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Assessing the Impacts of Climate Change: A Literature Review

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ASSESSING THE IMPACTS OF CLIMATE CHANGE: A LITERATURE REVIEW

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ABSTRACT/RÉSUMÉ

Assessing the impacts of climate change: a literature review

Climate change is expected to have significant implications for the world economy and, more broadly, for many areas of human activity. The purpose of this review is twofold. First, it is to summarise current estimates of the impacts of climate change and to explain how these estimates are built in order to identify the main sources of uncertainty and approximation affecting them. Second, the paper discusses how this uncertainty should influence policymaker's decisions. A main conclusion of the review is that there are large uncertainties, which are not fully reflected in existing estimates of global impacts of climate change in monetary units. Nonetheless, despite these uncertainties, policy action may be justified, provided that policies are cost-effective, even if the marginal cost of GHG emissions mitigation exceeds the marginal damage of one additional ton of carbon. This is because two features of the impacts of climate change tilt the balance in favour of action: their irreversibility, and the risk that they are extreme.

JEL classification: Q00; Q54.
Keywords: climate change; impact; uncertainty; irreversibility; extreme events.

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Évaluer les impacts du changement climatique : une revue de la littérature

Le changement climatique devrait avoir des conséquences importantes sur l'économie mondiale et, plus généralement, sur un large éventail d'activités humaines. L'objectif de cette revue est double. D'une part, il s'agit de résumer les estimations récentes des impacts du changement climatique et d'expliquer comment ces estimations sont obtenues afin d'identifier les principales sources d'incertitude et d'approximation qui les entourent. D'autre part, la façon dont cette incertitude devrait influencer les décisions des responsables politiques est discutée. L'une des conclusions principales de cette revue est qu'il existe un grand nombre d'incertitudes autour des impacts du changement climatique qui ne sont pas pleinement reflétées dans les estimations des impacts globaux exprimés en unité monétaire. Néanmoins, en dépit de ces incertitudes, une politique active pourrait être justifiée, à condition que ces politiques soient efficaces au regard des coûts, même si le coût marginal de réduction des émissions des gaz à effet de serres est supérieur au coût marginal d'une tonne additionnelle de carbone. Ce résultat provient de deux caractéristiques des impacts qui inclinent la balance en faveur de l'action : leur irréversibilité et le risque qu'ils soient extrêmes.

Classification JEL : Q00 ; Q54.
Mots-Clés : changement climatique ; impact ; incertitude ; irréversibilité ; événements extrêmes.

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ASSESSING THE IMPACTS OF CLIMATE CHANGE: A LITERATURE REVIEW

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Stéphanie Jamet and Jan Corfee-Morlot[1]

1. Introduction and main findings

1. Estimating the impacts of climate change is key to any discussion of mitigation or adaptation policies. In order to decide whether action is needed or not, and to choose the target, policymakers need to know the cost of inaction and how the cost of mitigation policies weighs against the benefit of acting. The purpose of this review is twofold. First, it is to summarise current estimates concerning the impacts of climate change and to explain how these estimates are built in order to identify the main sources of uncertainty and approximation affecting them. Second, it discusses the way this uncertainty should influence policymaker decisions.

2. The main conclusions are the following:

- The uncertainties on the side of the impacts of climate change are large. There are at least five sources of uncertainty:
  - greenhouse gas (GHG) emissions projections;
  - the accumulation of emissions in the atmosphere and how the resulting concentration will affect the average global temperature;
  - the physical impacts of a given increase in temperature, in particular for non-market impacts, such as health;
  - the valuation of physical impacts in terms of GDP;
  - the risk of abrupt climate change that would trigger some irreversible impacts.
- These uncertainties are not fully reflected in existing estimates of global impacts in monetary units. First, most existing estimates do not consider the risk that a given level of GHGs concentration may lead to exceptionally high increases in temperatures. Second, existing global estimates do not consider the whole range of possible impacts and the uncertainty around them. Finally, the risk of extreme events with large consequences is seldom integrated into the

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estimates. Hence, uncertainty around the cost of the impacts of climate change is under-estimated. In particular, the risk of large impacts is not fully reflected in existing estimates.[2]

- In theory, adaptation constitutes a downward risk to estimates of the impact of climate change. However, since the treatment of adaptation varies across studies, the extent of this downward risk is unclear. In any case, it is unlikely that this downward risk could offset the upward risk coming from the incompleteness of the estimated impacts.

- Despite these uncertainties, the literature suggests that the impacts of climate change could be large. Moreover, although the evolution of GHG concentration can be reversed by reducing emissions, at least on a sufficiently long period of time, some of the impacts of climate change will be irreversible.

- There is a trade-off between avoiding irreversible policy cost and irreversible damages. While it is not possible to change the irreversible nature of some damage caused by climate changes, their cost to society can be lowered through efficient adaptation policies. The irreversibility of the cost of mitigation policy can be partly reduced by avoiding policies that encourage irreversible investments that could prove, *ex post*, not to be cost-effective solutions. Least-cost policies would also lower the overall cost.

- Provided that policies are cost-effective, the uncertainty and irreversibility of the impacts of climate change may justify policy action even if the marginal cost of mitigation exceeds the marginal damage of one additional ton of carbon.

2. Main impacts of climate change

3. Climate change involves not only global warming but also other physical changes such as precipitation, the intensity and frequency of storms and the occurrence of droughts and floods. As well, the widespread melting of the Greenland and West Antarctic ice sheets, which would imply a large sea level rise, and changes in the thermohaline circulation (THC)[3] - the global density-driven circulation of the oceans - which would amplify climate change, are considered as two of the main irreversible risks associated with climate change.

4. Temperatures have already increased by an estimated 0.7°C compared with pre-industrial levels. There is still some controversy on the contribution of anthropogenic GHG emissions to temperature increases. However, the last report of the Intergovernmental Panel on Climate Change (IPCC, 2007), based on the most recent research in this area, attributes most of the observed increase in global average temperatures since the mid-20th century to anthropogenic causes with a probability of more than 90%. Furthermore, this report also identifies a range of already observed impacts of climate change.

5. Climate change is likely to have consequences in many areas of human activity, and some of these consequences are already being observed. As summarised in Table 1, consequences are often classified in two broad categories depending on whether they directly affect the economy such as for instance agriculture production, energy consumption, called “market” impacts or whether they more broadly affect humans and society (health, environment), then called “non-market” impacts. Another

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[2] Except in the Stern review, but for other reasons, the results of the Stern review have been questioned as well.

[3] For instance, the Gulf Stream is a branch of the global thermohaline circulation. An increase in temperature would lead to a slowdown of the Gulf Stream, which would imply lower temperatures in Northwestern Europe.

category that is sometime distinguished is "socially contingent impacts" (Downing *et al.* 2005). This category in fact cuts across market and non-market impacts. It includes all the social impacts that would be contingent on the direct impacts, such as for instance conflicts, large migration flows that would come from a large sea level rise, or significant problems coming from a decrease in water and food availability.

[Table 1. The main impacts of climate change]

6. While some of the impacts can be positive to both the economy and society, at least for moderate increases in temperature, most are expected to be negative. Furthermore, the severity of the impacts is likely to be non-linear at higher temperatures. This is because when some threshold temperature increases are crossed, the probability to experience large damages on the economy and the ecosystem becomes higher (Keller *et al.* 2006). Although there are still large uncertainties concerning the understanding of these thresholds, empirical evidence tends to suggest that such threshold effects may be significant (Schneider and Lane 2004). According to recent studies:

- An increase in temperature by 1.5°C relative to pre-industrial levels would initiate the melting of the Greenland ice sheet that could lead to a 7m sea-level rise and coral bleaching.

- A larger increase (2.5°C and above) would lead to the disintegration of the West Antarctic ice sheet and an additional 5m sea level rise.

- The weakening of the thermohaline circulation is expected at low increase in temperature, but there are large uncertainties regarding the threshold that would trigger its collapse including for instance the disappearance of the Gulf Stream.

3. Assessing global economic impacts of climate change

7. Estimating the economic impacts of climate change raises a number of difficult issues. First, the knowledge on the physical impacts of climate in every possible area is limited. Second, aggregating specific impacts into a single estimate of the net impact of climate change also raises a number of problems. These mainly arise because impacts have to be aggregated along three dimensions: *i)* across impacts, which requires the use of a common measure for market and non-market impacts; *ii)* across regions, which raises an equity issue, and *iii)* over time, which implies the use of a social (consumption) discount rate.

3.1 The impacts of climate change in specific areas

8. A relatively large number of studies have attempted to estimate the impacts of climate change in specific areas using various methodologies. The typical approach of early studies consists in combining a climate model that projects climate change for a given level of CO_2 concentration (generally, a doubling from pre-industrial level), with either an "economic" model that captures the market impacts or another type of model that incorporates non-market impacts. These studies estimate *static* and *physical* impacts of climate change on "today's world" mainly for modest increases in temperatures and cover a limited number of regions, often only the United States. The main results that can be drawn from this literature are the following (Fankhauser 1995, Nordhaus, 1991, Tol, 2002):

- One of the most important impacts expected from climate change is to deteriorate health. Its size may be understated since estimates are largely incomplete. The number of additional deaths coming from an increase in temperatures has been estimated only for specific diseases (Malaria, heat- and cold-related cardiovascular mortality, heat-related respiratory mortality). Furthermore, the indirect consequences of climate change on health through food availability, water constraints, air quality or conflicts induced by climate change are mainly unknown.[4]

- Climate change can lead to a significant rise in sea level and catastrophic events with implications on migration and the capital stock. Part of these impacts can be avoided through adaptation policies.

- Climate change is expected to damage infrastructure but this effect can also be partly offset by adaptation strategies.

- Climate change would also have a negative impact on biodiversity and the ecosystem, although these effects are still partly unknown.

- The "sign" of the impact of climate change on agriculture is uncertain, at least for moderate increases in temperatures. Main difficulties to estimate this impact come from our limited knowledge of the impact of climate change on precipitation. Furthermore, there are also debates on whether CO_2 fertilisation occurs, according to which the increase in CO_2 concentration in the atmosphere enhances photosynthesis rates, thereby allowing stronger growth of plants and more effective carbon fixation; this has the potential to mitigate or even to offset the negative impact of climate change in the agriculture and forestry sector.[5] Finally, adaptation can also mitigate the impact of climate change in this sector. Despite these caveats, estimates suggest that climate change would lower gross agricultural production when no adaptation is assumed in most countries (but not in Central and Eastern Europe and in some Asian countries) but that adaptation could offset this negative impact.

- Climate change can increase or decrease energy consumption and water resources and demand. The impact is expected to strongly depend on regions, with warm regions being more negatively affected than cooler ones.

9. The literature also suggests that there is a large range of uncertainty surrounding these estimates. First, physical impacts are only partially understood. The incompleteness of estimates is an upward risk (regarding health and extreme events for instance). Second, adaptation is a downward risk, mainly for agricultural and sea-level rise impacts. Finally, carbon fertilization is a downward risk for agricultural impacts at lower levels of global warming.[6]

3.2 Aggregating across impacts

10. A large part of the impacts of climate change (''non market impacts'') are measured in physical units, such as number of annual deaths, number of people threatened by forced migration and the species

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[4] It is important to note that more recent studies consider socio-economic development in parallel with climate change and this could be expected to limit damages in this area, as development will lower vulnerability to climate change e.g. by increased provision and access to health services (see Tol and Dowlatabadi, 2001 and Tol, 2005b).

[5] Reilly et al. (2007) find that climate change below 3°C relative to 2000 levels would have a positive effect on agriculture production because of this effect (when the negative impact of ozone on agriculture production is not considered).

[6] Beyond the regional interactions with soil conditions, above temperature increases of more than 3o C relative to 2000 levels, fertilisation effects are expected to be offset by heat stress effects (Ainsworth and Long 2005).

lost. In order to obtain an economic measure of all these impacts, one needs to convert them into a single monetary unit, typically GDP percentage points.

11. Since there is no particular market for mortality risk reduction (or for the maintenance of biodiversity), the method to "value" these non-market goods consists of using situations where individuals implicitly reveal how much they value mortality risk reduction in decisions they make. A price of the reduction of the risk can then be inferred and applied to value physical impacts (Box 1). Concerning damages to health caused by climate change, the central estimate is the so-called value of statistical life (VSL), which is the value attached to a unit reduction in the number of deaths. In addition to the difficulties of estimating the VSL, there are several issues regarding its use in the field of the impact of climate change. VSL estimates are typically based on the labour market context for the environmental policy in question; transferring such estimates from one place to another requires that populations have similar risk characteristics, which is not necessarily the case, for example since some particular age-groups of the population are expected to be more affected by climate change impacts. Furthermore, it is generally agreed that VSL increases with income implying that more weight is put on impacts in rich countries than in poorer ones, which is controversial for ethical reasons (Fankhauser *et al.* 1997).

Box 1. Valuation methods for non-market impacts

Physical impacts on human health are expressed in monetary terms by using the so-called value of statistical life, which is the value attached to a unit reduction of the number of deaths. The value of statistical life has been mainly estimated in the labour market context by considering that the extra pay individuals require to accept jobs posing additional risk reflects implicit tradeoffs between life risk and money. The extensive literature, based on such estimates using US labour market data, typically shows a VSL in the range of $4 million to $9 million (Viscusi and Aldy, 2003).

One particular issue is whether VSL varies with income. Existing estimates show that developing countries tend to have lower values of statistical life than values in developed countries, which may reflect that safety is a normal good (Viscusi, 1978). Hence, the VSL should increase with per capita income and the income elasticity is estimated to be in the range of 0.50 to 0.60 (Viscusi and Aldy, 2003).

Another important issue is whether the benefit of reducing risks to the old is less than for younger age groups. Older individuals should be willing to pay less for reduced mortality risk because they are purchasing fewer additional years of life expectancy (Viscusi and Aldy, 2007). If VSL is assumed to decrease with age, then transferring labour market VSL estimates to an environment policy context may not be correct since the impact of climate change on health is expected to affect more particularly some age-groups of individuals. For this reason, the European Commission recommended that member countries use a VSL that declines with age (European Commission, 2001).

Finally, estimating VSL requires choosing between willingness-to-pay (WTP) and willingness-to-accept (WTA) approaches, which has some implications for the estimate. According to the WTP concept, the question is how much an individual would pay to avoid the negative impact of climate change, while under the WTA approach, the question is how much should be given to an individual to compensate for the losses induced by climate change. While in theory those two approaches should lead to similar results, in practice, WTA gives higher value than WTP, especially for public goods such as the environment. The difference may reflect that losses (WTA approach) are weighted far more heavily than gains (WTP approach), or from the fact that incomes may limit WTP estimates. Since most VSL estimates are based on the WTP approach, they may be downward biased (Pearce, 2002; Hanemann 1991).

There are also several problems with attaching a value to other non-market impacts. In order to convert environment impacts (loss of species, loss of biodiversity) into monetary units, three components of the value are generally distinguished: the use value, the option value (the possibility to use the good in the future), and the existence value. For example, there exist some estimates of these values that are based on the medicinal value of plants or current wildlife protection expenditure. Finally, the cost attributed to migration is generally set on an arbitrary basis.

12. Once impacts are expressed in a common monetary unit, their estimated distribution across areas, including market and non-market impacts, varies strongly across countries (Table 2). For instance, larger impacts are expected on agriculture in middle-income countries and on health in Africa.

[Table 2. Distribution of impacts of 2.5°C warming across types of impacts, by regions, per cent of GDP]

3.3 Aggregating across countries

13. There are large variations in the size of impacts across countries with developed countries being, in general, less affected than developing ones (Figure 1). These variations make the issue of aggregating impacts across countries or regions particularly important and potentially politically sensitive, as aggregation conceals distributional issues. The simple sum of regional impacts is useful for discussion of the global effect of climate change, but it ignores the disparity between regions in terms of impacts and, because the value attributed to non-market impacts (such as health) generally decreases with income (see Box 1), a simple sum implicitly puts less weight on impacts in poor countries than in richer ones. To take these factors into account, the choice of an appropriate social welfare function plays a central role. For instance, weighting countries by the inverse of their income-per-capita gap relative to the United States would offset the positive link of VSL to income and would in fact put the same weight on each individual. Tol (2002a) found that the total impact of a 1°C increase in global mean temperatures would be either a net gain of 2.3% of income when using a simple mean and a net loss of 2.7% when using the average WTP/WTA for non market impacts.

[Figure 1. Regional economic impacts]

14. Furthermore, the way impacts are aggregated across countries influences the preponderance of one impact over the others at a global level, and, more generally, the distribution of global impacts within sectors. This is because regions are not equally exposed to each type of impact. For instance, climate change is expected to have a large impact on health in developing countries and large market impacts in developed countries. As a result, when impacts by countries are weighted by population, which gives more weight to impacts in non-OECD countries, global impacts (excluding catastrophic events) appear to be mainly driven by non-market impacts while they appear to be mainly driven by market and coastal impacts when impacts by countries are weighted by income (Figure 2).

[Figure 2. Global impacts of climate change for different rules of aggregation across countries, for a 2.5°C warming]

3.4 Aggregating across time

The role of the discount rate

15. Because most of the impacts of climate change are expected to occur in the long-run, the social discount rate (SDR), which measures the importance of the welfare of future generations relative to the present, strongly shapes the global impact estimate of climate change. There is a widespread and longstanding disagreement among economists about the appropriate level of the SDR (Weitzman, 2001), which received renewed attention with the publication of the Stern review (Stern, 2007a), where a relatively low discount rate was applied. The consensual framework for analysing the social discount rate is the so-called Ramsey rule, which states that in an infinite horizon deterministic optimal growth model with one good the SDR can be written as $SDR = PRTP + mu * g$, where PRTP is the pure rate of time preference, *mu* is the elasticity of the marginal utility of income, and *g* is the future trend growth rate of the economy. Sources of disagreement among economists include *inter alia*:

- *The choice of the PRTP:* one open issue is whether the PRTP values that prevail at the individual level, which reflect “impatience”, also apply at the society level. Indeed, the higher the PRTP, the lower the weight assigned to future generations relative to current ones in (discounted) social utility calculations. In line with a long line of economists (*e.g.* Ramsey, 1928; Harrod, 1948; Solow, 1974), Stern (2007a) has argued that ethical considerations call for a zero or near-zero PRTP, while others dismiss this assumption on the grounds that it is inconsistent with actual individual behaviour (*e.g.* Nordhaus, 2007a, Weitzman, 2007a). Differences in the choice of the SDR make a large difference in practice. For instance, the impact estimates presented in the Stern Review (Stern, 2007a) fall rapidly under higher PRTP assumptions (Table 3).

- *The choice of mu:* estimates for this parameter may in principle be derived from existing evidence about inter-temporal income distribution (the inter-temporal elasticity of substitution), which is the concept implicit in the Ramsey formula. More broadly, however, *mu* captures the "curvature" of the social utility function, and as such its choice could also reflect theory and/or empirical evidence about intra-temporal income distribution (degree of social preference for equal household income distribution) and attitudes towards risk (degree of risk aversion). In practice, these three approaches may yield conflicting views (Stern, 2008). Also, whether the inter-temporal elasticity of substitution at the social level can be inferred from (the aggregation of) observed individual behaviours – as reflected in (aggregate) saving rates – is subject to debate. Even abstracting from this issue, the value of *mu* that may be derived from observed saving behaviour is highly sensitive to both the structure and parameters of the underlying theoretical growth model used, *e.g.* on the rate of technological progress (De Long, 2006).

- *The impact of uncertainty:* uncertainty may influence the SDR on at least two grounds. First, uncertainty about future income growth rates or about the SDR itself may call for time-declining SDRs, *i.e.* for the use of lower discount rates for distant impacts (Gollier, 2002; Weitzman, 2001). Second, the risk of large damages of low but unknown probability may be roughly captured through the use of a relatively low SDR, in a context where incorporating such risk explicitly in standard cost-benefit remains challenging (Weitzman, 2007b).

- *The distinction between environmental and other goods:* compared with the Ramsey formula, the existence of two goods (one reproducible consumption good and one environmental good) rather than one could lower the discount rate to be used for distant damages, all the more so as the relative price of environmental goods is expected to rise in the future as a result of their growing scarcity (Hoel and Sterner, 2007).[7]

[Table 3. The influence of the social discount rate on the estimated impacts of climate change]

Toward estimates of the dynamic impact of climate change

16. The impact of climate change is *dynamic* in so far as it would depend on the path of GHG emissions (and thus on population growth, economic growth and technological change), future adaptation and the feedback effect of GDP reductions (relative to BAU) on emissions. Integrated Assessment Models (IAM) try to capture the whole process of human-induced climate change, from economic growth to emissions and their consequences on the physical climate and then to the impacts of emissions over time to estimate their aggregate global socio-economic impacts. However, these models currently have several limitations (Box 2). First, they suffer from uncertainties surrounding estimates of physical impacts and from the difficulty to aggregate impacts across areas, regions and time. Second, they have to adopt a very rough representation of the impact of climate change through at most a couple of equations that are often disconnected from most recent findings at a more disaggregate scale. Third, the response functions and the

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[7] These models also assume perfect substitutability between man-made capital and natural capital, which has some consequences for the optimal policy that is obtained within this type of analytical framework, Neumayer (1999).

optimal emission paths are derived assuming that impacts are certain.[8] Since intrinsic uncertainty is omitted from objective functions, the derived response functions and emission paths differ from those that would be optimal in the presence of uncertainties. Taking explicitly into account the underlying uncertainty is likely to lead to more precautionary behaviour, to enhance adaptation, and, hence, to lower the estimated cost of the impacts. Finally, although these models attempt to capture the *dynamic* impacts of climate change, estimates remain largely determined by static impacts.

Box 2. Main features of Integrated assessment models (IAMs)

Integrated Assessment Models try to estimate the global and *dynamic* impact of climate change, which would depend on the path of GHG emissions and thus on population growth, on their consequences on climate and finally, on the socio-economic impacts of climate change, which would be influenced by technological change and future adaptation. These models consist of:

- An objective function, usually inter-temporal maximization of welfare. An assumption needs to be made regarding the discount rate. The output of the model is then an optimal GHG emissions path.
- A very simple economic module with exogenous growth and production being allocated between consumption and investment with constant exogenous shares. The (regional) production function includes a carbon energy input that emits GHG.
- A relatively detailed geophysical module that links GHG emissions to weather changes, in terms either of temperatures only or also of precipitations, storms and sea level rise.
- The "impact function", which is at the core of the model. It describes the costs to society of the changing climate by relating climate change to its socio-economic impacts expressed in monetary units. In a number of cases, it consists of one or two equations sometimes with regionally-differentiated parameters. When there are two equations, a distinction is typically made between market and non market impacts.[9] In more detailed models, each impact is represented by one equation.[10] The impact functions are usually calibrated in order to reproduce the estimates of the impact of climate change from a narrow set of studies (Nordhaus, 1991, Fankhauser, 1995, Tol, 1996). These studies combine the literature on impacts (measured in physical units) so as to derive a global impact in monetary units, sometimes by regions, for a specific change in CO_2 concentration. The global impact is often a function of one climate variable, generally the global mean surface temperature. The impacts in terms of precipitation, sea level, hurricane activity, storms are seldom taken into account.[11]

These models are used to estimate the impacts of climate change conditional to both a growth scenario and assumptions regarding adaptation to climate change. They are also used to compute the optimal path of GHG emissions reduction. The main limitations of these models are the following:

- The impact function is very simple, mainly determined by static impacts and does not always take stock of the most recent findings. Most commonly, damages are fed back by subtracting monetized damages to output, which would require adopting a broader definition of GDP so as to incorporate non market impacts.
- The calibration of impacts is made on the basis of very specific studies, reporting on the impact in developed countries (often the United States) and for a doubling of CO_2 concentration between the pre-industrialised period and 2050. Deriving impacts for the whole economy and for any range of change in temperature by extrapolating from such specific scenarios may imply biases of unknown direction and magnitude.

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[8] Some IAMs treat uncertainty by allowing the parameters to vary within some ranges (using Monte-Carlo simulations) but this is very different from introducing uncertainty in the objective functions and finding the response functions that are optimal under uncertainty (PAGE model).

[9] This is the case of the PAGE model that is used in the Stern Review (Stern, 2006)

[10] As in the FUND model (Tol, 2002).

[11] Some models take them into account but by relating these impacts to change in temperature, which is a questionable assumption and implies that there is a bias on the impact. The impact of sea level rise is for instance under estimated when sea level rise is directly linked to changes in temperatures (Tol, 1998).

- Partly for this reason, disparities in vulnerability to climate change across countries (*e.g.* developing countries being more exposed than developed ones), are not fully taken into account in these models. The impact of climate change on the economy and society depends on vulnerability to extreme weather events, which in turn is determined by several factors such as the production structure, technical change, demography factors and social organisation.
- Adaptation, which plays a central role in determining the level of damages, should be an efficient response to climate change and hence, endogenous. Yet, in practice, adaptation is either not taken into account or assumed to be exogenous. However, some models do endogenously introduce adaptation (IMAGE, FUND, PAGE).
- Almost none of these models include uncertainty.

17. On the whole, estimates of the global impact of climate change have not changed much over the last 10 years according to the IPCC (Figure 3). However, the Stern review estimates are much larger than in other studies. As already mentioned, this is mainly due to a low discount rate, and to a lesser extent to new information regarding the impacts (Nordhaus, 2007a; Dasgupta, 2007). Nevertheless, use of a low discount rate may involuntarily yield more plausible estimates than those in the rest of the literature (Weitzman, 2007). This is in part because there are large uncertainties on the impacts of climate change, which are explained in more detail in the following section.

[Figure 3. Estimates of the global damages of climate change]

4. Uncertainty

18. There are large uncertainties around the estimates of the impacts of climate change. The purpose of this section is to explain the sources of these uncertainties and to try to quantify their magnitude. The overall uncertainty surrounding the economic impacts of climate change can be decomposed into three main categories (Table 4):

i) *Economic and technological uncertainty*: the uncertainty around emission projections which in turn mainly reflects uncertainty around macroeconomic projections and the energy mix.

ii) *Environmental uncertainty*: uncertainty around the impact of GHGs concentration on the physical climate.

iii) *Economic and valuation uncertainty*: for a given climate change (in terms of temperatures, precipitations, or pattern of extreme event, etc.), uncertainty on its impacts on the economy and society. This uncertainty is magnified by difficulties in the economic valuation of the non-market impacts as explained in the section above.

[Table 4. Decomposition of the uncertainty on the impacts of climate change]

4.1 Economic and technological uncertainty

19. The uncertainty on emissions growth is large and increases as the time horizon gets longer (Figure 4). It comes from various sources including uncertainty on GDP and population growth as well as on technological progress.

[Figure 4. Projected CO_2 emissions across a range of previous studies]

4.2 Environmental uncertainty

20. Economic and technological uncertainty is reinforced by uncertainties on the physical link between emissions and concentrations. This link is affected by the degree of absorption of gases by the earth and the oceans and the persistence of gases in the atmosphere (Figure 5). Nonetheless, there is less variation in concentrations than in emissions projections because concentrations largely depend on past emissions.

[Figure 5. Projected trends in GHG concentration across a range of previous studies]

21. The uncertainty surrounding concentration levels is compounded by the uncertainty concerning the impact of a change in GHGs concentration on temperatures. Environmental uncertainty is generally summarized by the uncertainty around the so-called *climate sensitivity* parameter, which measures the impact on global mean temperature of a doubling of GHGs concentration from its pre-industrialisation level. The uncertainty around this parameter comes from the difficulties to estimate the impact of temperature increases on evaporation rates, which would increase the water vapour concentration (a GHG) and thus, the overall GHG concentration. An increase in evaporation also increases the extent of cloud cover and, in turn, reduces the solar radiation reaching the Earth's surface, thereby lowering the greenhouse effect. Knowledge of the value of the crucial climate sensitivity parameter has improved over time but remains highly uncertain. According to the fourth IPCC assessment report, it is *likely* (with a probability of at least 66%) to be in the range of 2°C to 4.5°C, with a central ("best" or median) estimate of 3°C. Even restricting the focus of analysis to this "likely" range, the uncertainty on the impact of a given concentration on long-run temperature increases is large (Figure 6). Focusing on this "likely" range for the climate sensitivity parameter ignores the risk of reaching high level increases in temperatures with relatively moderate levels of concentration. For instance, when the whole range of estimated possible values of the climate sensitivity parameter is considered, the probability to reach or exceed a 5°C long-run increase in temperatures with a stabilisation of GHG concentration at 700 ppm[12] is around 30 % (Figure 7).

[Figure 6. Link between long-run GHG concentration and global temperature]

[Figure 7. The risk of overshooting 2.5°C and 5°C equilibrium warming for different concentration stabilisation levels]

4.3 Global uncertainty

22. Uncertainties on emissions and on climate sensitivity are further enhanced by the uncertainty on the physical impacts and the difficulty to value them in monetary units for a given increase in temperatures (see Section 3). It is technically not possible to isolate the latter source of uncertainty from the first and second ones because the impacts of climate change are computed by IAMs that integrate the three sources of uncertainty. IAMs typically produce two types of estimates of the impacts of climate change:

- Estimates of the *social cost of carbon* (SCC), which is the net present value (over the simulation horizon) of the climate change impact of one additional ton of carbon emitted in the atmosphere today;

- Estimates of the global aggregate impact of climate change, which is the global impact of a given climate change relative to pre-industrial temperatures.

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[12] A 700 ppm concentration is expected to be reached before 2100 in a business as usual scenario in most of the estimates, including "low scenario" (see Figure 5).

23. In theory, the variance of the SCC or of aggregate impacts across models captures not only the uncertainties on emissions projections and on the climate sensitivity but also the uncertainty surrounding the valuation of impacts and the way they are aggregated across different impacts, countries and time periods. In practice, however, the dispersion of the SCC estimates or of the aggregate impacts very likely underestimates the aggregate uncertainty for several reasons (Figures 8 and 9, upper panel):

- most of these models adopt a climate sensitivity parameter between 2.5°C and 3°C, hence underestimating the environmental uncertainty;
- models typically do not take into account the risk of extreme weather events or impacts coming from other forms of climate change than temperature (e.g. precipitation), or sea level rise (Table 6);
- the impact functions of IAMs are usually calibrated on a very limited number of studies that do not include the full range of possible impacts (see Box 2 and Table 5).

[Table 5. Main impacts of climate change along two dimensions of uncertainty and their coverage in IAMs]

[Figure 8. Distribution of the social cost of carbon across a range of existing studies]

[Figure 9. Global impacts of climate change from various studies]

24. The implications of these sources of uncertainty for global impacts estimates have been partly taken into account in the Stern Review, on the basis of Hope (2006) (Table 6). Factors that can cause the largest fluctuations in the SCC are the most uncertain ones (the climate sensitivity parameter and the value of non-market impacts) or maybe the most controversial one (the discount rate). When high values for climate sensitivity are considered and non-market and catastrophic impacts are incorporated, the cost of temperature increases could rise significantly (Figure 9, lower panel). Nonetheless, because of the uncertainties on these impacts and of other reasons, including the choice of the discount rate, these estimates have been subject to criticism (Tol, 2006; Gollier, 2006; Nordhaus, 2007a,b; Weitzman, 2007a).

[Table 6. Major factors causing uncertainty in the social cost of carbon]

5. Consequences of the uncertainty of impacts for cost-benefit analysis

25. The uncertainty surrounding the impacts of climate change and, thus, of the benefits of mitigation policies should influence decision making. Economic theory gives some indication for how to incorporate uncertainty into optimal decision-making. In particular, two aspects of uncertainty are crucial: the interaction between uncertainty and irreversibility, and the risk of extreme events.

5.1 Uncertainty and irreversibility

26. Climate change entails some irreversibility. First, since GHGs stay in the atmosphere over periods that can be very long (especially as regards CO_2), the cost of any additional unit of GHG emission is reversible only over the very long run. More importantly, while most market impacts of climate change are likely to be reversible, some of the non market impacts and extreme events that could appear once a threshold is achieved show a large degree of irreversibility (Table 7).

[Table 7. Irreversibility of damages]

27. The more irreversible the impacts of climate change, the more urgent action to address it is warranted, *ceteris paribus*. This is because of the intrinsic value of keeping open the option to alleviate undesirable effects from climate change in the future, which could be high if valuable information can be expected to become available, thereby lowering uncertainty as time passes. The value of this option may justify acting even if the marginal cost of mitigation exceeds the marginal damage of one additional ton of carbon (Henry, 1974, Arrow and Fisher, 1974; Ambrosi *et al.* 2003). The irreversibility of impacts may also justify targeting a path for concentration without any overshooting.

28. However, the influence of the environmental irreversibility over decisions needs to be balanced against the fact that the cost of mitigation policies is also irreversible (economic irreversibility), which, in the presence of uncertain benefits of policies, justifies to keep open the possibility to take more adequate and less costly actions in the future, and thus, to postpone action (Dixit and Pindyck 1994, Pindyck 2000 and 2007). The issue of the "double" irreversibility - economic and environmental - has seldom or only partially been treated in economic modelling. Indeed, studies that incorporate both economic and environmental irreversibilities only include the environmental irreversibility that comes from the accumulation process of GHG, but not the irreversibility of impacts. Kolstad (1996) finds that in comparison to this type of environmental irreversibility, the capital or economic irreversibility has a stronger influence on today's control decisions and that the balance tends to be in favour of postponing actions. The main point is that, unlike the economic irreversibility, the environmental irreversibility coming from the GHG accumulation process is not fully binding since it is possible to decrease atmospheric concentrations in the future by lowering emissions (Ulph and Ulph 1995). The environmental irreversibility only holds when the levels of uncertainty and/or concentration are so large that negative emissions are likely to be optimal in the future. On the contrary, the economic irreversibility is binding since it clearly concerns expenditure that is irreversible. Still, Pommeret *et al.* (2008) find that for moderate cost of mitigation policy, the balance is in favour of action. However, none of these studies incorporate the irreversibility of impact, which would tilt more the balance towards action.

5.2 Dealing with extreme events or catastrophic events

29. Although there are methods to incorporate uncertainty in decision making when uncertainty can be represented by a known distribution of events, standard approaches fail to account adequately for the implication of large, uncertain impacts with small probabilities. Weitzman addresses the rational economic responses to highly uncertain catastrophes with tiny but highly unknown probabilities in the framework of the expected present discounted utility theory (Weitzman, 2007b). His main finding is that when there do not exist prior limits on damages, expected present discounted utility analysis of costs and benefits is likely to be dominated by considerations related more to catastrophe insurance than to the discount rate.

30. In order to deal with such extreme events, another branch of the literature proposes to abandon the expected utility framework that is based on the existence of an underlying distribution of probability of the uncertain aspect, known by agents who take decisions. The bottom line of the so-called "non-expected utility theories" is that decision-makers tend to put more weight on catastrophic events even though they have a low probability. Under expected utility, decision-makers behave as if they base decision on a single probability distribution by using the average. In fact, individuals seem to place excessive weight on the most pessimistic probability distribution (Ellsberg, 1961). One way to deviate from the assumption of a single underlying probability distribution is to allow for multiple priors.[13] Multiple priors of probability distribution are particularly relevant for the issue of climate change where decision-makers have to deal with a whole set of probability distributions generated by various and heterogeneous models. Their

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[13] The other way to represent choices under uncertainty is to consider that preferences are not formed over "lotteries" directly but, instead, over state-contingent commodity bundles, as introduced by Arrow (1953).

expectation can be represented according to a subjective distribution on the set of possible probability distribution (Klibanoff, Marinacci and Mukerji, 2005). For instance, decisions can be derived from the minimum expected utility obtained from the set of probability distributions in order to capture the role of the worst case (Gilboa and Schmeider, 1989). The size of the set of probability distributions represents the "ambiguity" and people show ''ambiguity aversion'' as a parallel with risk aversion. In this framework, with aversion towards ambiguity, but without explicitly taking into account the irreversible nature of the costs of policies, uncertainty decreases the optimal emission level of the first period (Lange and Treich, 2007).

31. On the whole, there is a difficult trade-off between avoiding irreversible policy cost and avoiding irreversible, and possibly extreme, damages, but policies can influence the trade-off. Efficient adaptation policies can mitigate the cost of climate change damages to society while adopting least cost mitigation policies would bias the trade-off towards action. Provided that policies are cost-effective, the uncertainty and irreversibility of the impacts of climate change is likely to justify policy action even if the marginal cost of mitigation exceeds the marginal damage of one additional ton of carbon.

REFERENCES

Ainsworth, E.A., S.P. Long, 2005: What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2., 165, pp. 351-372.

Ambrosi, P., J.C. Hourcade, S. Hallegatte, F. Lecocq, P. Dumas, and M.H. Duong, 2003: Optimal control models and elicitation of attitudes towards climate damages. *Environmental Modeling and Assessment*, 8(3), pp. 133-147.

Arrow, K. (1964), "The Role of Securities in the Optimal Allocation of Risk-Bearing", *The Review of Economic Studies*, Vol. 31, No. 2, pp. 91-96.

Dasgupta, P. (2006), "Commentary: The Stern Review's Economics of Climate Change", *National institute Economic Review*, Vol. 199, No. 1.

DeLong, B. (2006), "Partha Dasgupta Makes a Mistake in His Critique of the Stern Review", available at http://delong.typepad.com/sdj/2006/11/partha_dasgaptu.html.

Dixit, A and R. Pindyck (1994), "Investment Under Uncertainty", Princeton University Press, Princeton NJ.

Downing, Thomas E. *et al.* (2005), "The Social Costs of Carbon: A Closer Look at Uncertainty", SEI, Final Project Report for the UK Department for Environment, Food and Rural Affairs.

Ellsberg, D. (1961), "Risk, Ambiguity and the Savage Axioms", Quarterly Journal of Economics, Vol°75, pp. 643-669.

European Commission (2001), "Recommended Interim Values for the Value of Preventing a Fatality in DG Environment Cost Benefit Analysis", published online: http://europa.eu.int/comm/environment/enveco/others/recommended_interim_values.pdf.

Fankhauser, S. (1995), *Valuing Climate Change – The Economics of the Greenhouse* (EarthScan, London).

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

Fankhauser, S. and R.S.J. Tol (2005), "On Climate Change and Economic Growth", *Resource and Energy Economics*, Vol. 27, pp. 1-17.

Fankhauser, S. (2006), "The Economics of Adaptation", *EBRD Working Paper*.

Gilboa, I. and D. Schmeidler (1989): "Maxmin Expected Utility with a Non-Unique Prior," Journal of Mathematical Economics, Vol. 18, pp. 141-153.

Gollier, C. (2002), "Discounting an Uncertain Future", *Journal of Public Economics*, Vol. 85, No. 2.

Gollier, C. (2006), "An Evaluation of Stern's Report on the Economics of Climate Change", *IDEI Working Paper*, No. 464.

Hanemann, M., [1991], 'Willingness to pay and willingness to accept: how much can they differ?' *American Economic Review*, 81, pp. 635-647.

Harrod, R.F (1948), *Towards a Dynamic Economics: Some Recent Developments of Economic Theory and Their Application to Policy*, London: MacMillan.

Hitz, S. and J. Smith (2004), "Estimating Global Impacts from Climate Change", in OECD, *The Benefits of Climate Change Policies*, OECD, Paris.

Hoel, M. and T. Sterner (2007), "Discounting and relative prices". *Climatic Change,* Vol. 84, Nos. 3-4.

Hope, C. (2005), "Integrated Assessment Models" in D. Helm (ed.), Climate-Change Policy, Oxford: Oxford University Press, pp. 77-98.

Hope, C. (2006) "The Marginal Impact of CO_2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern", *Integrated Assessment*, 6(1).

IPCC (International Panel on Climate Change) (2007), *4th Assessment (WG1): The Physical Science Basis*, UNEP, Geneva.

IPCC (International Panel on Climate Change) (2007), *4th Assessment (WG2): Impacts, Adaptation and Vulnerability*, UNEP, Geneva.

IPCC (International Panel on Climate Change) (2007), *4th Assessment (WG3): Mitigation of Climate Change* UNEP, Geneva.

Keller, K., G. Yohe and M. Schlesinger (2007),"Managing the Risks of Climate Tthresholds: Uncertainties and Information Needs", An editorial essay, *Climatic Change*, in the press, published online, http://dx.doi.org/10.1007/s10584-006-9114-6.

Klibanoff, P., M. Marinacci and S. Mukerji (2005), "A Smooth Model of Decision Making under Ambiguity," Econometrica, Econometric Society, Vol. 73(6), pp. 1849-1892.

Kolstad, C.D. (1996), "Learning and Stock Effects in Environmental Regulation: The Case of Greenhouse Gas Emissions". *Journal of Environmental Economics and Management* Vol°31, pp. 1-18.

Lange, A. and N. Treich (2007), "Uncertainty, Learning and Ambiguity in Economic Models on Climate Policy: Some Classical Results and New Directions," Working Papers 07.16.237, LERNA, University of Toulouse.

Meinshausen, M. (2006), "'What Does a 2°C Target Mean for Greenhouse Gas Concentrations? - A Brief Analysis Based on Multi-Gas Emission Pathways and Several Climate Sensitivity Uncertainty Estimates", in J.S. Schellnhuber, W. Cramer, N. Nakicenovic, T.M.L. Wigley, and G. Yohe (eds.), Avoiding Dangerous Climate Change, Cambridge University Press, Cambridge.

Mendelsohn, R. and L. Williams (2004), "Comparing Forecasts of the Global Impacts of Climate Change", *Mitigation and Adaptation Strategies for Global Change*, Vol. 9, pp. 315-333.

Neumayer, E. (1999)_"Global warming: discounting is not the issue but substitutability is." *Energy Policy*, 27, pp. 33-43.

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

Nordhaus, W.D. (1999), *The Economic Impacts of Abrupt Climate Change*, Paper prepared for a meeting on Abrupt Climate Change: The Role of Oceans, Atmosphere and the Polar Regions, National Research Council, January.

Nordhaus, W.D. and J. Boyer (2000), **"**Warming the World: Economic Models of Global Warming, The MIT Press, 2000

Nordhaus, W.D. (2007a), "A Review of the Stern Review on the Economics of Climate Change", *Journal of Economic Literature*, Vol. 45, No. 3.

Nordhaus, W.D. (2007b), *The Challenge of Global Warming: Economic Models and Environmental Policy*, Yale University, New Heaven.

Pearce, D. (2002), "The Role of 'Property Rights' in Determining Economic Values for Environmental Costs and Benefits", Report to The Environment Agency, Bristol

Pearce, D. (2003), "The Social Cost of Carbon and its Policy Implications", *Oxford Review of Economic Policy,* Vol. 19, No. 3, pp. 362-384.

Pearce, D. *et al.* (2006), "*Cost-Benefit Analysis and the Environment"*, Paris, OECD.

Pindyck, R. (2000), "Irreversibilities and the Timing of Environmental Policy". *Resource and Energy Economics* Vol°22, pp. 233-259.

Pindyck, R. (2007), "Uncertainty in Environmental Economics", *Review of Environmental Economics and Policy*, Vol. 1, Issue 1, Winter 2007, pp. 45–65.

Mendelsohn, R., A. Dina and L. Williams (2006), "The Distributional Impact of Climate Change on Rich and Poor Countries", *Environment and Development Economics*, Vol. 11, pp. 159-178.

Pommeret, A. and F. Prieur (2008), "Double Irreversibility and Environmental Policy Design", "Document de travail IREGE, Université de Savoie".

Reilly, J., S. Paltsev, B. Felzer, X. Wang, D. Kicklighter, J. Melillo, R. Prinn, M. Sarofim, A. Sokolov, and C. Wang (2007), "Global Economic Effects of Changes in Crops, Pasture, and Forests due to Changing Climate, Carbon Dioxide, and Ozone", Energy Policy, Elsevier, Vol. 35(11), pp. 5370-5383.

Ramsey, F. (1928), "A Mathematical Theory of Saving", *Economic Journal,* Vol. 38, No. 152.

Schneider, S. and J. Lane (2004), "Abrupt Non-Linear Climate Change, Irreversibility and Surprise", Global Environmental Change 14 (2004) 245–258.

Solow, R.M. (1974), "The Economics of Resources or the Resources of Economics", *American Economic Review,* Vol. 64, No. 2.

Stern, N. (2007a), *Stern Review: The Economics of Climate Change* (Cambridge: CUP).

Stern, N. (2007b), Technical Annex to Postscript in *Stern Review: The Economics of Climate Change* (Cambridge: CUP).

Stern, N. (2008), “The Economics of Climate Change”, *American Economic Review,* Vol. 98, No. 2.

Tol, R.S.J. and S. Fankhauser (1998), “On the Representation of Impact in Integrated Assessment Models of Climate Change”, Environmental Modelling and Assessment 3, pp. 63–74.

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

Tol, R.S.J., S. Fankhauser, R. Richels and J. Smith (2000), “How Much Damage will Climate Change do? Recent Estimates”, World Economics, Vol. 1, N°4.

Tol, R.S.J. and H. Dowlatabadi, 2001: Vector-borne diseases, development & climate change, *The Integrated Assessment Journal*, Vol 2, pp 173-181.

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

Tol, R.S.J. (2002b), “New Estimates of the Damage Costs of Climate Change, Part II: Dynamic Estimates”, *Environmental and Resource Economics,* 21 (2), 135-160.

Tol, R.S.J. (2003), “The Marginal Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties”, *University of Hamburg, Sustainability and Global Change, Working Paper* FN-19.

Tol, R.S.J. (2005), “The Marginal Damage Costs of Carbon Dioxide Emissions”, *Energy Policy,* Vol. 33, pp. 2064-2084.

Tol, R.S.J., (2005b) Adaptation and mitigation: trade-offs in substance and methods. *Environmental Science & Policy,* Vol 8, pp. 572-578

Tol, R.S.J. (2006) The Stern Review of the Economics of Climate Change: A Comment. *Mimeo,* October 30. Economic and Social Research Institute, Vrije University, and Carnegie Mellon University.

Ulph, A., D. Ulph (1997), “Global Warming, Irreversibility and Learning”, *The Economic Journal,* Vol°107, No. ◦442, pp. 636-650.

Viscusi, W.K. (1978a). “Labor Market Valuations of Life and Limb: Empirical Evidence and Policy Implications,” *Public Policy* 26(3), 359-386.

Viscusi, W.K and J.E. Aldy (2007), "Labor Market Estimates of the Senior Discount for the Value of Statistical Life", Journal of Environmental Economics and Management, Elsevier, Vol. 53(3), pp. 377-392.

Viscusi, W.K. and J.E. Aldy (2003), "The Value of a Statistical Life: A Critical Review of Market Estimates throughout the World," *NBER Working Papers* 9487, National Bureau of Economic Research, Inc.

Warren, R., C. Hope, M. Mastrandrea, R. Tol, N. Adger, and I. Lorenzoni (2006), “Spotlighting Impacts Functions in Integrated Assessment, Research Report Prepared for the Stern Review on the Economics of Climate Change, Working Paper 91, Tyndall Centre for Climate Change Research.

Watkiss, P. *et al.* (2005), 'Methodological Approaches for Using Social Cost of Carbon Estimates in Policy Assessment, Final Report', Culham: AEA Technology Environment.

Weitzman, M.L. (2001), "Gamma Discounting", *American Economic Review,* Vol. 91, No. 1.

Weitzman, M.L. (2007a), "A Review of the Stern Review on the Economics of Climate Change", *Journal of Economic Literature*, Vol. 45, No. 3.

Weitzman, M. (2007b), "Structural Uncertainty and the Value of Statistical Life in the Economics of Catastrophic Climate Change", *NBER Working Paper* No. 13490.

Yohe, G. and M. Schlesinger (1998), "Sea Level Change: The Expected Economic Cost of Protection or Abandonment in the United States", *Climatic Change*, Vol. 38, No. 4.

Table 1. The main impacts of climate change

Impacts	**Main characteristics**
Market impacts	
Energy consumption	A rise in temperature would decrease the demand for heating in summer and increase the demand for summer air conditioning, leading to an ambiguous average effect.
Agriculture	The increase in temperature as well as changes in precipitation, the occurrence of floods and drought, would have some consequences on crop, yields and changes in the cultivated areas. The impacts would vary across regions.
Water resources and demand	Climate change will exacerbate water shortages in many water-scarce areas of the world.
Infrastructure	Sea level rise would damage coastal infrastructures and would include specific expenditures aimed at protecting coasts.
Tourism	The impact is expected to be negative on winter sports resorts and ambiguous on summer touristic resorts.
Non market impacts	
Health	The impacts include both an increase in (summer) heat stress and a reduction in (winter) cold stress, leading to a direct impact on mortality that could be small because these effects work in opposite directions. The more significant and negative impact on health would come from the development of vector-borne diseases (that are transmitted through an individual or animal, such as Malaria) and non vector-borne diseases (that could increase cardiovascular and respiratory mortality for instance). In vulnerable communities, indirect impacts on health could come through the effect of climate change on food and water supply.
Environment	Many species would be threatened by a too rapid climate change.
Migration	The sea level rise as well as water shortage in some vulnerable regions could lead to migration of certain population groups.

Source: OECD

Table 2. Distribution of impacts of 2.5°C warming across types of impacts, by regions, per cent of GDP

	Total	Agriculture	Other vulnerable market	Coastal	Health	Non-market time use[1]	Settlements[2]	Catastrophic impact
United States	-0.45	-0.06	0	-0.11	-0.02	+0.28	-0.1	-0.44
China	-0.22	+0.37	-0.13	-0.07	-0.09	+0.26	-0.05	-0.52
Japan	-0.5	+0.46	0	-0.56	-0.02	+0.31	-0.25	-0.45
OECD Europe	-2.83	-0.49	0	-0.6	-0.02	+0.43	-0.25	-1.91
Russia	+0.65	+0.69	+0.37	-0.09	-0.02	+0.75	-0.05	-0.99
India	-4.93	-1.08	-0.4	-0.09	-0.69	-0.3	-0.1	-2.27
Other high-income	+0.39	+0.95	+0.31	-0.16	-0.02	+0.35	-0.1	-0.94
High-income OPEC	-1.95	0	-0.91	-0.06	-0.23	-0.24	-0.05	-0.46
Eastern Europe	-0.71	-0.46	0	-0.01	-0.02	+0.36	-0.1	-0.47
Other middle-income	-2.44	-1.13	-0.41	-0.04	-0.32	+0.04	-0.1	-0.47
Other lower-middle income	-1.81	-0.04	-0.29	-0.09	-0.32	+0.04	-0.1	-1.01
Africa	-3.91	-0.05	-0.09	-0.02	-3	-0.25	-0.1	-0.39
Other low-income	-2.64	-0.04	-0.46	-0.09	-0.66	-0.2	-0.1	-1.09

Note: This table shows one summary estimate of the static impacts, by sector and country, of a 2.5°C increase in temperatures.

1: "Settlements" refers to the fact that some groups of population, cities or cultural treasures cannot immigrate with climate change and thus could be lost.
2: "Non-market time use" is the impact of climate change on leisure activities.
Source: Nordhaus (2000).

Table 3. The influence of the social discount rate on the estimated impacts of climate change

Pure Rate of Time Preference	**Social Discount Rate (%)**	**Discounted impacts**[1] (per cent loss in permanent consumption due to climate change)
0.1	1.3	10.9
0.5	1.8	8.1
1.0	2.3	5.2
1.5	2.8	3.3

1. Baseline climate scenario includes market and non-market impacts as well as risks of catastrophe.
Source: Stern (2007b).

Table 4. Decomposition of the uncertainty on the impacts of climate change

From GHG emissions to impacts	Macro-Economic projections and energy mix → Emissions	→ GHGs Concentration in the atmosphere → Climate change	→ Impacts
Uncertainty	(1) Economic and technological uncertainty	(2) Environmental uncertainty	(3) Economic and valuation uncertainty

Source: OECD

Table 5. Main impacts of climate change along two dimensions of uncertainty and their coverage in IAMs

	Uncertainty in the economic valuation of impacts		
Uncertainty in predicting climate change:	**Market Impacts** - Agriculture - Energy consumption - Forestry (wood market) - Water supply and demand - Infrastructure, coastal protection	**Non-market impacts** - Health - Migration - Ecosystem - Amenities	**Socially contingent** - Large migrations and induced conflicts - Conflicts on water and food reserves - Displacement of mega cities , social crises
Projection Change in temperature	Covered with some limits	Some studies *e.g.* Tol (2002) and Hope (2006)	None
Bounded risks - Change in precipitations - Intensity of storms, - Floods and droughts	Some studies *e.g.* Tol (2002)	Some studies *e.g.* Tol (2002)	None
System change and surprise - Large sea level rise - Changes to the THC - Collapse of the West Antarctic Ice Sheet	Nordhaus and Boyer (2000)/Hope (2006)	None	None

Note: Climate changes are classified into three categories with increasing uncertainty: global and regional temperatures that are projected within a confidence interval, changes in precipitations, additional risks of storms, floods, droughts that are more difficult to project but nonetheless are considered as “bounded” risks and extreme events such as radical changes in the THC or the melting of the West Antarctic ice sheet, which are possible outcomes to which it is not even possible to attach a measure of the uncertainty.

Sources: from Watkiss *et al.* (2005) and Stern (2006)

Table 6. Major factors causing uncertainty in the social cost of carbon

Parameter	Definition	Sign	Range	Importance
Climate sensitivity	Equilibrium temperature rises for a doubling of CO2 concentration	+	1.5 to 5°C*	100
PRTP	Pure rate of time preference	-	1 to 3% per year	66
Non-market impact	Valuation of non-market impact for a +2.5°C temperature rise	+	Losses of 0 to 1.5% of GDP	57
Market impact	Valuation of market impact for a +2.5°C temperature rise	+	Losses of 1% of GDP to gains of-0.1%	32
Equity weight	Negative of the elasticity of marginal utility with respect to income	-	0.5 to 1.5	50
Climate change half life	Half life in years of global response to an increase in radiative forcing	-	25 to 75 years	35

Note: relative importance is measured by the magnitude of the partial rank correlation coefficient between the parameter and the SCC, with the most important indexed to 100. A + sign shows that an increase in this parameter leads to an increase in the SCC.

(*): The range for the climate sensitivity parameter is broader than the IPCC “likely range”.

Source: Hope (2005)

Table 7. Irreversibility of damages

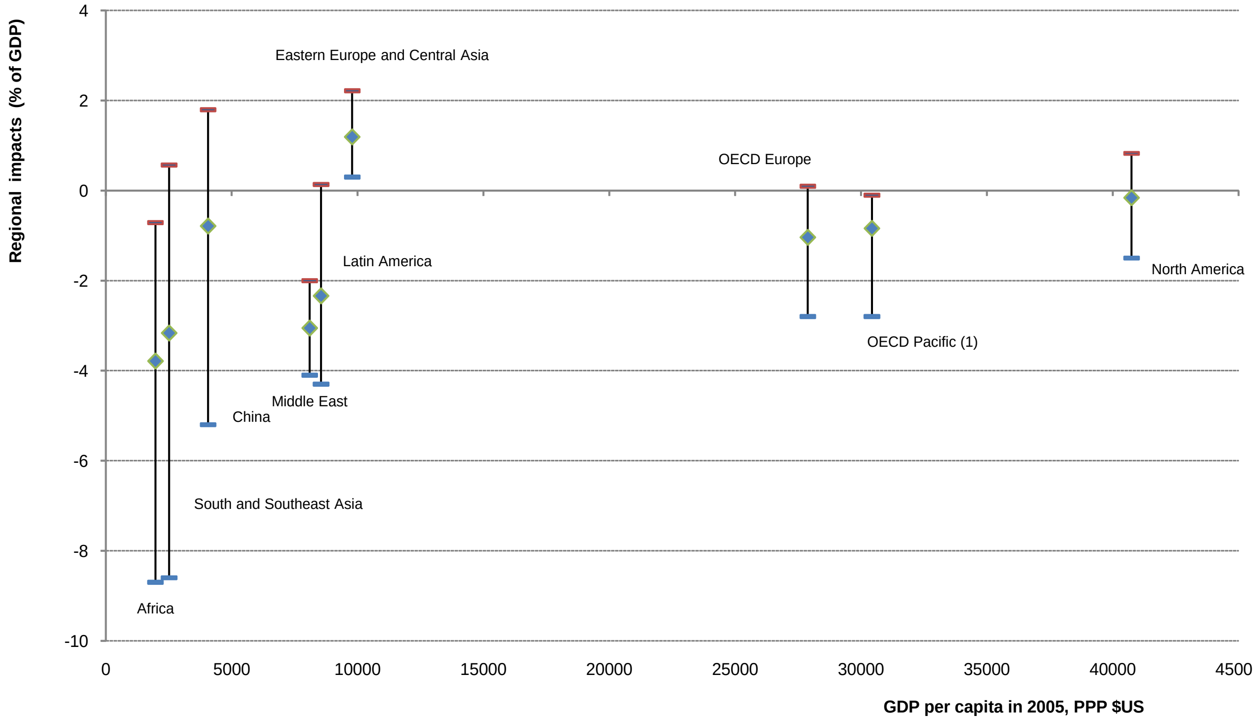
Impact	Degree of irreversibility	Explanations/Remarks
Market impact on agriculture, food supply	Reversible	Conditional to adaptation policies
Infrastructure	Partly Reversible	Conditional to adaptation policies
Health	Partly Reversible	Although the damages are irreversible for individuals, they are, at least partly, reversible for society as a whole
Energy consumption	Reversible	
Water resources	Partly Reversible	Conditional to adaptation policies
Migration and conflict	Partly Reversible	Although the damages are irreversible for individuals, they are, at least partly reversible for society as a whole
Extinction of species	Irreversible	
Loss of major ice sheets	Irreversible	
Loss of unique cultures	Irreversible	This could happen through the submergence of small islands as a result of sea level rise and, for Inuits of the North American Arctic, as a consequence of ice melting

Source: OECD

Figure 1. Regional economic impacts

(% of GDP)

Dispersion of long-run impacts across countries of a 2.0-2.5°C increase in temperature above its pre-industrial level



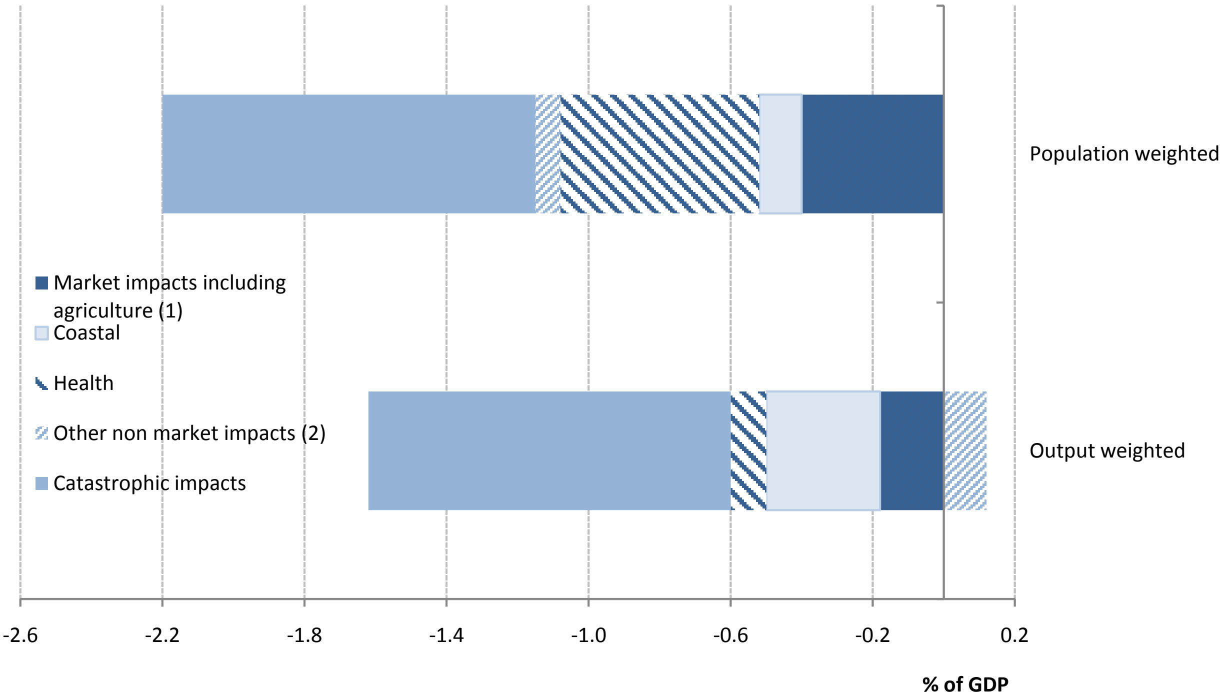
Note : Estimates come from different sources that are not entirely comparable. Those by Mendelsohn (2000) and Nordhaus and Boyer (2000) represent the annual GDP impact (relative to a no-climate-change scenario) observed at the time when a +2.5° increase in temperature is reached (i.e. in 2100 in both exercises). They are not entirely comparable to first-generation estimates surveyed by IPCC (1995), which are static estimates representing the annual GDP impact of a +2.5°C rise in temperature based on 1990 economic structures. The figure should be read as follows: For example, for Africa, the impacts of a warming of 2-2.5°C is expected to fall within the range of -1% to -9% of GDP according to existing estimates, with an average value of about -4% of GDP.

1. The OECD Pacific region includes Japan, which could not be featured separately due to the geographical aggregation of the underlying models. However, a few available estimates point to costs for Japan alone of -0.1 to -0.5% .

Source : Nordhaus and Boyer (2000), Mendelsohn et al. (2000) and IPCC (1995).

Figure 2. Global impacts of climate change for different rules of aggregation across countries, for a 2.5°C warming

Global impacts from climate change (in % of GDP) when impacts by countries are weighted by population or GDP



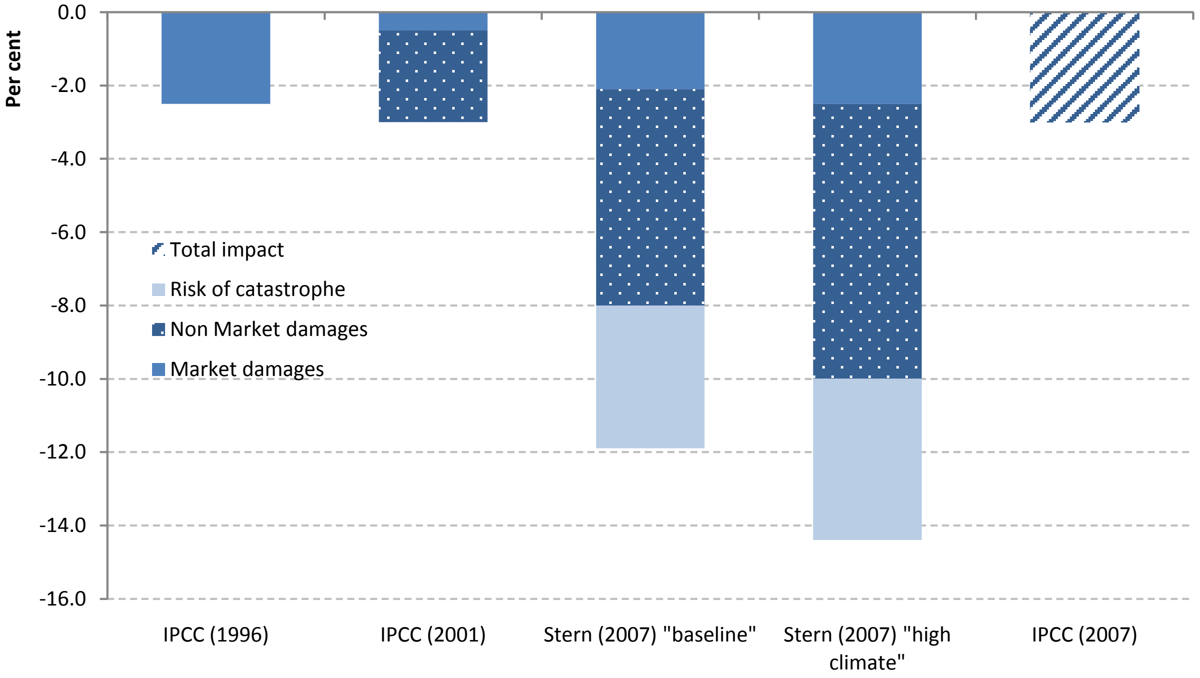
1. This category includes impacts on agriculture as well as on other modestly vulnerable sectors such as for instance energy and water supply and demand, and construction.

2. Other non market impacts include the cost of settlements (the fact that some groups of population, cities or cultural treasures cannot emigrate with climate change) and the value of non market time use, which is expected to increase with temperatures since time spent on climate-related activities (golfing and swimming) increases with warm weather.

Source : Nordhaus and Boyer (2000).

Figure 3. Estimates of the global damages of climate change

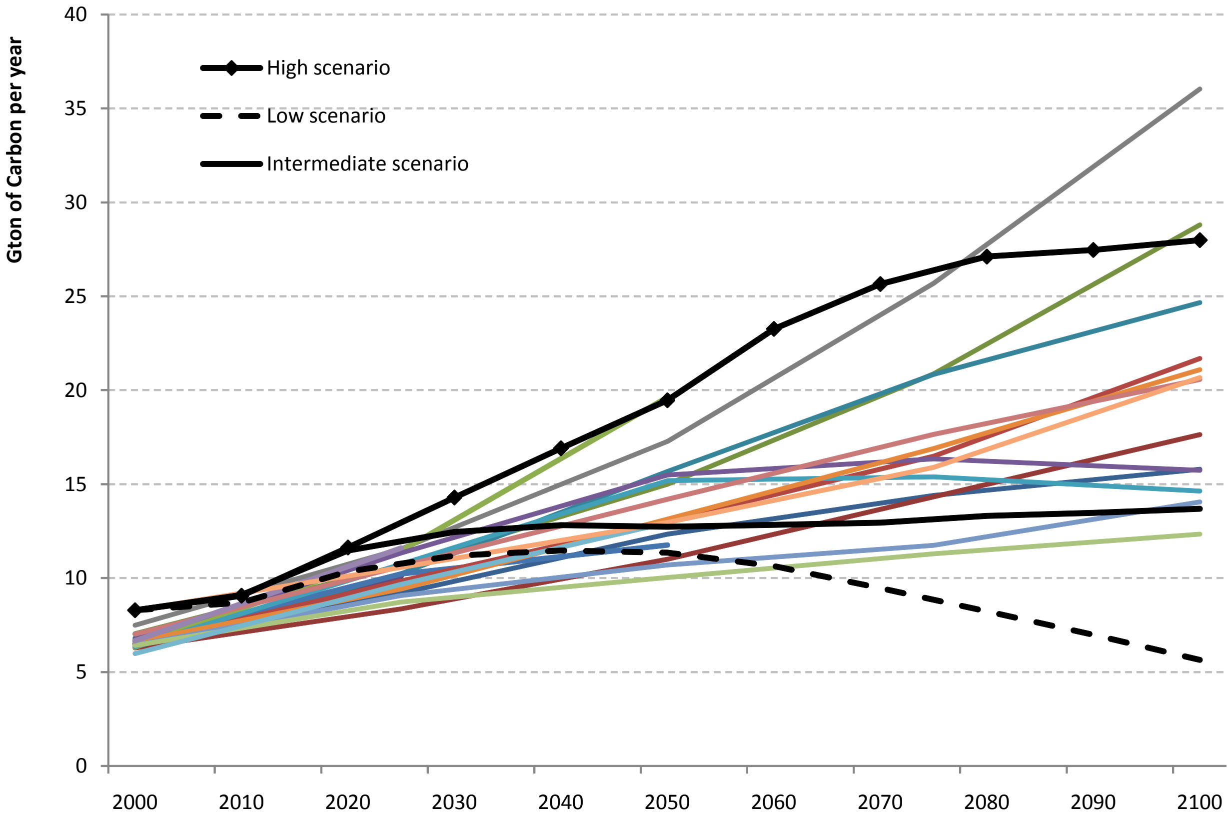
(Per cent of world GDP)



Note . IPCC estimates represent the consensus among experts of the impact of climate change. IPCC(1996) estimates only include market impacts. IPCC (2007) estimates are the average of the range of possible values that is quoted in the report (from 1 to 5 %). Stern "baseline" scenario produces an average mean warming of 3.9° relative to pre-industrial in 2100 while temperature changes are pushed to higher levels in Stern "high climate" scenario through the action of amplifying feedbacks in the climate system.

Source : IPCC (1996), IPCC (2001), IPCC (2007), Stern (2007),

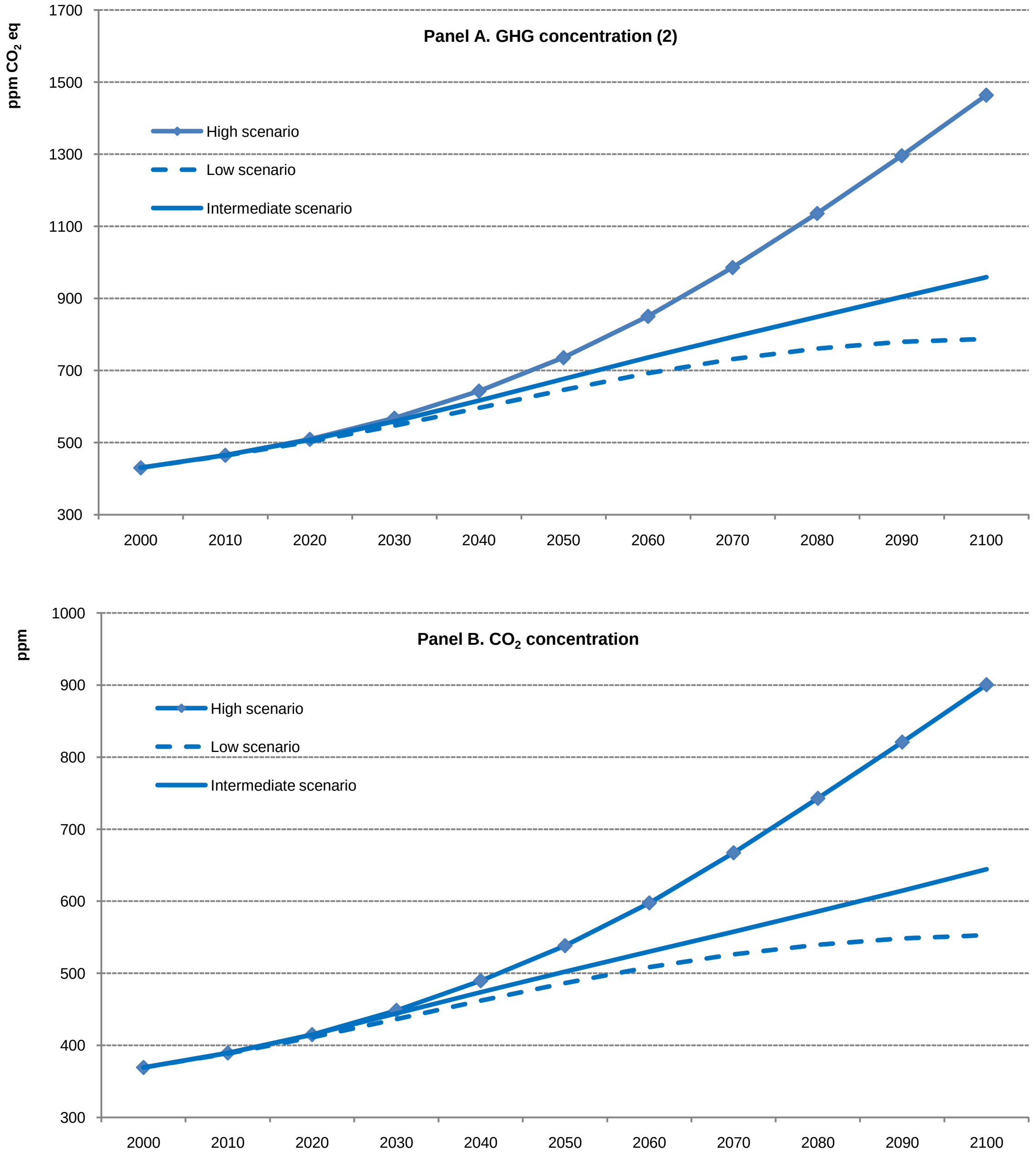
Figure 4. Projected CO_2 emissions across a range of previous studies



Note : CO2 emissions from 18 models discussed in the Energy modeling forum and 3 scenarios (High, Low and Intermediate) that are representative of the various existing scenarios discussed at the Intergovernmental Panel on Climate Change.

Source : Energy Modelling Forum-21 (Weyant et al., 2006) and IIASA GGI Scenario Database (Version 1.0.9).

Figure 5. Projected trends in GHG concentration across a range of previous studies[1]

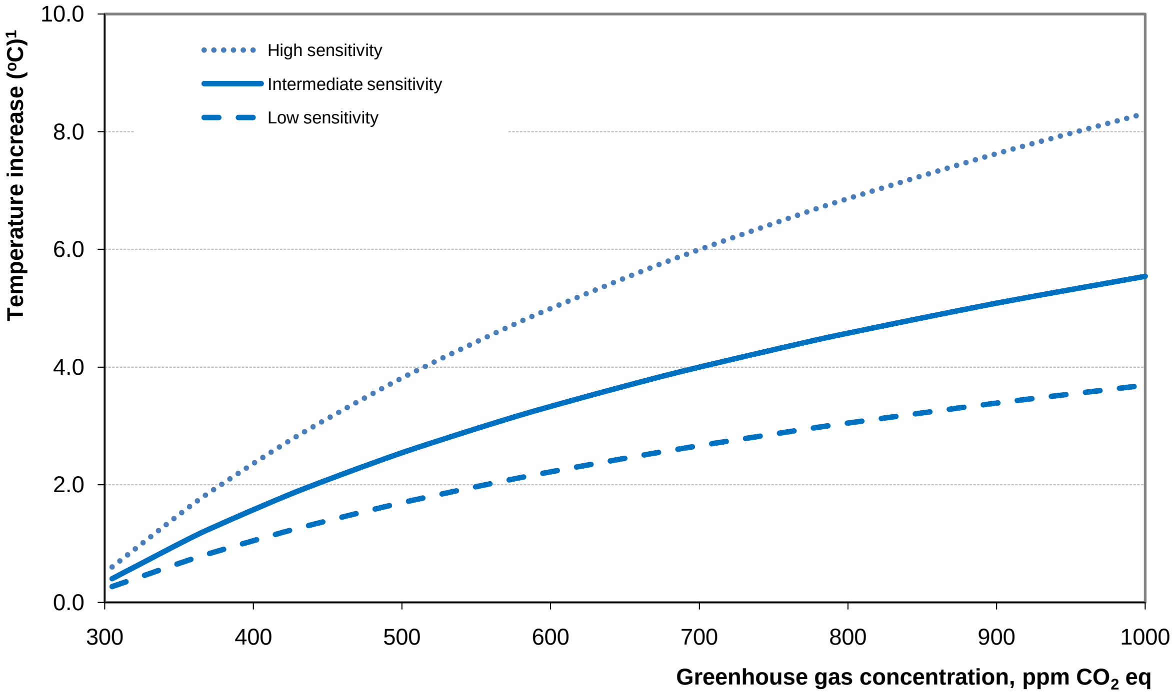


1. The three baseline scenarios have been constructed to be representative of the various existing scenarios discussed at the Intergovernmental Panel on Climate Change (IPCC) and the Energy Modeling Forum (EMF) (Riahi *et al*., 2006). They do not include any explicit climate policies beyond those already in place.
2. GHG concentration in CO_2eq, covering six types of GHGs, namely Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6).

Source: IIASA GGI Scenario Database (Version 1.0.9).

Figure 6. Link between long-run GHG concentration and global temperature

Increases in temperature with concentration for the "likely" range of climate sensitivity values

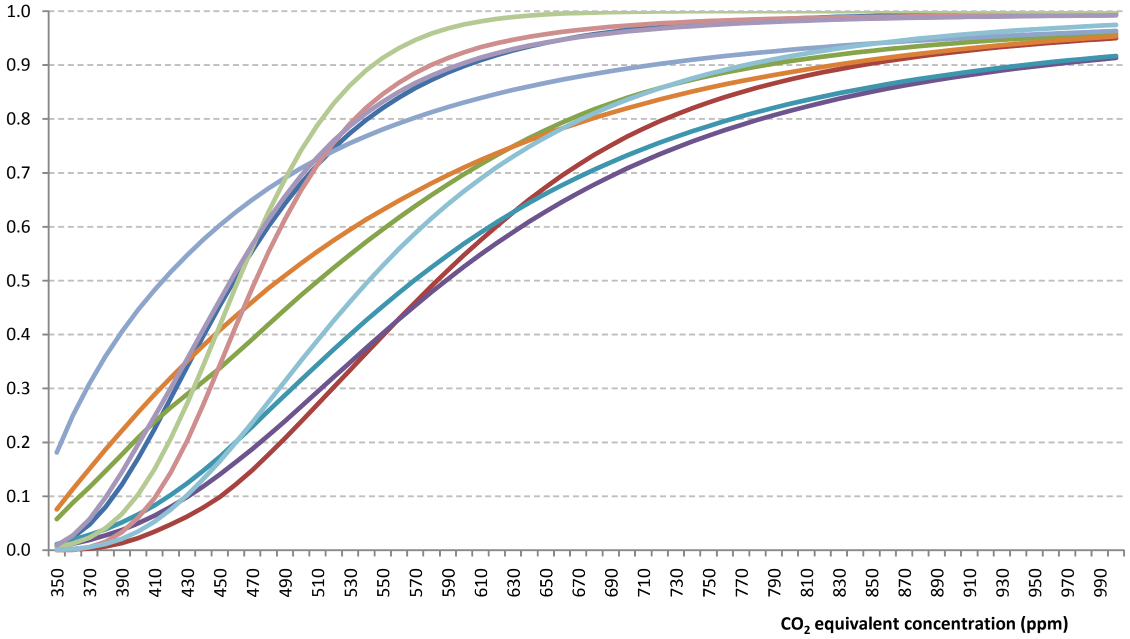


Note: The climate sensitivity parameter measures the impact on temperature of a doubling of concentration and determines the link between long-run GHG concentration and global temperature at the steady state. Because of the inertia of the system, steady-state temperatures may be reached several decades after concentration stabilisation. This parameter equals 4.5 in the "high sensitivity" scenario, 3 in the "intermediate sensitivity" scenario, and 2 in the "low sensitivity" scenario.

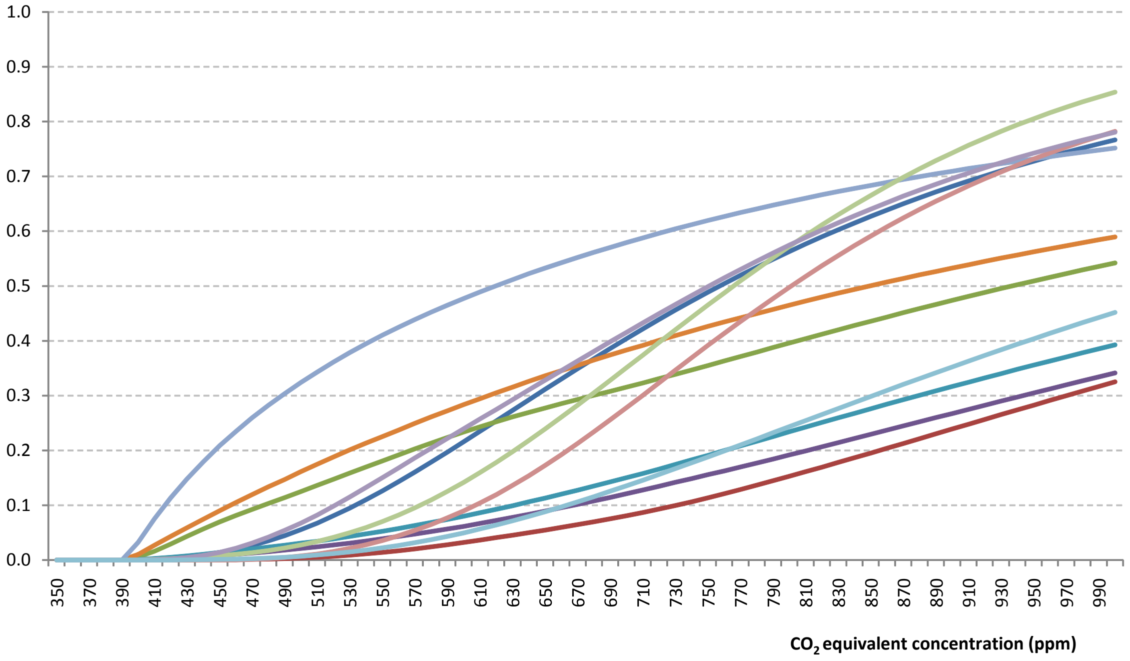
Source : IPCC (2007), AR4.

Figure 7. The risk of overshooting 2.5°C and 5°C equilibrium warming for different concentration stabilisation levels

Panel A. Various estimates of probability of exceeding 2.5°C increase in global equilibrium temperatures

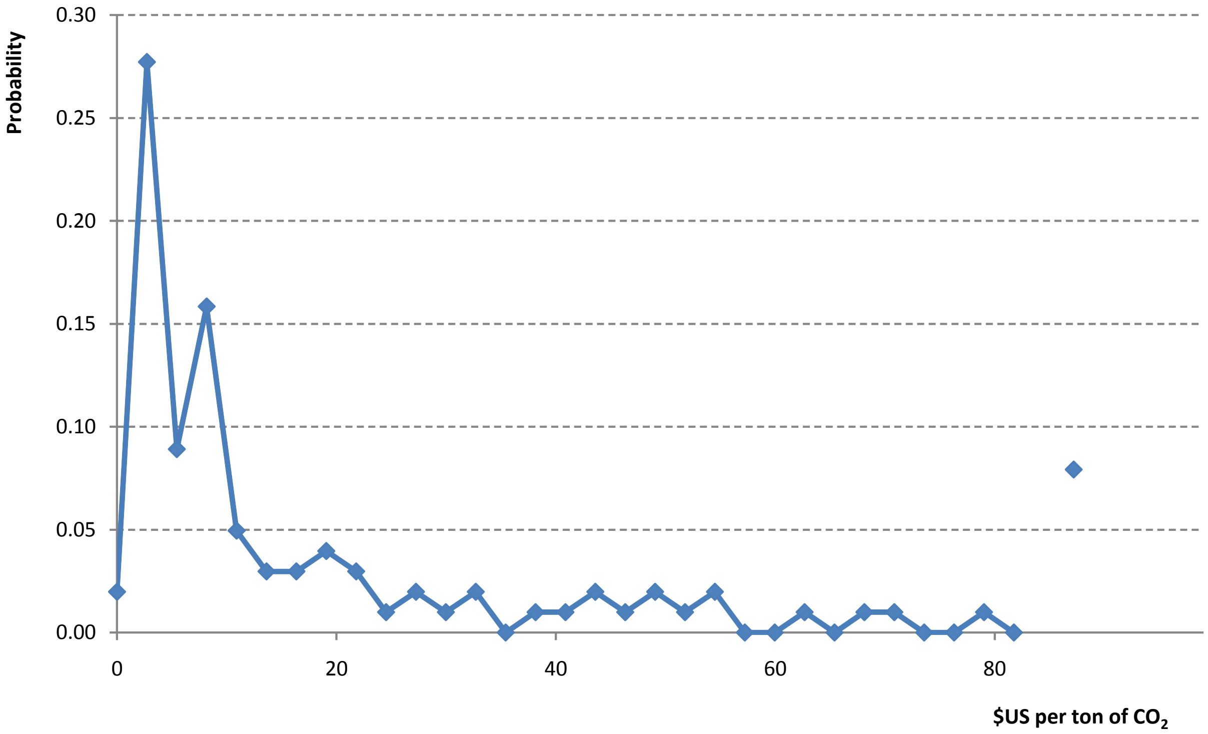


Panel B. Various estimates of probability of exceeding 5°C increase in global equilibrium temperatures



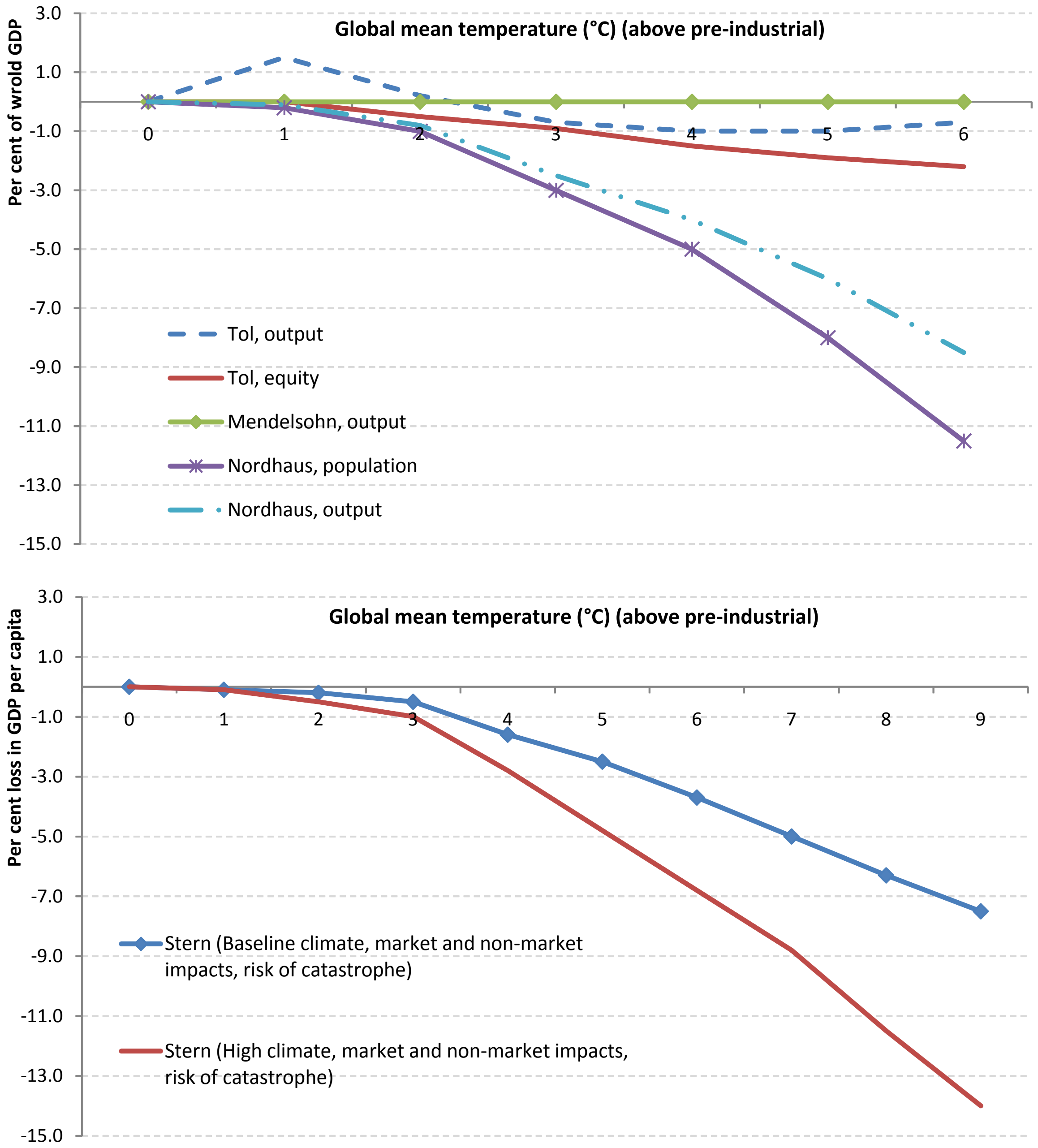
Note . Each curve represents the probability function from one estimate (see Meinshausen, 2006, for references corresponding to the various estimates). The figure should be read as follows: with a concentration of 600 ppm, the probability to reach a +2.5°C increase in temperatures, according to existing recent estimates is estimated to be more than 50% and could reach 100% (Panel A). The probability to exceed 5°C increase with the same concentration is estimated to be of 10% for a group of low estimates (lower curves) and around 25% according to the group of high estimates (higher curves) (Panel B).
Source : Meinshausen, (2006).

Figure 8. Distribution of the social cost of carbon across a range of existing studies[1]



1. The social cost of carbon is the net present value (over the simulation horizon) of the climate change impact of one additional ton of CO_2 emitted in the atmosphere today. The observation on the right hand side of the figure is the cumulative probability of Social Cost of Carbon in excess of 85$/t$CO_2$.
Source : Tol (2004).

Figure 9. Global impacts of climate change from various studies[1]



1. Estimates represent the annual GDP impact (relative to a no-climate-change scenario) of a given increase in temperature, as observed at the time when this increase in temperature is reached. They come from studies by Tol (2002), Mendelsohn (1998), Nordhaus and Boyer (2000) and Stern (2007). In “Tol, output”, impacts across regions are simply added while in “Tol, equity”, they are weighted by regional per capita income. In “Nordhaus output”, impacts are weighted by GDP while in “Nordhaus equity”, they are weighted by population. Stern "baseline” scenario produces an average mean warming of 3.9° relative to pre-industrial in 2100 while temperature changes are pushed to higher levels in Stern "high climate" scenario through the action of amplifying feedbacks in the climate system.

Source: IPCC (2007) and Stern (2007)

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