The Damage Costs of Climate Change Toward More Comprehensive Calculations

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Abstract. It is argued that estimating the damage costs of a certain benchmark climate change is not sufficient. What is needed are cost functions and confidence intervals. Although these are contained in the integrated models and their technical manuals, this paper brings them into the open in order to stimulate discussion. After briefly reviewing the benchmark climate change damage costs, region-specific cost functions are presented which distinguish tangible from intangible losses and the losses due to a changing climate from those due to a changed climate. Furthermore, cost functions are assumed to be quadratic, as an approximation of the unknown but presumably convex functions. Results from the damage module of the integrated climate economy model *FUND* are presented. Next, uncertainties are incorporated and expected damages are calculated. It is shown that because of convex loss functions and right-skewed uncertainties, the risk premium is substantial, calling for more action than analysis based on best-guess estimates. The final section explores some needs for further scientific research.

Key words. Climate change damage costs; cost functions; uncertainty.

1. Introduction

The greenhouse effect is a hot topic. The discussion on the climatological aspects of the changing composition of the atmosphere remains a lively one, but by now it is widely acknowledged that human-induced climate change is real, though uncertain in its details, and may have adverse impacts (Houghton *et al.*, 1992). The impacts of climate change constitute another major field of research. Most attention is being paid to the direct impacts while the socio-economic aspects have engendered much less effort. This is not surprising as the indirect impacts result from the still hotly debated direct impacts, which in turn are caused by the highly uncertain regional and local climatic changes. Still, an overall view of the economic and societal impacts is required to guide the policy makers. Such studies are scarce (Ayres and Walter, 1991; Cline, 1992; Fankhauser, 1993a, 1994; Nordhaus, 1991; Titus, 1992; Tol, 1993a) and focus on point estimates for a certain benchmark climate change (mostly 2 × CO_2, i.e., doubled atmospheric carbon dioxide concentrations compared to the pre-industrial level). However, what is needed are *cost functions* (cost as a function of climate change) to express the damage costs of other than benchmark climate change and to measure the benefits (read: avoided damage) of greenhouse gas emission reduction and *confidence intervals* to express the uncertainties. So far, the attempts to do so lie hidden in

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the software and technical manuals of some of the integrated assessment models (*PAGE* – Hope *et al.*, 1993; *ICAM* – Dowlatabadi and Morgan, 1993; *DICE* – Nordhaus, 1993; *CETA* – Peck and Teisberg, 1991; *MERGE* – Manne *et al.*, 1993). This paper brings the cost functions and particularly the uncertainties into the open in order stimulate discussion.

This paper is organised as follows. Section 2 is a short review of the (scarce) literature on the assessment of the socio-economic costs of climate change, and slightly modifies the costs based on recent literature;costs are assessed for nine major world regions. Section 3 attempts to derive the costs as functions of the total and the pace of global warming and sea level rise, and presents numerical results from one particular model. Section 4 incorporates the huge uncertainties surrounding global warming and its impacts, and calculates the expected costs, using the cost function of the third section as input. Section 5 identifies some of the needs for further research, and points out some possible directions. Section 6 concludes.

2. The Damage Costs of Climate Change – A Short Review

The most important studies on the socio-economic impacts of climate change are those of Nordhaus (1991, 1993), Cline (1992), Fankhauser (1993a, 1994), Titus (1992) and Tol (1993a). These studies attempt to assess the tangible and intangible damages due to a doubling of atmospheric carbon dioxide at a highly aggregated level, based on the literature on case studies, and educated guesswork and extrapolation. Their findings are summarised in Table I.

The five studies generally agree on the damages in the USA, with Nordhaus on the lower side (despite the higher benchmark) and Titus and Tol on the higher; note that Titus' study is based on a higher benchmark and includes the impact of climate change on air and water pollution. Major loss categories are sea level rise and agriculture. The damages in the world as a whole differ more, with Fankhauser and Nordhaus in close agreement but Tol's damages being considerably higher, based on the recent literature on agriculture, which reports only limited impacts of carbon dioxide fertilisation (e.g., Erickson, 1993) and more adverse impacts on agriculture in general (e.g., Fischer *et al.*, 1993). Other reasons are the higher values attached to human life by Tol (somewhere in the middle of the range reported by Cline, whereas the figures of Fankhauser and Cline are at the lower end; note that life/morbidity costs constitute about half of Tol's totals), and (intangible) losses due to people migrating (thrice the per capita income per displaced person in the year of flight; cf. Jansen, 1993) to represent their hardship. The Appendix contains the estimated damages for nine major world regions, based on Tol (1994c). Notice that the figures in based on Table I and in the Appendix represent the losses for the *present* economy. Some of the damage costs will grow with the economy and the population, others will decline relatively,

Table I. US climate change damage ($2\times CO_2$ – 10^9\$).[a]

Loss category	Fankh. (2.5 °C)	Cline (2.5 °C)	Nordhaus (3.0 °C)	Titus (4.0 °C)	Tol[b] (2.5 °C)
Coastal defence	0.2	1.0	7.5		1.5
Dryland loss	2.1	1.5	3.2[c]		2.0
Wetland loss	5.6	3.6	–	5.0[d]	5.0
Species loss	7.4	3.5	–	–	5.0
Agriculture	0.6	15.2	1.0	1.0	10.0
Forestry	1.0	2.9	–	38.0	–
Energy	6.9	9.0	–	7.1	–
Water	13.7	6.1	–	9.9	–
Other sectors	–	1.5	38.1[e]	–	–
Amenity	–	–	–	–	12.0
Life/morbidity	10.0	> 5.0	–	8.2	37.7[f]
Air pollution	6.4	> 3.0	–	23.7	–
Water pollution	–	–	–	28.4	–
Migration	0.5	0.4	–	–	1.0
Natural hazards	0.2	0.7	–	–	0.3
Total USA	60.2	> 53.5	50.3	121.3	74.0
(% GDP)	(1.2)	(> 1.1)	(1.0)	(2.5)	(1.5)
Total world	269.6		220.0		315.7
(% GDP)	(1.4)		(1.33)		(1.9)

[a] Table adapted from Fankhauser (1993a, 1994), Tol (1993a, 1994c) and Nordhaus (1993).
[b] Including Canada.
[c] Total land loss (dry- and wetlands).
[d] Total costs of sea level rise (protection plus dry- and wetland loss).
[e] Including those not assessed.
[f] Tol values an American life more than twice as high as Fankhauser does.

such as agricultural losses in developing countries, and others will increase, particularly the intangibles.

Unfortunately, the distinction between tangible and intangible damages is often not really clear, as is the distinction between the damages due to a *changed* climate and those due to a *changing* climate. The former distinction is important because the impact of tangible and intangible losses on the society and the economy are rather different. The latter distinction is important because slowing the pace of climate change has more implications than just postponing the damages, as it allows more time to adjust and adapt. Also, only direct impacts are assessed, with some corrections for abatement and adjustment. Third, most studies primarily concern the OECD, or just the USA, while the figures for the developing regions are based on extrapolation (cf. also Grubb, 1993). Fourth, presenting the damage at a highly aggregated level masks the real pain, which is felt in individual sectors, companies and households. Obviously, it is ridiculous to state, as some do, that the total loss of agricultural production, in the USA for instance, would cost no more than its share of the gross domestic product. Not only is food a non-substitutable input for human welfare, domestic food production is politically highly desirable and food exports are an important factor in the international balance of power (cf. also Kennedy, 1993). Finally, all estimates are tied to the benchmark of a doubling of atmospheric carbon dioxide, which is presumably accompanied by a global annual mean temperature rise of 2.5 °C, a global mean sea level rise of 50 cm, an increase in hurricane intensity of 40% to 50%, and so forth. However, this neglects or hides: (*i*) the regional, seasonal and interannual differences in climate change, (*ii*) changes in the frequency distributions of climatic parameters, (*iii*) the relationships between the steering variable (temperature) and the variables which actually cause the damage,[1] and, above all, (*iv*) the impact of climate change before and beyond the benchmark, and (*v*) the many and compounded uncertainties. Some of these objections are raised, or at least brought up in the next two sections. The others, and more, are discussed in Section 5.

3. Towards Damage Cost Functions

The functions to assess the damage costs of climate change proposed here raise three of the objections of the previous section. First, the damages are explicitly split into tangible and intangible losses (this is taken up in all models mentioned in the introduction except for *DICE* and *CETA*). Second, the damages due to total climate change and due to the pace of change are distinguished (this is only considered by *ICAM*, *CETA* and, to some extent, *PAGE*). Third, the damages are, as far as possible, coupled to the relevant climatic parameter (not yet considered in any model). Obviously, the introduction of (regional) cost functions allows for regional differentiation in climate change. As already mentioned in the introduction, the cost functions are presented to stimulate discussion, to serve as input for the next section, and to express the damage costs of other than benchmark climate change.

To simplify matters, the cost functions employed are all quadratic forms through the origin, $f(X) = \alpha X + \beta X^2$, as opposed to Nordhaus' (1993) $f(X) = \gamma X^\delta$. (In *DICE, ICAM* and *MERGE*, a quadratic damage cost function is used; Cline (1992) uses $\delta = 1.3$; *PAGE* uses a linear function; *CETA* employs linear, quadratic and cubic functions as a sensitivity analysis). There are a number of reasons for this. First of all, the cost function is split into a linear and a convex part, which is more easy to interpret and to assess (and so to reflect upon). For each loss category, an educated guess can be made as to which share of the loss is homogeneous of the first order (doubled warming leads to doubled costs) and which share is homogenous of a higher, in this case the second-order (doubled warming leads to more than doubled, say quadrupled costs). Normalising climate change on its $2\times CO_2$ benchmark readily translates these shares into corresponding parameters in the cost function. Besides, a quadratic form can be interpreted as the knotted (at the second term) power series expansion of the unknown 'true' cost function. Finally, quadratic forms are analytically more convenient in the uncertainty analysis employed in Section 4.

At this point, we have eight parameters (tangible–intangible, total change–rate of change, linear–quadratic) per loss category per region. At this stage of the study of the socio-economic impacts of climate change we are hardly able to assess with any confidence Nordhaus' two parameters (one region, aggregate losses), let alone the numerous ones proposed here. Nevertheless, we feel that it is important to present so many parameters in order to render all assumptions clear and open to discussion. Besides, aggregation is much easier than disaggregation.

We now briefly discuss how the benchmark estimates of Table I are transformed into eight-parameter cost functions. The parameters themselves are presented in the Appendix. This part forms the basis of the damage module, the integrated climate-economy model *Climate FUND* (Climate Framework for Uncertainty, Distribution and Negotiation), version 1.4 (cf. also Tol, 1993b, 1994b, for more details of the model and its outcomes). The cost functions have the same form for all regions; the parameters differ. The principle of insufficient reason is frequently used to divide the costs over the categories. As a conservative choice, linear functions are preferred unless there is a clear reason to assume quadratic damage. The principle of insufficient reason is frequently used to divide the costs.

The costs of wetland loss are assumed to be linear in sea level rise. Half are due to the pace of sea level rise, i.e., they are too slow to adjust, and half are due to total sea level rise, i.e., they are inhibited from migrating inward due to obstacles such as sea walls. Also, half of the costs are assumed to be intangible. The costs of dryland loss and coastal protection are linear, tangible, and due to total sea level rise. Drylands too valuable to be lost are supposed to be protected. The (tangible[2]) costs are one-half due to total sea level rise (linearly) and the other half are due to the pace of the rising sea level (one quarter linearly and the other quadratically); faster implemented protection will cause costs to increase more than proportionally, because of budget and capacity constraints (cf. Jansen *et al.*, 1993; cf. Fankhauser, 1993b, for a more extensive discussion on the costs of sea level rise). The number of people leaving is assumed to be linear in total sea level rise. Note that problems such as aridity can also force people to move; however, sea level rise is the major cause in the literature reviewed. The intangible costs of people leaving are set at three times the average per capita income per person. The tangible costs of people entering are assumed to be partly linear and partly quadratic in the number of people, because of budget and capacity constraints. Note that people who are displaced are counted as both leaving and entering a region. The agricultural losses are assumed to be partly quadratic in the pace of global warming, with a quarter of the damage associated with the quadratic term, and partly linear in the total amount of warming; cf. Tables A2 and A3. The agricultural damages are completely tangible. The damages due to enhanced natural disasters are assumed to be quadratic in total hurricane increase.[3] Fankhauser (1993a) assumes linearity. However, damage depends on approximately the third power of windspeed (Olsthoorn and Tol, 1994). How damage depends on storm frequency is less clear: on the one hand, the most vulnerable objects are destroyed in the first storm; on the other hand, not yet fully recovered areas are more vulnerable. One-quarter of the benchmark damage costs is associated with the quadratic term, a conservative choice. The natural hazard damages are split into tangible and intangible losses, the latter represented by the additional loss of human life. The intangible costs of the loss of species due to climate change is assumed to be quadratic in total temperature rise and its pace, with equal shares; the linear parameter represents three-quarters of the costs, as a conservative choice.[4] The intangible damages due to loss in human amenity and increased mortality and morbidity are assumed to be quadratic in the pace of (five-sixths) and total of (one-sixth) global warming; Cline (1992) cites Kalkstein's figures of 6,055 additional deaths without and 958 with acclimatisation. Note that we do not follow Cline's adjustment of Kalkstein's figures: Cline chooses to neglect the fact that acclimatisation leads to additional deaths in winter; we do not.

Figure 1 displays the global warming damage costs for *FUND*'s business-as-usual scenario[5] for the period 1990–2100, without feeding the damages back

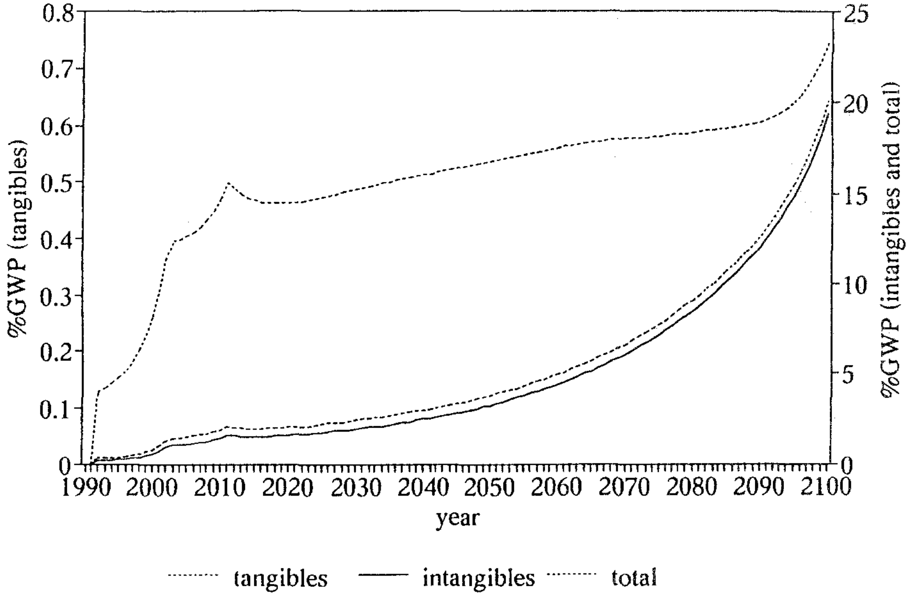

Fig. 1. Global warming damage costs (as percentage of gross world product).

into the economy. The tangible damages quickly jump up to about half a percent of Gross World Product (GWP) around 2010, and increase steadily afterwards.[6] This is a result of the fact that a large part of the damage is attributed to the rate of climate change, which is more or less steady throughout the whole of the projected period (and indeed the past). The damage due to absolute changes is more remote and only really starts to bite at the end of the next century, as the convexity of the loss function lowers the damages before the occurrence of the benchmark climate change (Parry, 1993). The intangible costs outweigh the tangibles by a factor 4 in 2010 and a factor 25 in 2100. This increase is because the valuation of intangible losses is assumed to increase linearly with the average per capita income, based on Pearce (1980; cf. Tol, 1994a, for the consequences of this assumption on the optimal control of greenhouse gases).

Figure 2 depicts the global mean temperature increase and the corresponding tangible damage costs of global warming for climate sensitivities of 1.5 °C, 2.5 °C and 4.5 °C for *FUND*'s business as usual scenario. While the 2100 temperatures differ by less than a factor three, the damage costs differ by a factor six. The benchmark warming of 2.5 °C occurs around 2095, 2057 and 2031, respectively, leading to tangible damages of 0.33%, 0.55%[7] and 1.09% of GWP, respectively. This serves to illustrate the impact of the rate of warming, but overstates it somewhat because of the declining share of agriculture in the economy.

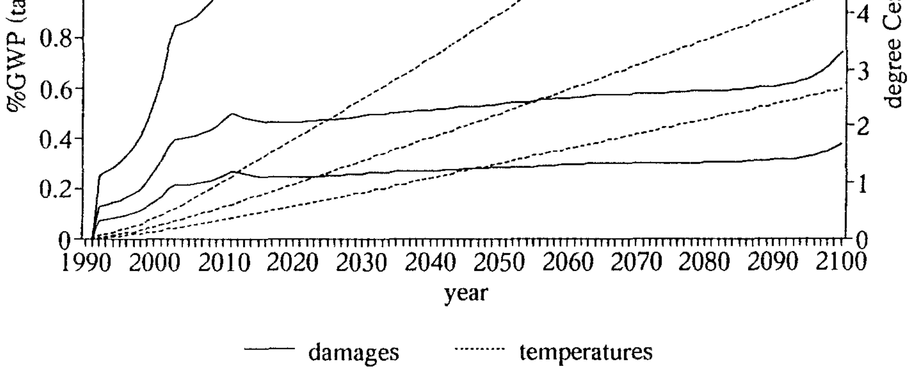

Fig. 2. Global warming damage costs (as percentage of gross world product).

4. Towards Incorporating Uncertainties

Uncertainties abound in climate change research. Instead of closing one's eyes to everything that has not yet been proved or avoiding everything that might be harmful, a more rational option is to assess carefully what is known, translating uncertainties into probabilities, and to evaluate the value of the consequences and their plausibility. The previous section dealt with the value of the consequences of the enhanced greenhouse effect. Alas, very little is known about the range of possible climate change, notable exceptions being the studies of Titus and Narayanan (1991) on sea level rise and of Tol and de Vos (1993) on global warming. First, some general notions of how uncertainties work through are presented; after that, the cost functions of the previous section, including their uncertainties, and the expected costs are presented. Again, most of the analysis is based on educated guesswork and heroic *ad hoc* assumptions.

First the general principles. Assume some probability distribution function for the states of the climate, CS, given the atmospheric composition, AC, with probability density function $f(\mathrm{CS}|AC)$; all climate parameters are in deviation from some reference climate, e.g., pre-industrial times. For practical reasons, the climate should be represented by one indicator, such as the global mean temperature. Next, assume a distribution for the (meteorological) parameter of interest, PI, given the state of the climate indicator, say with density $f(PI|CS)$. Finally, assume a distribution for the damage costs, DC, given the state of the parameter of interest, say with density $f(DC|PI)$.

Assume that one is interested in the *expected* damage costs, given the atmospheric composition (see Section 5 for comments on this)

$$\begin{aligned} &\mathrm{E}[DC|AC] \\ &\quad = \int DC f(DC|AC)\,\mathrm{d}DC \\ &\quad = \int DC \int f(DC|AC, PI) f(PI|AC)\,\mathrm{d}PI\,\mathrm{d}DC \\ &\quad = \int DC \int f(DC|AC, PI) \int f(PI|AC, CS) f(CS|AC)\,\mathrm{d}CS\,\mathrm{d}PI\,\mathrm{d}DC \\ &\quad = \int DC \int f(DC|PI) \int f(PI|CS) f(CS|AC)\,\mathrm{d}CS\,\mathrm{d}PI\,\mathrm{d}DC, \end{aligned} \tag{1}$$

where the first line is by definition, the second and the third by the rule of total probability and the last by the notion that the information contained in the atmospheric concentration reaches the damage costs only through the climate sensitivity and the climate parameter of interest. Then, by changing the order of integration.

$$\mathrm{E}[DC|AC] = \int f(CS|AC) \int f(PI|CS) \int DC f(DC|PI)\,\mathrm{d}DC\,\mathrm{d}PI\,\mathrm{d}CS. \tag{2}$$

The inner integral equals the expected damage costs given the parameter of interest. Note that the costs discussed above are to be interpreted as best guesses, so the choice of the density does matter. As the damage cost function is assumed quadratic, the inner integral results in a weighted sum of the moments of the damages, given the parameter of interest.

We now work out two hypothetical examples to illustrate the general method described above. Let us first assume that the total warming, T, is our parameter of interest ($PI = T$) as well as the indicator of the state of the climate ($CS = T$). In this case, the two outer integrals of (2) coincide. Assume that the best-guess damage cost function is quadratic in T, $DC(T) = \alpha T + \beta T^2$. Assume further that the distribution of the cost function is symmetric. In this case, the expected costs equal the best-guess costs (the mode), i.e., $\mathrm{E}[DC|T] = DC(T)$. Thus,

$$\begin{aligned} \mathrm{E}[DC|AC] &= \int \alpha T + \beta T^2 f(T|AC)\, \mathrm{d}T \\ &= \alpha \mathrm{E}[T|AC] + \beta(\mathrm{E}^2[T|AC] + \mathrm{Var}[T|AC]), \end{aligned} \tag{3}$$

as, by definition, $\mathrm{E}X^2 = \mathrm{E}^2X + \mathrm{Var}X$. The IPCC (Houghton *et al.*, 1992) states that global warming due to 2×CO_2 falls within a range of 1.5 °C to 4.5 °C, with a best guess of 2.5 °C. This implies that $f(T|AC)$ is skewed to the right. Because we do not want to exclude global *cooling a priori*, and because we think we need thick tails to describe the tremendous uncertainties, a Gumbel(ζ, ϑ) distribution seems an appropriate choice. So

$$f(T|AC) = \frac{1}{\vartheta} \exp\left(-\frac{T-\zeta}{\vartheta}\right) \exp\left\{-\exp\left(-\frac{T-\zeta}{\vartheta}\right)\right\}, \tag{4}$$

with mode ζ, expectation $\zeta + 0.58\vartheta$, and variance $\pi^2\vartheta^2/6 \approx 1.64\vartheta^2$ (Johnson and Kotz, 1970; 0.58 is Euler's constant). Assume T to depend on the natural logarithm of the atmospheric concentration of carbon dioxide equivalents,[8] $T = \gamma \ln AC$, then the modal value of γ is $\gamma = 2.5/\ln(2) \approx 3.6$. If we interpret the 1.5–4.5 °C interval to be a 67% confidence interval, ϑ equals 2.0.[9] Scaling ϑ to the atmospheric concentration, T is distributed as Gumbel ($3.6 \ln AC$, $2.0 \ln AC$). The chance of global cooling associated with a doubling of atmospheric carbon dioxide equals 0.2%; the chance of global warming above 10 °C is 4%. The expected cost function thus looks like

$$\begin{aligned} \mathrm{E}[DC|AC] &= \alpha\gamma \ln AC + \beta(\gamma \ln AC)^2 + 0.58\alpha\vartheta \ln AC \\ &\quad + \beta(0.58^2\vartheta^2 + 0.58\vartheta\gamma) \ln^2 AC \\ &\quad + 1.64\vartheta^2 \ln^2 AC \\ &\approx 4.7\alpha \ln AC + 24.7\beta \ln^2 AC, \end{aligned} \tag{5}$$

where the first line represents the best guess, the second line the switch from best guesses to expectation and the third line the risk premium. The fourth line corresponds to the choices for γ, ζ and ϑ described above. Decomposing this last line leads to $3.6\alpha + 13.0\beta$ for the best guess, $1.1\alpha + 5.4\beta$ for the expectation, and 6.3β for the risk premium. This illustrates the common statistical decision analytic proposition that uncertainty is never a reason for inaction and often a reason for additional, precautionary action.

The next example again assumes T to be the steering parameter ($CS = T$). The cost function is now supposed to be quadratic in hurricane increase H ($PI = H$), with a symmetric density to express the uncertainties. The benchmark change in the hurricane intensity is an increase of 50%, represented by $H = 1.5$, due to a warming of 2.5 °C. To express the large uncertainties surrounding the incidence and intensity of hurricanes under $2\times CO_2$ (cf. e.g., Olsthoorn and Tol, 1994; Vellinga and Tol, 1993), a Pareto distribution is chosen

$$F(x) = 1 - \left(\frac{\kappa}{x}\right)^{\alpha}, \quad \kappa > 0, \alpha > 0, x \geq \kappa, \tag{6}$$

with expectation $\alpha\kappa/(\alpha - 1)$ and variance $\alpha\kappa^2/(\alpha - 2)^2/(\alpha - 1)$. We set $\kappa = 1$, i.e., we exclude hurricane decreases but the best guess is that hurricanes stay the same. We set $\alpha = 3$, i.e., the expected hurricane increase is 50%. The chance that the increase will exceed 300% (Ryan *et al.*, 1992, suggest this figure for hurricane frequency) equals 3.7%. $\mathrm{E}H = 1.5$, $\mathrm{Var}H = 1.5$ and $\mathrm{E}H^2 = 3.75$. If we assume a linear relationship between hurricane increase the global warming, then

$$\begin{aligned}\mathrm{E}[DC|AC] &= \int f(T|AC) \int \alpha H + \beta H^2 f(H|T)\, \mathrm{d}H\, \mathrm{d}T \\ &= \int 1.5\alpha(T/2.5) + 3.75\beta(T/2.5)^2 f(T|AC)\, \mathrm{d}T.\end{aligned} \tag{7}$$

This can readily be solved along the lines of the first example. The risk premium (for hurricane uncertainty) is 1.5β in this case; the overall risk premium is thus raised by 150%. The remainder of (7) is due to the switch from best guesses to expectations (the best guess is zero). This second example illustrates the effect of cascading uncertainties (cf. also Shlyakhter *et al.*, 1994). The parameters of the distribution describing the hurricane uncertainty are uncertain themselves, being functions of global warming. This can do nothing but enhance the overall uncertainty.

Given the many levels of uncertainties, one may be inclined to think that the final outcome will be infinitely uncertain. However, uncertainties are not only ‘vertical’. Regional and sectoral differences do exist, and bad luck in one place is counterbalanced by good luck elsewhere. Thus, the total portfolio of impacts is more certain than the individual impacts, provided that the impacts are not too positively correlated.

Note that the Gumbel distribution used in the examples for T is a rather pessimistic choice. The heavy tails, plus the assumed wide confidence interval, plus the right skew combined with the convex cost function inflate the risk premiums enormously.[10] If we had assumed a normal distribution with expectation 2.5 °C and standard deviation σ the risk premium would have been $\beta\sigma^2 \ln^2 AC$. Tol and de Vos (1994) suggest a standard deviation of 1.0 °C, a reduction of the risk premium by more than a factor of six. Also, assuming a symmetric distribution (as the normal is) implies that the shift from best guesses to expectations does not inflate the costs. This illustrates and stresses the need to asses carefully what the uncertainties are.

The differences in the expected costs between highly and moderately uncertain climate change serves to elucidate a nice paradox. If decision makers act as statistical decision analysis advises them to, the advocates of drastic action should stress and exaggerate the uncertainties, as the opposition to greenhouse gas emission abatement is presently doing.

Let us now calculate the expected damage costs of climate change using the damage functions of Section 3. As in the general case above, three levels of uncertainty are assumed to apply. First, climate sensitivity is uncertain. Second, the reaction of the driving climate parameter on climate change is uncertain. Third, the influence of the driving climate parameter on the damage costs is uncertain. In reality, all these factors consist of many levels of interactions. This is neglected here in order to keep the analysis manageable. The driving scenarios (such as economic growth, technological development, population growth) are assumed fixed as this paper concerns the damage costs. The evaluation of intangible damages (such as the value of a statistical life or a species lost) is not taken to be uncertain, as it reflects a choice made by the decision maker; sensitivity analyses should be used in these cases, but are outside the scope of this analysis. The shape of the damage cost functions (linear, quadratic), their interpretation in terms of central estimate (mode, median, mean), and the distributions (Gumbel, Pareto) are assumed to be certain in order to restrict the analysis to a reasonable effort.

The global mean temperature is assumed to be the steering parameter. The Gumbel distribution is chosen to represent the uncertainties surrounding the global mean temperature change, in order to incorporate the right-skewness and heavy tails of the uncertainties and not to exclude global cooling. The mode is set at 2.5 °C for a doubling of atmospheric carbon dioxide. The scale parameter ϑ is determined by assuming that there is a 99.9% chance that the climate sensitivity lies between 0 and 10 °C; thus, $\vartheta = 1.56$, and the IPCC's 1.5–4.5 °C interval has 77% confidence. As outlined in Table A2, there are three driving parameters: (*i*) global mean temperature (coinciding with the steering parameter), (*ii*) global mean sea level, and (*iii*) hurricane intensity and incidence. The uncertainty surrounding the global mean sea level is also modelled by a Gumbel distribution with mode $\zeta = 50$ cm and scale parameter $\vartheta = 17.6$ for a global mean temperature rise of 2.5 °C. The choice of ϑ sets the coefficient of variation equal to the one obtained in the Monte Carlo study of Titus and Narayanan (1991), i.e., about 2.7; the chance that sea level rise exceeds 1 m for 2.5 °C warming is 6%. Hurricane uncertainties are represented by a Pareto distribution as described above. This implies that we exclude a hurricane decrease; in the knowledge of the present author, no model projected decreased intensity, although some weak theoretical hints in that direction exist (Idso *et al.*, 1990). The models that find a decrease in the number of hurricanes point at the same time to an increase in the frequency (Broccoli and Manabe, 1990; Olsthoorn and Tol, 1994), supposedly annihilating one another in the impact. By putting the modal change at zero, we follow IPCC 1990 and 1992 (Houghton *et al.*, 1990, 1992) as well as IPCC 1995 (Kattenberg, personal communication; cf. also Maunder, 1994).

In the examples above, uncertainties in the damage costs have been assumed to be symmetric, equating best guesses with expectations. This assumption is valid for the costs of change in the global mean temperature for agriculture and human amenity. These damages can be higher as well as lower, with an equal probability. The assumption is not valid for the other categories. Absolute losses, such as species and wetland losses, and adaptation losses, induced by the changing climate, are bounded from below. These categories of uncertainties are described by lognormal distributions; the others by normal distributions. In case the best guess equals zero, a gamma distribution is assumed, with the expectation set to 0.05% of GDP, except for hurricane damage or people leaving, in which case the zero guess is maintained, i.e., it is assumed that no hurricane will hit Europe or the former Soviet Union and that no one will leave the OECD, the former Soviet Union or Central and Eastern Europe because of the enhanced greenhouse effect. The damage categories studied most (protection, dryland loss, and agriculture) are assumed to have coefficients of a variation of 1.5, the others of 3. These choices are not in conflict with the outcome of the expert's poll reported by Nordhaus (1994), which clearly points at a positive skew and fat tails in the damage costs uncertainties. The choice for constant coefficients of variation implies that the mean and standard deviation grow at the same rate; uncertainties autonomously growing over time are excluded from the analysis.

Figure 3 displays the best guess tangible damage costs (corresponding to

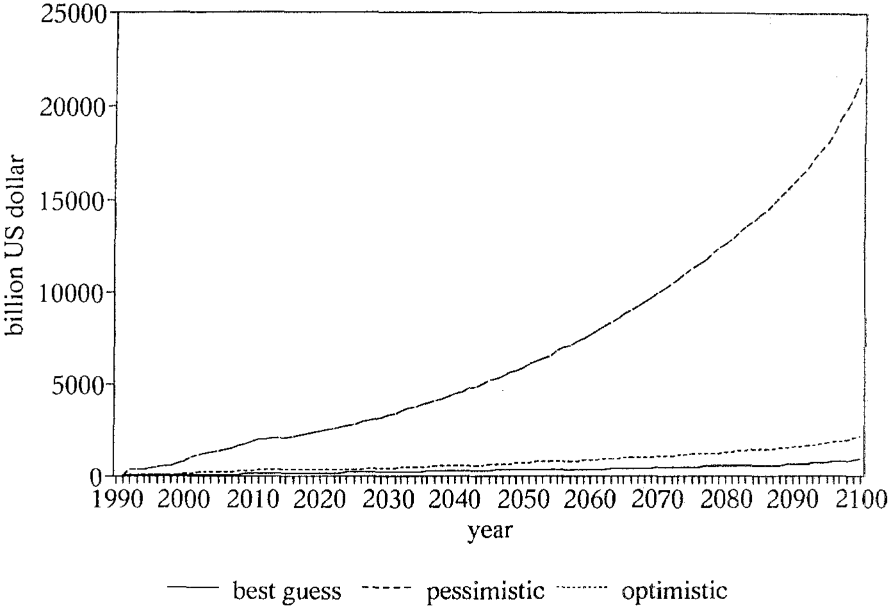

Fig. 3. Global warming damage costs best guess vs expected tangible damages.

Figures 1 and 2), and the expected tangibles damages (based on a Monte Carlo simulation with 30 000 drawings for 147 random variables). As hinted above, the expected damages are much larger than the best guess costs: in this particular example, the tangible damages expected by 2100 are about twenty-five times are large as the best guesses, and the expected intangibles about fifty times; the figures for the year 2000 are fifteen and sixty, respectively (cf. Table II). The fact that the uncertainty surrounding the intangible damage costs is larger in 2000 than in 2100 is due to the fact that the intangible losses are dominated by lifes losses and emigration costs, combined with the fact that these changes are fed back into the model: if the odds are all bad, and loss of life and emigration are severe, fewer people will be left in 2100, and so less damage can be done. The, at first sight, extraordinarily high figures are explained as follows. The switch from a best guess to a lognormal expectation with a coefficient of variation of 3 solely leads to an increase with a factor 32; this applies to the life/morbidity damages, the dominant cost factor. The costs of sea level rise, about one-sixth of the total, has three levels of uncertainties, with two underlying Gumbel distributions. So, as the uncertainties in the initial assumptions are large, and the uncertainties are partly placed on top of one another, the uncertainties in the final outcome are overwhelming, and the expected damage costs are many times larger than best-guess costs.

To illustrate this point further, the calculations above are repeated under very conservative assumptions. The best guesses are all kept the same. The 1.5–4.5 °C climate sensitivity range is interpreted as a 99% confidence interval. The chance that sea level rise exceeds 1 meter for a 2.5 °C is set at 0.5%. Hurricane uncertainty is assumed to follow a lognormal distribution, with an

Table II. Climate change damage costs: Monte Carlo results.[a]

	Pessimistic uncertainties			Optimistic uncertainties		
	Tangible	Intangible	Total	Tangible	Intangible	Total
Expected						
2000	14.27	62.57	47.11	2.10	4.32	3.61
2100	24.53	53.05	51.99	2.45	3.62	3.58
Minimum						
2000	-3.57	-1.10	-0.99	0.74	0.78	0.83
2100	-3.57	-0.65	-0.66	-0.60	0.59	0.61
Maximum						
2000	775.18	5307.28	3624.27	10.47	29.43	22.60
2100	3942.19	3164.90	3051.78	15.13	27.75	26.85

[a] The figures in the table represent the ratio of the expected, minimum and maximum damage costs to the best guess costs for the years 2000 and 2100.

expected increase of 50%. The coefficients of variation of the damage costs are one-third of those discussed above. The expectation for the zero best guesses is set at 0.01% of GDP. The resulting expected tangible damage costs are displayed in Figure 3. In spite of conservative assumptions, the expected tangible damages by 2010 are about 2.5 times as large as the best guesses; for the intangibles this amounts to a factor 3.5. So, even if one is overly certain, the best-guess costs are much smaller than the expected costs.

5. Future Prospects

This section attempts to identify some of the priorities in our future research task. Obviously, this paper is but one of the first tiny steps on the long road to understanding the impacts of climate change on society. At the end of Section 2, we have already brought up some of the questions economists need to answer.

First of all, we need a better understanding of what climate means, in economic terms. Our society developed within the conditions set by nature, and we gradually delinked ourselves from our environment and started to think about the year-to-year climate variability as noise (Knox, Lovell and Smith, 1985). However, all our activities, and especially our agriculture, infrastructure and insurance, are still designed for the old, outdated range of weather events. Weather extremes are likely to shift much faster than the mean, and are much harder to predict. Thus, a small change of climate might lead to large-scale crop damage, transport disruptions and insolvencies in the insurance sector. These problems can be overcome, but can hardly be anticipated. This leads to the notion that climate change will be felt through *events*, and *not* through *gradual changes* (as this paper has also presumed up to now). However, the discipline of economics has paid relatively little attention to the macroeconomic impacts of exogenous shocks. Modelling the impact of events would require very detailed modelling, at a high time-resolution.

Second, the direct economic impacts of climate change need further attention, and economic modules need to be coupled to the models of physical and biological impacts. The need for integration is motivated, e.g., by the notions that it is not the crops that decide where and when to grow and that carbon taxes will be imposed on an economy under the stress of a changing climate. Although some models claim to be integrated, fully integrated models do not exist, as far as the present author is aware. Full integration would involve the coupling of models of the atmosphere, the oceans, the biosphere, agriculture, economy, demography and (international) politics.

Third, the uncertainties will not be resolved in the near future. Therefore, formal uncertainty analyses are required on all models and outcomes. However, analytical results, as presented in this paper, are intractable in only slightly more complicated models. Numerical methods, such as Monte Carlo analysis, suffer from the need to rerun the model many times, even if, e.g., Latin

Hypercube sampling is employed. Obviously, the modules of an integrated model need to be fast, simplified schemes of the state-of-the-art models, and less demanding methods of uncertainty analysis need to be studied. A promising approach might be the emulation/interpolation methods from the field of the design and analysis of computer experiments (e.g., Sacks *et al.*, 1989; Bernardo *et al.*, 1992). Another reason to carefully map the uncertainties is the need to identify the topics on which additional research is most urgent.

Fourth, the propagators of the so-called 'learn-then-act' strategy, postponing action until more certainty is gained (e.g., Kolstad, 1993a), are mistaken. First of all, any reasonable policy will be somewhere in between the extreme options, as Manne and Richels (1992) clearly point out. Irreversibilities (e.g., Kolstad, 1993b) work on both costs and benefits of emission reduction, but need not necessarily influence the optimal decision (Ulph and Ulph, 1994). Second, although the debate on the *global mean* temperature is expected to settle down before the year 2000 (Houghton *et al.*, 1990; but see Tennekes, 1990), the huge uncertainties surrounding local climate change and its impacts will survive much longer. Anyhow, neither scientific progress nor its direction can be relied upon, and *predictions* of future pathbreaking theories or empirical breakthroughs obviously do not contain any more information than the present knowledge (Dowlatabadi and Morgan, 1993; Jansen *et al.*, 1993; Shlyakhter and Kammen, 1992). Further, assuming a bimodal distribution for the state of nature (the enhanced greenhouse effect is either a serious or a negligible problem), and assuming that one of the modes will be diminished in a few years time, is a blunt caricature of reality.

Fifth, the present generation of climate-economy models all have some exogenously generated growth in them (for *DICE*, growth is driven by technological progress and population growth; for *ICAM, MERGE* and *CETA*, growth is driven by labour-productivity and population growth; for *PAGE*, growth itself is exogenous). This implies that the impacts of climate change can hamper economic growth, but not stop or reverse it; at least, according to the models. Note that in *PAGE* and *MERGE* the costs of climate change, adaptation and prevention do *not* influence the economy at all. Recessions, depressions and poverty traps, possibly induced or enhanced by climate change (which will not be smooth), are excluded from the analyses, *a priori*, but they do have the potential to substantially affect human welfare and successful adaptation to climate change.

Sixth and last, gross domestic product, even if corrected for intangible losses, does not reflect anyone's preferences. Human preferences are rather determined by multi-attribute functions, as lack of food cannot be compensated by additional video recorders. Also, only a small number of governments would prefer the gross domestic product to rise at the expense of certain sectors or households. So the real pain hides behind the aggregation of impacts, i.e., is cancelled out by the gains, and behind the measurement of pain. Related to this is the treatment of biodiversity, for instance, as a flow instead of a stock variable. The less diverse nature becomes, the more another species lost counts, but this not reflected if the damage costs of biodiversity are represented as a function of climatic change. The loss of biodiversity depends on climate change, but its valuation does not, directly.

6. Conclusions

This paper presents some attempts to express the socio-economic damages due to climate change in damage cost functions, and to incorporate uncertainties analytically. The aim of presenting functions and uncertainties is rather to stimulate discussion than to present final answers. Disaggregated cost functions are needed to evaluate non-benchmark climate change at a regional and sectoral level. Tentative functions are presented for nine regions and nine damage categories. These functions are second order polynomials in the rate and total change of global mean temperature, sea level and tropical cyclones. Analytical expressions for the uncertainties show climate change influence on costs and decisions more clearly than numerical results do. Generally, expected damages are greater than the best guesses because uncertainties are positively skewed, the damage functions are convex, and the uncertainties cascade through a number of levels. On the other hand, the total damage consists of a portfolio of individual damages, reducing overall uncertainty. This latter effect is of minor importance in the two numerical examples given. For future study, it is important to elaborate further on the influence of climate and weather on the economy, to develop further integrated models, to investigate more efficient means for uncertainty analysis, to endogenise economic growth, and to employ more realistic value functions.

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Appendix Additional Tables

Table A1. Climate change damage (2×CO_2 – $10^9\$^{(1988)}$).[a]

Regions[b]	1	2	3	4	5	6	7	8	9	Total
Coastal defence	1.5	1.7	1.8	0.5	0.0	1.0	2.0	0.5	0.5	9.5
Dryland loss	2.0	0.5	4.0	1.3	0.0	0.5	1.0	0.0	0.5	9.8
Wetland loss	5.0	4.0	4.5	1.3	0.0	1.5	1.5	0.5	0.5	18.8
Species loss	5.0	5.0	5.0	2.5	0.0	2.0	1.0	1.0	0.5	22.0
Agriculture	10.0	–4.2	–6.3	–32.5	0.7	11.8	21.0	–3.0	17.5	14.5
Amenity	12.0	12.0	12.0	–1.0	0.1	0.4	1.2	1.0	0.5	38.0
Life/morbidity[c]	37.7	36.6	36.9	18.8	0.6	11.4	21.6	15.4	9.01	88.0
Migration	1.0	1.1	0.6	0.5	0.0	2.4	4.4	2.6	1.3	13.8
Natural hazards	0.3	0.0	0.8	0.0	0.0	0.1	0.1	0.1	0.0	1.4
Total	74.0	56.5	59.0	–7.9	1.3	31.0	53.6	18.0	30.3	315.7
(% GDPP)	(1.5)	(1.3)	(2.8)	(–0.3)	(4.1)	(4.3)	(8.6)	(5.2)	(8.7)	(1.9)

[a] After Tol (1993a, 1994c).

[b] 1 = USA and Canada; 2 = OECD-Europe; 3 = Japan, Australia and New Zealand; 4 = Central and Eastern Europe and the former Soviet Union; 5 = the Middle East; 6 = Latin America; 7 = South and South East Asia; 8 = Centrally Planned Asia; 9 = Africa.

[c] The value of a statistical life is assumed to equal $250,000 + 175 times the average income per capita (thus ranging from $3.4 million for an inhabitant of the American parts of the OECD to $299,000 for an inhabitant of Centrally Planned Asia).

Table A2. Climate change damage costs functions.

	Tangible damage				Intangible damages				Parameter of interest
	PI	ΔPI	PI^2	ΔPI^2	PI	ΔPI	PI^2	ΔPI^2	
Coastal defence	0.5	0.25		0.25					Sea level
Dryland loss	1								Sea level
Wetland loss	0.25	0.25			0.25	0.25			Sea level
Species loss							0.5	0.5	Temperature
Aagriculture[a]	1	0.75		0.25					Temperature
Amenity							0.17	0.83	Temperature
Life/morbidity							0.17	0.83	Temperature[b]
Emigration[c]	1								Sea level
Immigration[d]					1				Sea level
Natural hazards	0.75		0.25						Hurricanes[e]

[a] Cf. Table A3. The damages due to a change climate correspond to the average over the three models and the two adaptation scenarios; the damages due to a changing climate correspond to the average over the three models under the no adaptation scenario.

[b] The presumed increase in hurricane intensity and incidence also induces some additional losses of human life.

[c] This represents the number of migrating people. The costs are set to three times the average income per capita times the number of people leaving.

[d] The number of people entering, N, is assumed to be linear in the total sea level rise. The costs of this supposedly equal $bN + 0.005N^2$; b equals 40% of the average income per capita in the host region; the benchmark estimate thus corresponds to the ones of Cline and Fankhauser.

[e] Hurricane intensity and incidence.

Table A3. Agricultural yield changes $2\times CO_2$ (percents of gross agricultural product).[a, g, h]

Model[b] Region/ scenario[c]	UKMO			GISS			GFDL			avg.	avg.	diff.
	1	2	3	1	2	3	1	2	3	2 + 3[d]	1[e]	avg.[f]
OECD-A	–20.0	-5.0	-5.0	-5.0	+10.0	+10.0	-5.0	+10.0	+10.0	+5.00	–10.00	-15.00
OECD-E	+5.0	+5.0	+5.0	+10.0	+10.0	+10.0	-5.0	-5.0	-5.0	+3.33	+3.33	0.00
OECD-P	+7.5	+7.5	+7.5	+7.5	+7.5	+7.5	+7.5	+7.5	+7.5	+7.50	+7.50	0.00
CEE&SU	-7.5	-7.5	-7.5	+22.5	+22.5	+22.5	+7.5	+7.5	+7.5	+7.50	+7.50	0.00
M-E	-22.5	-22.5	-7.5	-7.5	-7.5	+7.5	-7.5	-7.5	+7.5	-5.00	-12.50	-7.50
L-A	-22.5	-22.5	-8.5	-15.0	-15.0	-1.0	-10.0	-10.0	+4.0	-8.83	-15.83	-7.00
S&SEA	-20.0	-20.0	-10.0	-10.0	-10.0	0.0	-10.0	-10.0	0.0	-8.83	-13.33	-4.50
CPA	-7.5	+7.5	+7.5	+7.5	+22.5	+22.5	+7.5	+22.5	+22.5	+17.50	+2.50	-15.00
AFR	-20.0	-20.0	-20.0	-7.5	-7.5	+7.5	-15.0	-15.0	0.0	-6.67	-14.17	-7.50

[a] After Rosenzweig *et al.* (1993); cf. also Fischer *et al.* (1993), Rosenzweig and Parry (1994) and Reilly (1994).

[b] The climate change scenarios used are the equilibrium $2\times CO_2$ experiments according to the General Circulation Models of the United Kingdom Meteorological Office, the Goddard Institute for Space Studies and Geophysical Fluid Dynamics Laboratory.

[c] The scenarios concern no adaptation (1), minor shifts (2) and major shifts (3) in behaviour.

[d] The average of adaptation scenarios 1 and 2 over the three models.

[e] The average of the no adaptation scenario over the three models.

[f] The difference between the average described under notes e and f.

[g] The costs due to a changed climate correspond to the yield losses associated with the average over the three models and the two adaptation strategies. The costs due to a changing climate correspond to the difference between this average and the average over the three model without adaptation.

[h] The source can be criticised for two reasons: (*i*) the climate sensitivity of all three models is above the IPCC consensus best guess, and (*ii*) the carbon fertilisation effect is based on too high assumptions for the atmospheric concentration of carbon dioxide (Cline, personal communication). As the effects of this are unclear to the present author, but of opposite sign, they are supposed to cancel out.

Notes

[1] Note that only if the relevant climate parameter relates linearly to the global mean temperature, and the relationship is perfectly known, is the temperature an adequate proxy.

[2] Note that the intangible losses due to protection (such as naturally and historically valuable features lost due to building dikes) are neglected in the studies surveyed in Tol (1993a).

[3] The benchmark estimates discussed in Section 2 are based on an increase in hurricane intensity of 50%. However, the literature is more concerned with an increase in hurricane frequency, and the positions diverge widely. From this point on, hurricane incidence and intensity are taken jointly, as a compromise between the climate and impact literature.

[4] It would be more realistic, though less practical, to model biodiversity as a stock variable of which subsequent losses would be valued higher and higher.

[5] The business-as-usual scenario of *FUND* is based on *Global2100* (Manne and Richels, 1992).

[6] The bumpy behaviour in the first two decades is induced by the switch from observed greenhouse gas observations to calculated emissions, the assumed rapid phase-out of CFCs, the fast decline in China's growth rates to moderate levels, and the fact that the one-year time step scenarios are calibrated to ten-year time step scenarios, leading to discontinuities in the first derivative at the beginning of each decade.

[7] The benchmark tangible losses amount to approximately 0.3% of GWP. The declining vulnerability due to the decreasing share of agriculture in GWP is more than offset by the growing influence of the developing countries' vulnerability due to their rapidly growing economies and populations.

[8] Note that this is in fact only justified for carbon dioxide, not for the other greenhouse gases (Houghton *et al.*, 1990). IPCC '92 (Houghton *et al.*, 1992) has abandoned the concept of carbon equivalents which renders linear transformations of non-CO_2 to CO_2 doubtful. Reilly and Richards (1993) attempt to derive a trace gas index incorporating the entire range of environmental impact of greenhouse gases.

[9] If the interval were to be interpreted as a 75%, 90%, 95% or 99% confidence intervals the corresponding ϑ would be 1.6, 1.1, 0.6 or 0.6, respectively.

[10] Note that the cost functions and distributions are chosen such that the risk is what Collard (1988) calls weakly catastrophic. The product of the chance on large climate changes times their impacts tends to zero as climate changes grow larger. However, this does not necessarily holds true if the disutility of the damages if considered.

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