At the same time, the long time horizon makes the assessment highly sensitive to assumptions about the preferences and needs of future generations, about their vulnerability and their ability to adapt to climate change. It also raises questions of intergenerational equity and the rights of future generations compared to our own (see IPCC WGIII, 1995).

Working Group II of the Intergovernmental Panel on Climate Change (IPCC WGII) has extensively reviewed the potential impacts of climate change on both human society and natural ecosystems (see IPCC WGII, 1995 1994). This paper reviews the available economic assessments of these impacts, drawing on the work of IPCC Working Group III (IPCC WGIII, 1995; Fankhauser, 1995, 1994; Tol, 1995). It then analyses how economic assessments might change in the light of recent findings, and outlines further developments under way to improve on the current generation of damage assessments.

Results from equilibrium analysis

Information on the impacts of global warming is now available for several regions and countries (IPCC WGII, 1995; IPCC WGIII, 1995). The best studied regions are developed countries, in particular the USA, where climate change impacts have been analysed in a series of studies, following up on initial work by Smith and Tirpak (1989). Other OECD regional studies include CRU/ERL (1992) for the European Union; Parry and Duncan (1995) for the UK; and Nishioka *et al* (1993) for Japan. In the context of an Asian Development Bank (ADB, 1994; see also SAARC, 1992) project on climate change in Asia, global warming impacts have also been analysed for a number of Asian countries. Little information is available for other developing countries.

Studies usually deal with only a subset of damages, and are often restricted to a description of impacts in physical terms. By far the best studied areas are agricultural impacts (eg Rosenzweig and Parry, 1994; Reilly *et al*, 1994; Adams *et al*, 1994) and the costs of sea level rise (eg IPCC WGII, 1994; Turner *et al*, forthcoming; Yohe *et al*, forthcoming). Attempts at a comprehensive monetary quantification of all impacts are relatively rare, and usually restricted to the USA (Cline, 1992a; Nordhaus, 1991; Titus, 1992). Among the most comprehensive studies with respect to regional coverage and the number of included impacts are those by Fankhauser (1995) and Tol (1995).

Although studies tend to emphasize damages, they generally deal with both the costs of adaptation (such as sea level rise protection) and the costs of residual damages (such as the inundation of unprotected areas). However, the assumed level of adaptation is usually arbitrarily chosen rather than derived from an optimization calculus.

Equilibrium (2 × CO_2) analysis

The scientific research on global warming impacts has focused predominantly on an (arbitrarily chosen) scenario called 2 × CO_2 – the impacts of an atmospheric CO_2 concentration of twice the preindustrial level. Most of the figures reported below are based on the 2 × CO_2 scenario.

Climate change impacts can be classified as either market related (effects which will be reflected in the national accounts) or non-market related (impacts affecting intangibles such as ecosystems or human amenity). Table 1 categorizes the expected impacts from global warming. It also assesses how carefully they have been estimated in the literature so far.

Climate change impacts can be expressed either quantitatively, or in a common unit of measurement such as money. Monetary estimates of both market and non-market damages are ideally expressed in the form of willingness to pay (WTP), or willingness to accept compensation (WTA). WTP measures the amount of income a person is willing to forgo in exchange for an improved state of the world, and WTA is an estimate of the compensation required in order to accept a deterioration. Both measures are used in welfare economics as a money metric for individuals' preferences. Unfortunately, WTP/WTA estimates are not always available for the assessment of global warming impacts. Reductions in revenues, the return on input factors (such as capital or land), and other indicators are frequently used to approximate the welfare impacts of climate change. In addition, several damages that could not so far be estimated were ignored altogether (IPCC WGIII, 1995).

Available estimates on the costs of climate change are therefore neither accurate nor complete, and a considerable range of error can be expected. Figures on developing countries in particular are usually based on approximations, and are clearly less reliable than those for developed regions. Nevertheless, the available estimates can serve as an indication of the relative vulnerability of different regions.

Based on an extensive survey of the literature, IPCC Working Group III (1995) expects the following aggregate damages for 2 × CO_2:

(1) world impact: 1.5–2.0% of world GNP;
(2) developed country impact: 1–1.5% of national GNP;
(3) developing country impact: 2–9% of national GNP.

Note that these figures include both adaptation costs and residual damages. Examples of the former include the costs of coastal protection, the costs of migration, and the change in energy demand due to alterations in space heating and cooling requirements (see Table 1). Examples of residual damages include agricultural impacts, and the loss of dry and wetlands. The underlying adaptation assumptions, however, are not explicitly stated for most impact categories. Monetization of physical impacts was achieved by using the WTP/WTA approach or approximations, in the way outlined above.

The above list indicates that the damages faced by developing countries could be more than twice those for developed countries. The figures are best guess estimates – they do not reflect the uncertainties, they neglect the possibility of impact surprises, and of low probability/high impact events (such as a shut down of the ocean conveyor belt). To avoid long-term predictions, figures have been derived by

Table 1 Overview on climate change impacts

Damages	Market impacts				Non-market impacts		
	Primary economic sector damage	Other economic sector damage	Property loss	Damage from extreme events	Ecosystem damage	Human impacts	Damage from extreme events
Fully estimated based on willingness to pay	Agriculture		Dryland loss Coastal protection		Wetland loss		
Fully estimated using approximations	Forestry	Water supply		Hurricane damage	Forest loss		Hurricane damage
Partially estimated	Fisheries[a]	Energy demand Leisure activity	Urban infrastructure	Damage from droughts[b]	Species loss	Human life Air pollution Water pollution Migration	Damage from droughts[b]
Not estimated		Insurance Construction Transport Energy supply		Non-tropical storms River floods Hot/cold spells Other catastrophes	Other ecosystems loss	Morbidity Physical comfort Political stability Human hardship	Non-tropical storms River floods Hot/cold spells Other catastrophes

[a]Often included in wetland loss
[b]Primarily agricultural damage

Source: IPCC WGIII (1995).

imposing 2 × CO_2 on to a society with today's structure. The long-term vulnerability profile could change as a consequence of economic development and population growth (see below for a further discussion on this).

Considerable regional differences are likely, with potentially higher impacts for some individual countries, such as small island states. Table 2 shows some of the estimates underlying the above conclusions in more detail, highlighting the substantial differences between regions. For the former USSR, for example, damage could be as low as 0.7% of GNP, or even negative (climate change is beneficial). Asia and Africa, on the other hand, could face extremely high damages, mainly due to the severe life/morbidity impacts. Mortality estimates are extremely volatile and controversial, however, and should be interpreted with caution (see the discussion in IPCC WGIII, 1995). Developing countries generally tend to be more vulnerable to climate change than developed countries (for a possible explanation of this fact see below).

The wide range of results shows that, although a rough picture on regional vulnerability to climate change is starting to emerge, much more research is still necessary to improve our currently limited understanding of the issue.

New findings in equilibrium analysis

The scientific understanding of climate change and climate change impacts is increasing rapidly. Socioeconomic analysis, which is based on these scientific findings, will inevitably lag behind scientific progress. Most of the studies surveyed in the previous section work with the climate and impact scenarios of the 1990 and 1992 IPCC reports (IPCC WGI, 1992, 1990; IPCC WGII, 1995). New findings and methodological advancements that have taken place since then only now start to trickle down into socioeconomic analysis. Important recent developments include:

(1) Increased emphasis on adaptation: the important role of adaptation in climate change impact assessment has been increasingly recognized, and particularly in agricultural impact work, individual and societal responses to a changing climate are now regularly included in the analysis. As it turns out, model results are quite sensitive to assumptions on adaptability. Comparisons of model results with and without adaptation suggest that low cost adaptation measures may reduce agricultural damages by about 30–60% (IPCC WGIII, 1995).

(2) Increased emphasis on variability and extreme events: while many of the earlier studies focused on changes in the mean, mostly the global mean temperature, increasing attention is being paid to the variability around that mean, changes in which can dominate the impact on agriculture (Mearns *et al*, forthcoming; Mearns, 1995), and to weather extremes. Extremes, such as floods, droughts, heatwaves, and storms, do not only determine a large share of the damage, but also drive adaptation (Tol *et al*, 1994).

(3) Increased emphasis on non-climate change related stress factors: in many cases climate change will add to already existing stress on natural ecosystems. Example of such multiple stress situations include the development of coastal zones, water use, and land use change. The existence of multiple stress factors could seriously compound ecosystem impacts (IPCC WGII, 1995; Turner *et al*, forthcoming; by implications, measures that tackle current environmental problems would seem to be a low cost, or even no regret, strategy to strengthen the resilience of ecosystems). A similar argument could also hold with respect to imperfections affecting the performance of the economic system, such as restrictions in the trade of agricultural goods, or insufficient nutritional and health standards.

(4) Importance of integrated assessment: there are strong interlinkages between the different sectors affected by climate change, as well as between affected sectors and those not directly touched by climate change. For example, agricultural, forest and ecosystem impacts are linked through land use competition; the scope for irrigation as an adaptive measure in the agricultural sector depends on the impacts felt in the water sector, and so on. In addition, there may be repercussions between impacts and possible mitigation policies, eg in the forestry, agriculture and energy sectors. To capture these effects climate change studies have increasingly made use of integrated assessment models (for a survey of available integrated assessment models, cf. IPCC WGIII, 1995).

How do these and other scientific developments affect the damage assessment of the previous section? Three broad tendencies seem to emerge.

Trend 1: increasing regional and sectoral differences

Recent findings stress the regional diversity of impacts. The notion that a warmer world will know winners as well as losers now features far more prominently than in the first generation of assessments. A recent study for Finland, for instance, finds this country to be a net winner from climate change (Kuoppamaki, 1995). Agricultural studies like Rosenzweig and Parry (1994) or Reilly *et al* (1994) identify many developed and other northern latitude countries as possible winners, provided farmers take adequate adaptation measures. Food insecurity in the south, on the other hand, is likely to further intensity.

Differences are also increasingly emphasized between different regions within a country, and between different agents, sectors and commodities. A US forestry study by Callaway *et al* is a good example. It estimates annual losses in US welfare that are comparable to eg Cline's initial estimate (US$2.5–6.5 million pa for 2.5°C warming, compared to Cline's US$3.3 million), but with significant differences for individual regions and products. For example, softwood yields are expected to decrease, except in the northwest, while yields in hardwood would mostly increase, except perhaps in the south. Producers could significantly gain as a consequence of higher prices, while consumer surplus is expected to drop (Callaway *et al*, 1994).

Table 2 Monetary 2 × CO_2 damage in different world regions and share of tangible damage (annual damages)

	Fankhauser US$ billion	GDP %[a]	Tangible	Tol US$ billion	GDP %[a]	Tangible
European Union	63.6	1.4	0.58			
USA	61.0	1.3	0.61			
Other OECD	55.9	1.4	0.59			
OECD America				74.2	1.5	0.25
OECD Europe				56.5	1.3	0.04
OECD Pacific				59.0	2.8	0.08
Total OECD	180.5	1.3	0.59	189.5	1.6	0.13
Eastern Europe/former USSR	18.2[b]	0.7[b]	0.72[b]	−7.9	−0.3	3.36
Centrally planned Asia	16.7[c]	4.7[c]	0.69[c]	18.0	5.2	0.03
South and South-east Asia				53.5	8.6	0.55
Africa				30.3	8.7	0.67
Latin America				31.0	4.3	0.55
Middle East				1.3	4.1	0.50
Total non-OECD	89.1	1.6	0.64	126.2	2.7	0.31
World	269.6	1.4	0.61	315.7	1.9	0.20

[a]Note that the GDP base may differ between the studies.
[b]Former USSR only.
[c]China only.
Source: IPCC WGIII (1995), based on Fankhauser (1995) and Tol (1995).

Trend 2: lower market impacts in developed countries

Reassessments of market related impacts in developed countries have in many cases led to a reduction in expected impacts compared to earlier estimates. Yohe *et al* (forthcoming), for example, observe a continuous decrease in estimated damage costs from sea level rise. Calculations for the US by Rosenthal *et al* (1994) suggest that earlier estimates of energy sector costs may have been too high, and that climate change may in fact be beneficial for many US regions. More recent agricultural estimates also tend to be lower than earlier assessments (eg Adams *et al*, 1994).

Adjustments in estimates have occurred for a variety of reasons. In the case of sea level rise, much of the downscaling occurred as a result of more modest rise scenarios. One of the reasons for lower damages in the Adams *et al* (1994) study is their extension of the model to include more heat tolerant crops such as fruits and vegetables. In many cases, however, lower estimates are predominantly the result of better incorporating the effect of adaptation.

Whether this trend to decreasing market impacts can be extended from industrialized countries to other regions is not clear. The answer depends on the exact reasons that have led to a reassessment. Reductions associated with adaptation effects, for example, will not extend to other regions as easily as, say, the effect of a lower sea level rise projection. It is often suspected that developing countries will lack the financial, institutional and technical capacity to efficiently adapt to a warmer world in the same way as industrialized countries will (see below; IPCC WGIII, 1995; Rosenzweig and Parry, 1994; in fact, this is one of the reasons why regional variability of damages is higher in recent studies). Estimates of market impacts in developing countries may therefore fall to a lesser extent.

Trend 3: increasing importance of non-market impacts

While estimates of market impacts are often corrected downwards, new results on non-market impacts suggest that these effects may initially have been underestimated. Improvements in this area have not so much occurred with respect to the accuracy of figures – it remains low – as with respect to their comprehensiveness. Some non-market impacts that were neglected in earlier analysis for lack of data can now be quantified. This is most notably the case for health impacts, where numerical estimates are now available for the expected spread of malaria in a warmer world. Integrated modelling work by Matsuoka *et al* (1994) suggests a 10–30% increase in areas with potential malaria risk, while Martens *et al* (1994) expect several million additional malaria cases by the year 2100. Recent speculation about a link between climate change and the spread of diseases such as cholera and dengue fever suggest that the health impacts of climate change may have been underestimated so far (Stone, 1995).

Results from dynamic analysis

The analysis so far has been confined to comparative statics. All figures in Table 2 are estimates of the impact of one specific change of the climate (2 × CO_2) on the current economy. This is clearly insufficient. Not only will we, for the larger part of the future, be confronted with climate change substantially different from 2 × CO_2, but socioeconomic vulnerability to climate change will also shift as a consequence of economic development.

What would be relevant to know from a policy point of view are marginal figures, ie estimates of the extra damage done by one extra tonne of carbon emitted. Unfortunately, the requirements for marginal damage calculations go far beyond the information available from 2 × CO_2 studies. Greenhouse gases are stock pollutants. That is, a tonne of gas emitted will affect climate over several decades, as fractions of the gas remain long in the atmosphere. Calculating marginal costs therefore requires the comparison of two present value terms: the discounted sum of future damages associated with a certain emission scenario is compared to the sum of damages in an alternative scenario with marginally different emissions in the base period (in estimates based on optimal control models, the marginal cost is calculated as the shadow price of carbon, ie the carbon tax necessary to keep emissions on the socially optimal trajectory: Nordhaus, 1994; Peck and Teisberg, 1993).

The current generation of models deals with this challenge in a rather *ad hoc* manner, using very simplistic representations of the complex dynamic processes involved. In older studies damage costs were typically specified as a polynomial (usually linear to cubic) function of global mean temperature, calibrated around the 2 × CO_2 estimates. Damage is usually fully reversible and typically assumed to grow with GNP. Only recently studies have started to emerge which explicitly incorporate regionally diversified temperatures and sea levels, model individual damage categories (eg agriculture) separately, or at least distinguish between damages related to absolute temperature level and those related to the rate of change (Dowlatabadi and Morgan, 1993; Hope *et al*, 1993; Tol, 1995); see below.

Table 3 provides a list of estimates of the marginal damages obtained from polynomial damage models. Estimates range from about US\$5 to US\$125 per tonne of carbon, with most estimates at the lower end of this range. The wide range reflects variations in model assumptions, as well as the high sensitivity of figures to the choice of the discount rate (IPCC WGIII, 1995). Estimates are expected to rise over time as a consequence of economic growth and increasing concentration levels.

Using a model called DICE, Nordhaus (1994) finds that the shadow price begins at only about US\$5 per tonne of carbon in 1995, rises to about US\$10 by 2025, and reaches US\$21 by 2095 (at 1990 prices). Peck and Teisberg (1993) find values of a similar order of magnitude. Tol's (1994) alternative specification of DICE yields shadow prices of US\$13 for 1995, rising to US\$89 for 2095. These model runs all assume that parameter values are known with certainty. In the case of DICE, expected shadow prices more than double once uncertainty is added to the model. This result arises because of the skewedness in the damage distribution, which allows for low probability–high impact events (Nordhaus, 1994); risk aversion and concave damage functions further enhance this effect (Tol, 1995). All three authors assume a pure rate of time preference (or utility discount rate) of 3% (for a discussion on discounting see IPCC WGIII, 1995; Nordhaus, 1994). In contrast, Cline (1993, 1992b) finds significantly higher shadow prices by using a zero utility discount rate. His reproduction of the DICE model generates a path of shadow prices beginning at about US\$45 per tonne, reaching about US\$243 by 2100. Other parameter specifications provide even higher values.

Fankhauser (1994) identifies a lower and flatter trajectory for the shadow price of carbon, rising from US\$20 per tonne by 1991–2000 to US\$28 per tonne by 2021–2030, with confidence intervals of US\$6–45 and US\$9–64, respectively. Fankhauser uses a probabilistic approach to the range of discount rates, in which low and high discount rates are given different weights. His sensitivity analysis with the discount rate suggest that moving from high (3%) to low (0%) discounting could increase marginal costs by about a factor 9, from US\$5.5 to US\$49 per tonne of carbon emitted now.

Advancement in dynamic analysis

The simple damage functions used in most current models are clearly insufficient. The complex question of how impacts would evolve over time and under different climate scenarios has been solved by making damage a polynomial function of the temperature level. The issue of how socioeconomic vulnerability will change because of economic development is at best mentioned in passing. There has been little research on these aspects. In the remainder of the paper we will outline the most central issues and address their potential importance.

Climate can be considered a resource, some manifestations of which are beneficial, some are neutral, and some are malificial. Individuals, companies and governments seek to take advantage of the positive sides of climate, and to mitigate its adverse consequences. If the climate were stable this search would eventually lead to a well designed mix of practices, technologies, financial mechanisms etc. The resulting mix would consist of both benefits from the opportunities climate offers and costs from the defensive action taken. If climate changed and restabilized, a well-adapted society would again evolve. The difference in welfare between the two states is the cost associated with the level of climate change. It consists of opportunity costs plus defensive expenditures. (An analytical difficulty with such permanent costs is that they become an accepted fact of life, and may not be readily recognized as a cost. They are also likely to induce significant higher order effects to the effect that that the different states become incomparable. A possible example might be the Channel. The loss of a land connection between England and the Continent at the end of the last ice age may have imposed a large opportunity cost. But history would have evolved in a completely different way without it.)

In addition, society will go through a transition in which it is maladapted to the actual climate. This is because climate change cannot be predicted accurately and because adaptation takes time. In this period of maladaptation, opportunities are missed, avoidable losses are suffered, and unnecessary investments are made. The efforts needed for adaptation (that is, the effort needed to establish the optimal level of defence against climate) and the losses due to maladaptation together constitute the costs of the rate of cli-

Table 3 The marginal social costs of CO_2 emissions (current value (1990) US$/tC)[a]

Study	Type	1991–2000	2001–2010	2011–2020	2021–2030
Nordhaus	MC		7.3 (0.3–65.9)		
Ayres and Walter	MC		30–35		
Nordhaus, DICE	CBA				
Certainty/best guess		5.3	6.8	8.6	10.00
Uncertainty/expected value		12.0	18.0	26.5	na
Cline	CBA	5.8–124	7.6–154	9.8–186	11.8–221
Peck and Teisberg	CBA	10–12	12–14	14–18	18–22
Fankhauser	MC	20.3 (6.2–45.2)	22.8 (7.4–52.9)	25.3 (8.3–58.4)	27.8 (9.2–64.2)
Maddison	CBA/MC	5.9–6.1	8.1–8.4	11.1–11.5	14.7–15.2

[a]MC = marginal social cost study, CBA = shadow value in a cost-benefit study. Figures in brackets denote 90% confidence intervals.

Sources: IPCC WGIII (1995); see also Ayres and Walter (1991), Nordhaus (1994), Cline (1992b, 1993), Peck and Teisberg (1993), Fankhauser (1995) and Maddison (1994).

mate change. It is convenient to ascribe these costs to the rate of change as climate change introduces a shock the consequences of which gradually ebb away. Alternatively, climate change damage can be ascribed to the deviation of the actual climate from the reference climate; adapation then alters the reference climate.

In a purely abstract sense, at a high level of aggregation, damage (D) at time t is a function of past climate changes

$$D_t = f(\Delta T_t, \Delta T_{t-1}, \Delta T_{t-2}, ...) \tag{1}$$

where T is the climate index, say global mean surface air temperature. It is more insightful, however, to express damage in the level (L) and the rate (R) of (smooth) climate change. The rate of change is the difference in climate between this year and last; the level of change is then the sum of the rate of changes (since the reference period). Adaptation enters the equation by a gradual waning of the importance of past rates of change. A parsimonious representation of (1) is then

$$\begin{aligned} D_t &= L_t + R_t + \rho R_{t-1} \\ L_t &= g(T_t - T_0) \\ R_t &= h(\Delta T_t) \end{aligned} \tag{2}$$

where ρ is the rate of adaptation. Obviously, ρ is of critical importance in determining the total damage. If $\rho = 1$, damage in the rate of change is in fact damage in the level of change. Rate and level are seperated because two difference equations of the form (1) do not add up to a simple difference equation. In fact, we will argue below for separate ρs for separate damage categories. Higher differences in T are left out for simplicity's sake.

Unfortunately, ρ is not very well known. The speed of adaptation depends on whether adjustments are needed in short-lived or long-lived capital, whether alternatives exist and can readily be applied, whether the change in climate is anticipated or detected, and on the size of the shock. The question of which share of the damage is due to the level and which share is due to the rate of change is of equal importance. Table 4 provides some indication. It provides a series of informed guesses, the assumptions that underlie the damage module of the FUND model.

In addition, temporary damages may also occur because restoration takes time. Examples include buildings damaged by a flood or storm, or landscape, species or ecosystem lost (in which case the human value attached to it will slowly fade away, because of the limited human memory and the growing appreciation of the replacement). Equation (1) thus becomes

$$\begin{aligned} D_t &= L_t + R_t + \rho R_{t-1} + \varphi D_{t-1} \\ &= L_t + \varphi L_{t-1} + R_t + (\rho + \varphi) R_{t-1} \end{aligned} \tag{3}$$

As ρ, φ is a very important but largely unknown parameter. Again, φ can differ widely between various damage types. Buildings can be rebuilt in a few years time, the nostalgic value of specific landscapes fades within a generation, but key species lost (eg the dodo bird) may be valued hundreds of years. Obviously, in some cases, $\varphi = 1$, that is, the damage is irreversible and irreplaceable. An example would be if the only potential cancer cure ever available to mankind were lost because of climate change.

Table 5 presents an idea on the values of ρ, φ, and Table 4 assesses the share of the damage due to the rate of change for some of the damage categories of Table 1.

Table 4 Time damages endures, per category[a]

Category	Years
Agriculture	10
Dryland	50
Emigration	5
Heat/cold stress, amenity	15
Hurricanes	5
Immigration	5
Life loss	30
Species loss	100
Wetland (tangible)	10
Wetland (intangible)	50

[a]Given is the time it takes for 99% of the damage to disappear, because of adaptation, restoration, or value adjustment.

Source: Tol (forthcoming).

Table 5 Share of damages due to rate of change, per category

Category	Share
Agriculture	3.7[b]
Amenity	5/6
Coastal protection	1/4
Dryland	1/2
Emigration	1
Heat/cold stress	5/6
Hurricanes	5/6
Immigration	1
Species loss	1[a]
Wetland	1

[a]Species loss neglects the potential loss of unique values;
[b]The figure for agriculture is greater than one, as Parry and Rosenzweig (1994) find benefits for agriculture under full adaptation, but losses without adaptation.

Source: Tol (forthcoming).

Changes in socioeconomic vulnerability are just as important as the actual shape of the damage function. Adaptation is mentioned above, as is the adjustment of human values to a new situation. These are not in fact changes in vulnerability, but changes induced by climate change. Vulnerability will also change exogenously to climate change. The rough pattern of such change is obvious from Table 2: poorer regions are more vulnerable to climate change than richer ones; in addition, the share of tangible damages is greater in the poorer regions, even though the projected increase in mortality is far higher in developing countries. Hence, with growing affluence, tangible vulnerability will fall (relative to income) and intangible vulnerability will rise.

The reason why the less affluent are more vulnerable to climate change (or any other change for that matter) is that their financial, institutional and technical capacities are limited. With economic growth, adaptation will become easier and cheaper, particularly if changes are anticipated. Another major factor is that, with economic development, dependence on the primary sector (agriculture, fisheries) falls, as well as the dependence of the primary sector on weather and climate, because of insurance, technology, management and weather forecasts. Infrastructure and protection against weather hazards are likely to improve, and possible losses are more easily redistributed in well developed financial markets. Capital is less scarce in developed economies so adaptation of machinery and infrastructure is easier. Increased availability and affordability of medical services will reduce human morbidity and mortality. Obviously, economic growth will also result in more and different things being damaged by climate change. In addition, it is sometimes argued that although the OECD countries are increasingly robust to small weather variations, they become also increasingly sensitive to large shocks. If a major communication, data or financial centre, or a power plant gets hit by a flood or a cyclone, or if a major insurer or bank went bankrupt overnight, immense consequences could result (Tol *et al*, 1994). The chances of this happening are tiny, and the consequences speculative, however. On the whole, tangible vulnerability tends to fall with economic growth.

The situation is reversed with regard to intangible vulnerability. Roughly in accord with Maslow's pyramid of wants, if primary needs (food, shelter) and economic aspirations (car, compact disc player) are fullfilled, higher goals are pursued, of which nature and equity are important components. Ecosystems and species will be under stress of climatic change, and the distributional effects are generally considered to be unfair as the poor and largely irresponsible are likely to suffer most. With growing affluence, such considerations will be valued higher. The question is, by how much? Based on limited empirical evidence, Pearce tentatively concludes that the total share of their income that people are willing to pay for intangibles grows linearly with per capita income (Pearce, 1980); hence, on a macro-scale, intangible vulnerability is quadratic in GDP. The question is, of course, whether it is justified to extrapolate this finding too far. Manne and Richels employ a logistic function for intangible vulnerability, a more plausible approach (Manne and Richels, 1995). However, letting damage converge at 2% of GDP seems low (although it is a lot of money), particularly since it is an absolute cap (whatever happens, 2% is the maximum).

Conclusions

In this paper we assess the trends which will lead us from the current state of the art of estimates of the damage costs of climate change, as reflected in the Second Assessment Report of the IPCC, to a new generation of improved estimates. Earlier studies estimate the aggregated monetized damage due to climate change at 1.5–2.0% of world GNP; the OECD would lose 1.0–1.5% of GDP; the developing countries 2.0–9.0%. These figures are not comprehensive and highly uncertain. Ongoing research updates and extends the estimates, but formal assessments of uncertainty remain rare. Newer studies increasingly emphasize the power of adaptation, the importance of weather variability and extreme events, the influence of stress factors other than climate change, and the need for integrated assessment of damages. As a result, the difference in impacts between regions and between sectors might increase. Estimates of market damages in developed countries have tended to fall, while non-market impacts have become increasingly important.

Marginal damages and damage profiles are more interesting from a policy point of view. Earlier estimates of the marginal range from about US$5 to US$125 per tonne of carbon, with most estimates at the lower end of this range. These figures are based on polynomial functions in the level of climate change, but the rate of change may be equally important, as are the speed of adaptation, damage restoration and value adjustment. However, little explicit attention has been paid to these matters. In addition, future vulnerability to climate change will obviously be different from current vulnerability. On the whole, the market impacts fall (relatively) with economic growth while the non-market impacts rise (relatively) with growth. Mortality and morbidity losses may be an exception as the absolute numbers fall with medical standards while the value per case rises with per capita income.

In sum, the first generation of estimates of the damage costs of climate change is being substantially updated, extended and complemented, without, as yet, invalidating the earlier results. The most crucial research topics for the next period appear to be (1) damage estimates for less developed countries; (2) improved estimates for non-market losses, particularly human morbidity and unmanaged ecosystems; (3) assessment of the importance of variability and extreme events; (4) models of the process of adaptation and the dynamics of vulnerability; and (5) formal uncertainty assessments and analyses on the outcomes.

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