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The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties

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Abstract

One hundred and three estimates of the marginal damage costs of carbon dioxide emissions were gathered from 28 published studies and combined to form a probability density function. The uncertainty is strongly right-skewed. If all studies are combined, the mode is \$2/tC, the median \$14/tC, the mean \$93/tC, and the 95 percentile \$350/tC. Studies with a lower discount rate have higher estimates and much greater uncertainties. Similarly, studies that use equity weighing, have higher estimates and larger uncertainties. Interestingly, studies that are peer-reviewed have lower estimates and smaller uncertainties. Using standard assumptions about discounting and aggregation, the marginal damage costs of carbon dioxide emissions are unlikely to exceed \$50/tC, and probably much smaller.

JEL classification: Q25

Keywords: Climate change; Carbon dioxide; Marginal damage costs

1. Introduction

Climate change is one of the major environmental concerns of today. People may argue that climate change is a problem because it would cause unacceptable hardship for particularly vulnerable populations. Others are concerned about the potential threat to particular unique and valuable ecosystems. Still others worry that climate change would increase the probability of large-scale climate instabilities. Some are concerned about the aggregate impacts of climate change. They argue that emission reduction is costly too, and that abatement costs should be balanced against the avoided costs of climate change (Smith et al., 2001). This paper particularly caters to the last reason for concern.

A key challenge when assessing the impacts of climate change is the need to reduce the complex pattern of local and individual impacts to a more tractable set of indicators, so that impacts in different regions, sectors or systems can be summarized and compared in a meaningful way. Various indicators have been advanced, such as number of people affected (e.g., Hoozemans et al., 1993), change total plant growth (White et al., 1998), runoff (Arnell, 1999), and number of systems undergoing change (e.g., Alcamo et al., 1995). Such 'physical'' metrics may be suited to measure the impact on natural systems but they are inadequately linked to human welfare, the ultimate indicator of concern, particularly for systems that are managed by humans. Some recommend the use of different metrics for different types of impacts (Schneider, 1997). Composite vulnerability profiles have been proposed but not fully implemented (e.g., Downing et al., 2001). The final comparison and aggregation are left to policy makers, as is the trade-off between avoided impacts and the costs of emission reduction.

If the aim is to explicitly compare the impacts of climate change with mitigation costs, it is necessary to express the benefits of mitigated climate change in the same metric as the costs of emission reduction, net of its

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ancillary benefits (Pearce et al., 1996; Smith et al., 2001). Emission reduction costs are typically expressed in money, and this metric is particularly well suited to measure impacts that are linked to market transactions and directly affect GDP. Using a monetary metric to express non-market impacts, such as effects on ecosystems or human health, is more difficult but not impossible. But economic valuation can be controversial, and requires sophisticated analysis that is still mostly lacking in a climate change context (e.g., Pearce et al., 1996).

Expressing total impacts in monetary terms is not sufficient to allow for a consistent comparison of the (avoided) impacts of climate change to mitigation costs, or to compare climate policy to other policies, e.g., on education, public health care, or urban air quality. To be able to do that, one needs to gain an understanding of the impact of climate change at the margin, i.e., the effect that can be achieved by a small alteration in greenhouse gas emissions.

Estimates of the marginal damage costs of carbon dioxide emissions, however controversial and uncertain, are useful if only to provide a benchmark for the costs of emission reduction policies. In this paper, I review 27 studies of marginal damage costs, which produced a total of 94 estimates, and combine these estimates to form a joint probability density function.

In Section 2, I discuss the limitations of climate change impact studies, which are briefly reviewed in Section 3. Section 4 discusses the 28 studies of marginal damage costs of carbon dioxide emissions, with a further interpretation given in Section 5. Section 6 concludes.

2. Limitations

Research into the economic impacts of climate change is still at an early stage.

A major difficulty in impact assessment is our still incomplete understanding of climate change, particularly its regional details (Mahlman, 1997). Impacts are local, and impacts are related to weather variability and extremes. Current climate change scenarios and current climate change impact studies use crude spatial and temporal resolutions, too crude to capture a number of essential details that determine the impacts.

Knowledge gaps continue at the level of impact analysis. Despite a growing number of country-level case studies (e.g., US Country Studies Program, 1999), our knowledge of local impacts is still too uneven and incomplete for a careful, detailed comparison across regions. Furthermore, differences in assumptions often make it difficult to compare case studies across countries. Only a few studies provide a coherent global picture, but even these assessments are often based on case studies with a more limited scope, which are then extrapolated to other regions. Such extrapolation is difficult. Not all analyses are equally careful in undertaking this task.

While our understanding of the vulnerability of developed countries is improving—at least with respect to market impacts—good information about developing countries remains scarce. Non-market damages, indirect effects, horizontal interlinkages, and the socio-political implications of change are also still poorly understood. Uncertainty, transient effects, and the influence of change in climate variability are other factors that deserve more attention.

Adaptation is hard to capture adequately in an impact assessment. Adaptation will entail complex behavioral, technological, and institutional adjustments at all levels of society, and not all population groups will be equally adept at adapting. The goals of adaptation are not always the same across studies. For example, in some studies the (implicit) goal is to maintain current cropping patterns, others want to maintain current farmers' incomes, or adjust existing practices in the most efficient manner. Different goals lead to different adaptation costs and different residual impacts. Various approaches are used to model adaptation (e.g., spatial analog, micro-economic modeling), but they all either underestimate or overestimate its effectiveness and costs. Impact studies are largely confined to autonomous adaptation, i.e., adaptations that occur without explicit policy intervention from the government. But in many cases, governments too will embark on adaptation policies to avoid certain impacts of climate change, and may start those policies well before critical climatic change occurs. Current studies lump together adaptation costs and residual impacts. Tol et al. (1998) attempt to separate the two, concluding that adaptation is treated very differently not only in different studies but also in different sectors. For instance, adaptation costs only are considered in energy demand, whereas adaptation is excluded from climate change impacts on unmanaged ecosystems.

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

Aggregating impacts requires an understanding of (or assumptions about) the relative importance of impacts in different sectors, in different regions and at different times. This involves value judgments. The task is simplified if impacts can be expressed in a common metric, but even then aggregation is not possible without value judgments. Azar (1999), Azar and Sterner (1996), and Fankhauser et al. (1997, 1998) discuss regional aggregation, Arrow et al. (1996) and Portney and Weyant (1999) aggregation across time and Rothman (2000) across sectors.

3. Impacts of climate change

A number of studies have estimated the total impact of climate change in different regions of the world. Table 1 shows aggregate, monetized impact estimates for a doubling of atmospheric carbon dioxide on the current economy and population from three recent studies and the earlier review by Pearce et al. (1996). The numerical results remain speculative, but they provide insights on signs, orders of magnitude, and patterns of vulnerability. Results are difficult to compare because different studies assume different climate scenarios, make different assumptions about adaptation, use different regional disaggregation and include different impacts. The Nordhaus and Boyer (2000) estimates, for example, are more negative than others, partly because they factor in the possibility of catastrophic impact. The Mendelsohn et al. (1998) and Tol (2002a) estimates, on the other hand, are driven by optimistic assumptions about adaptive capacity and baseline development trends, which results in mostly beneficial impacts.

Standard deviations are rarely reported, but likely amount to several times the 'best guess'. They are larger for developing countries, where results are generally derived through extrapolation rather than direct estimation. This is illustrated by the standard deviations estimated by Tol (2002a), which, however, probably

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

	Pearce et al.	Mendelsohn et al.		Nordhaus/Boyer	Tol[b]
	2.5°C	1.5°C	2.5°C	2.5°C	1.0°C
North America	−1.5				3.4 (1.2)
USA	−1.0 to −1.5		0.3	−0.5	
OECD Europe	−1.3				3.7 (2.2)
EU	−1.4			−2.8	
OECD Pacific	−1.4 to −2.8				1.0 (1.1)
Japan			−0.1	−0.5	
Eastern Europe and fUSSR	0.3				2.0 (3.8)
Eastern Europe				−0.7	
fUSSR	−0.7				
Russia			11.1	0.7	
Middle East	−4.1			−2.0[c]	1.1 (2.2)
Latin America	−4.3				−0.1 (0.6)
Brazil			−1.4		
South and Southeast Asia	−8.6				−1.7 (1.1)
India			−2.0	−4.9	
China	−4.7 to −5.2		1.8	−0.2	2.1 (5.0)[d]
Africa	−8.7			−3.9	−4.1 (2.2)
DCs		0.12	0.03		
LDCs		0.05	−0.17		
World					
Output weighted	−1.5 to −2.0		0.1	−1.5	2.3 (1.0)
Population weighted				−1.9	
At world average prices					−2.7 (0.8)
Equity weighted					0.2 (1.3)

Source: Pearce et al. (1996); Mendelsohn et al. (1998); Nordhaus and Boyer (2000); Tol (1999a).

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

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

[c] High-income OPEC.

[d] China, Laos, North Korea, Vietnam.

still underestimate the true uncertainty, for example, because they exclude omitted impacts and severe climate change scenarios.

Overall, the current generation of aggregate estimates may understate the true cost of climate change because they tend to ignore extreme weather events; exclude low probability/high consequence scenarios, such as a shutdown of the thermohaline circulation (Keller et al., 2000) or a collapse of the West-Antarctic ice sheet (Oppenheimer, 1998); underestimate the compounding effect of multiple stresses; and ignore the costs of transition and learning. However, studies may also have overlooked positive impacts of climate change (e.g., on amenity; Maddison, 2003; Maddison and Bigano, 2003) and not adequately accounted for how development could reduce impacts of climate change.

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

- Market-impacts are lower than initially thought, and may be in some countries and sectors positive—at least in developed regions. The downward correction is largely due to the effect of adaptation, which is more fully captured in the latest estimates.
- Even so, market impacts could be significant in some conditions, such as a rapid increase in extreme events, which might lead to large losses and/or costly over-adaptation.
- Non-market impacts will be more pronounced than early aggregate studies conveyed, as many (but not all) of the effects that have not yet been quantified could be negative. There is concern about the impact on human health and mortality, but particularly the impact on water resources and ecosystems is not well understood.
- Developing countries are more vulnerable to climate change than developed countries because their economies rely more heavily on climate-sensitive activities, many already operate close to environmental and climatic tolerance levels, and the lack of technical, economic and institutional resources may prevent successful adaptation.
- Differences in vulnerability will not only be observed between regions, but also within them. Some individuals, sectors, and systems will be less affected, or may even benefit, while other individuals, sectors, and systems may suffer significant losses.
- Estimates of global impact are sensitive to the way figures are aggregated. Because the most severe impacts are expected in developing countries, the more weight is assigned to developing countries, the more severe are aggregate impacts. Net aggregate benefits do not preclude the possibility of a majority of people being negatively affected, and some population groups severely so.

Most impact studies assess the consequences of climate change at a particular concentration level or a particular point in time, thus providing a static "snap shot" of an evolving, dynamic process. One of the main challenges of impact assessments is to move from this static analysis to a dynamic representation of impacts as a function of shifting climate characteristics, adaptation measures and exogenous trends like economic and population growth. Little progress has been made in this respect, and our understanding of the time path aggregate impacts will follow under different warming and development scenarios, is still severely limited, particularly if we move beyond $2CO_2$ (see Sohngen and Mendelsohn, 1999; Tol, 2002b; Tol and Dowlatabadi, 2001; Yohe et al., 1996).

4. Marginal damage cost estimates

The marginal damages caused by a metric ton of carbon dioxide emissions in the near future were estimated in the Second Assessment Report at US$5—125 per tC. Most estimates are in the lower part of that range, and higher estimates only occur through the combination of a high vulnerability with a low discount rate (see Pearce et al., 1996). Tol et al. (2001) review more recent studies as well. They concur with Pearce et al. (1996), concluding that "estimates in excess of $50/tC require relatively unlikely scenarios of climate change, impact sensitivity and economic values". How robust are these conclusions?

Table 2 lists 28 studies of marginal damage costs of carbon dioxide emissions. All of these studies use an estimate of the total damage costs (see Section 3), and then slightly perturb the total damages to obtain an estimate of the marginal damage costs.[1] Table 2 also includes the average of the marginal damage costs estimates. Four alternative averages are used. Firstly,

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[1] Li et al. (2004) use a different approach. Li et al. report a contingent valuation study of the willingness to pay for greenhouse gas emission reduction in the USA. They find that the median American household is willing to pay some $00 per year for reducing climate change, which corresponds to about $15/tC, which is reassuringly well within the range of estimates reported here.

Table 2
Characteristics of the marginal costs estimates

Source	C. Est.	Unc. range	CDR	PRTP	TH	EW	AW	PR	New	MC	Dyn	Scen
Ayres and Walter (1991)	119.0			1	2100	N	1	Y	Y	N	N	N
Nordhaus (1991)	26.8			1	2100	N	1	Y	Y	N	N	N
Cline (1992)		5.8–124.0[a]			2500	N	1	N	Y	Y	N	Y
Hohmeyer and Gaertner (1992)	1666.7		0		2100	N	1	N	Y	N	N	Y
Nordhaus (1993)	5.0			3	2500	N	1	Y	N	Y	N	Y
Peck and Teisberg (1993)	10.0			3	2100	N	1	Y	N	Y	N	Y
Reilly and Richards (1993)	14.3		5		2100	N	0.5	Y	N	Y	N	N
	21.2		5		2100	N	0.5					
Fankhauser (1994)	20.3	6.2–45.2[a]			2100	N	1	Y	Y	Y	N	Y
Nordhaus (1994)	5.3			3	2500	N	1	N	Y	Y	N	Y
Maddison (1995)	16.5		5		2100	N	1	Y	N	Y	N	Y
Schauer (1995)	8.3	21.2[c]	5		?	N	0.5	Y	Y	Y	N	Y
	112.5	149.8[c]	5		?	N	0.5					
Plambeck and Hope (1996)	3.0	1.0–6.0[a]	5		2200	N	0.3	Y	Y	Y	N	Y
	8.0	3.0–12.0[a]	5		2200	N	0.1					
	8.0	6.0–18.0[a]	5		2200	N	0.1					
	21.0	10.0–48.0		3	2200	N	0.3					
	46.0	20.0–94.0[a]		2	2200	N	0.1					
	440.0	390.0–480.0[a]		0	2200	N	0.1					
Azar and Sterner (1996)	85.0			0	2300	N	4/90	Y	N	Y	N	Y
	200.0			0	3000	N	8/90					
	75.0			0.1	2300	N	3/90					
	140.0			0.1	3000	N	6/90					
	32.0			1	2300	N	2/90					
	33.0			1	3000	N	4/90					
	13.0			3	2300	N	1/90					
	13.0			3	3000	N	2/90					
	260.0			0	2300	Y	8/90					
	590.0			0	3000	Y	16/90					
	230.0			0.1	2300	Y	6/90					
	410.0			0.1	3000	Y	12/90					
	95.0			1	2300	Y	4/90					
	98.0			1	3000	Y	8/90					
	39.0			3	2300	Y	2/90					
	39.0			3	3000	Y	4/90					
Downing et al. (1996)	53.5		0		2100	N	0.5	N	Y	N	Y	Y
	18.3		0		2100	N	0.5					
Hohmeyer (1996)	800.0		0		2100	N	1	N	N	N	N	Y
Hope and Maul (1996)	7.0	3.0–11.0[a]		2	2200	N	0.1	Y	Y	Y	N	N
	24.0	0.0–270.0[a]		2	2200	N	1					N
	5.0	2.0–7.0[a]		2	2200	N	0.8					Y
	29.0	12.0–45.0[a]		2	2200	N	0.1					N
Nordhaus and Yang (1996)	6.2			3	2500	N	1	Y	Y	Y	N	Y
Nordhaus and Popp (1997)	11.6	0.0–34.0[b]		3	2500	N	0.9	Y	N	Y	N	Y
	6.3			3	2500	N	0.1					
Eyre et al. (1999)	170.0		1		2100	Y	0.5	N	N	Y	Y	Y
	70.0		3		2100	Y	0.5					
	160.0		1		2100	Y	0.5					
	74.0		3		2100	Y	0.5					
Roughgarden and Schneider (1999)	40.4	0.0–193.3[a]		3	2500	N	1	Y	Y	Y	N	Y
Tol (1999)	60.0	26.0–178.0[a]	3		2100	Y	0.25	Y	Y	Y	Y	Y
	62.0		3		2200	Y	0.05					
	23.0		3		2100	N	0.05					
	66.0		3		2100	Y	0.05					
	65.0		3		2100	Y	0.05					
	56.0		3		2100	Y	0.05					
	317.0	158.0–962.0	0		2100	Y	0.05					
	243.0		0		2200	Y	0.01					
	142.0		0		2100	N	0.01					
	360.0		0		2100	Y	0.01					
	348.0		0		2100	Y	0.01					

(*Continued on next page*)

Table 2 (*continued*)

Source	C. Est.	Unc. range	CDR	PRTP	TH	EW	AW	PR	New	MC	Dyn	Scen
	288.0		0		2100	Y	0.01					
	171.0	81.0–512.0[a]	1		2100	Y	0.05					
	172.0		1		2200	Y	0.01					
	73.0		1		2100	N	0.01					
	192.0		1		2100	Y	0.01					
	187.0		1		2100	Y	0.01					
	156.0		1		2100	Y	0.01					
	26.0	11.0–77.0[a]	5		2100	Y	0.10					
	26.0		5		2200	Y	0.02					
	9.0		5		2100	N	0.02					
	28.0		5		2100	Y	0.02					
	28.0		5		2100	Y	0.02					
	25.0		5		2100	Y	0.02					
	6.0	2.0–17.0	10		2100	Y	0.05					
	6.0		10		2200	Y	0.01					
	2.0		10		2100	N	0.01					
	6.0		10		2100	Y	0.01					
	6.0		10		2100	Y	0.01					
	6.0		10		2100	Y	0.01					
Nordhaus and Boyer (2000)	5.9			3[d]	2300	N	1	N	Y	Y	N	Y
Tol and Downing (2000)	26.1			1	2100	Y	0.1	N	N	Y	Y	Y
	3.5			1	2100	N	0.1					
	45.8			1	2100	Y	1					
	5.1	3.2[c]		1	2100	N	0.8					
Clarkson and Deyes (2002)	101.5	51.0–203.0[a]		1	2100	Y	1	N	Y	Y	N	Y
Tol (2002a, b)	19.9			0	2150	N	1/12	N	Y	Y	Y	Y
	16.1			0	2150	Y	2/12					
	3.8			1	2150	N	2/12					
	6.6			1	2150	Y	4/12					
	−6.6			3	2150	N	1/12					
	−0.5			3	2150	Y	2/12					
Pearce (2003)	23.5	6.5–40.5[a]		1	2100	Y	1	Y	Y	Y	N	Y
Mendelsohn (2003)		1.0–2.0[a]		3	2100	N	1	N	Y	N	N	N
Newell and Pizer (2003)	5.7		4		2400	N	0.10	Y	N	Y	N	Y
	10.4		4[e]		2400	N	0.20					
	6.5		4[f]		2400	N	0.20					
	21.7		2		2400	N	0.05					
	33.8		2[e]		2400	N	0.10					
	23.3		2[f]		2400	N	0.10					
	1.5		7		2400	N	0.05					
	2.9		7[e]		2400	N	0.10					
	1.8		7[f]		2400	N	0.10					
Arithmetic mean	97	203[c]										
Author weights	122	320[c]										
Quality weights	86	86[c]										
Peer-reviewed only	43	43[c]										

C. Est., central estimate; Unc. range, uncertainty range; CDR, Consumption discount rate; PRTP pure rate of time preference; TH, time horizon; EW, equity weighted; AW, author weight; PR, peer-reviewed; New, new impact study; MC, marginal cost methodology; Dyn, dynamic impact study; Scen, realistic climate scenario.

[a] 90% confidence interval.

[b] 80% confidence interval.

[c] Standard deviation.

[d] The discount rate falls over time; the initial discount rate is specified.

[e] The discount rate falls over time according to a random walk model; the initial discount rate is specified.

[f] The discount rate falls over time according to a mean-reverting model; the initial discount rate is specified.

the simple average is calculated. The advantage is that this is "objective", the disadvantage is that studies which report alternative estimates count more. Secondly, each study is given equal weight—with the exception of Eyre et al. (1999), Hope and Maul (1996), and Tol and Downing (2000), which report results from two independent models and therefore receive a double weight. For those studies that report alternative estimates, I distributed the weight according to the preference expressed by the original author(s). Thirdly, I added

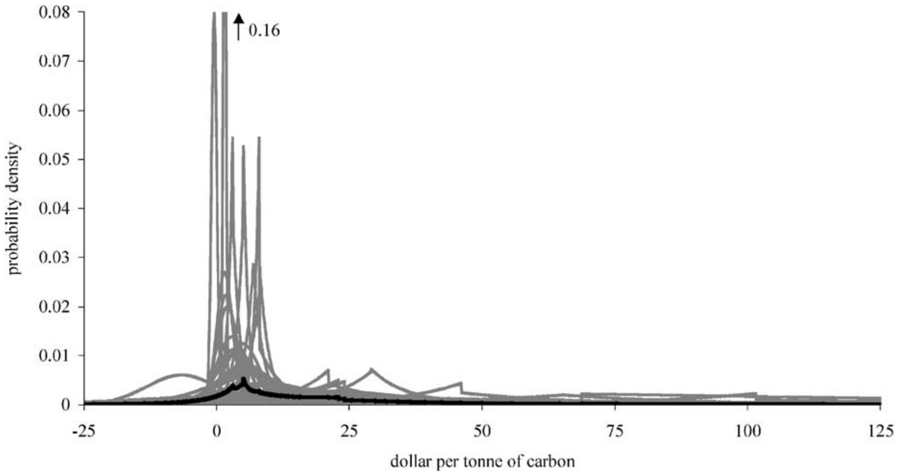

Fig. 1. The probability density functions of the 103 estimates of the marginal costs of carbon dioxide emissions (gray) and the composite probability density function (black).

subjective quality weights. These consist of five criteria. Is the study peer-reviewed? Is the study based on an independent impact assessment? Is the study based on dynamic climate change scenario? Is the study based on economic scenarios? Does the study estimate the marginal damage costs (rather than average costs)? The maximum score is five, the minimum is zero. In addition, I add the age of the study, with 0.1 points per year since 1990. Fourthly, the same weights are used but only peer-reviewed studies are included. These four alternative weightings serve also as a sensitivity analysis.

The mean of estimates is \$97/tC, with a standard deviation of \$203/tC. Using the author-weights, the mean is \$122/tC, with a standard deviation of \$320/tC. The explanation of this increase is that some studies (Azar and Sterner, 1996; Tol, 1999) deliberately reproduce the low estimates of Nordhaus (1994) and then argue that his assumptions are biased downwards. The quality-weights result in a mean of \$86/tC, with a standard deviation of \$249/tC. Clearly, some of the highest estimates are based on faulty methods (e.g., Hohmeyer and Gaertner, 1992). Excluding the studies that were not reviewed,[2] the mean is \$43/tC, with a standard deviation of \$83/tC. The highest estimates are in the grey literature.

Some studies report standard deviations, confidence intervals or even an entire probability density. Most studies, however, report only a "best guess". For those studies, I assumed that they are distributed normally, with the standard deviation equal to (the absolute value of) the mean. For studies that report a standard deviation, I also assume the distribution is normal. For studies that report a confidence interval, I use a combined exponential and negative exponential distribution—with the middle of the interval if no best guess is reported.

Fig. 1 shows the 103 probability density functions. It also contains a composite probability density function. The composite probability density function is based on "vote counting". For each interval of marginal damage costs,[3] each study gives a vote, corresponding to the relative probability in each study; the composite use the same "quality" weights as above.

Fig. 2 displays the same quality-weighted composite PDF as well as the composite PDF if only peer-reviewed studies are considered. Fig. 3 displays the corresponding cumulative density function. Table 3 shows some characteristics of the uncertainty. Both the table and the figures show that a substantial part of the larger cost estimates are in the so-called gray literature; the peer-reviewed work is less pessimistic about the impacts of climate change. The mean marginal damage cost, for instance, is \$50/tC in the peer-reviewed literature but \$93/tC in all literature (and \$129/tC without quality weighting).[4] The gray literature also contributes substantially to the large uncertainty. The 90-percentile marginal damage cost, for instance, is \$245/tC in the peer-reviewed literature but \$350/tC in all literature (and \$635/tC without quality weighting).

The mode of the quality-weighted PDF is \$1.5/tC, and the same value obtains for many variations. The source of this number is Mendelsohn (2003), who reports a remarkably narrow confidence interval of \$1–2/tC.

Table 3 also includes the characteristics of the composite probability density function if the coefficient of variation is not set at 1.0 for those studies that do not specify the uncertainty, but at 0.5 and 1.5. The

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[2] Or, more precisely, not published in peer-reviewed journals.

[3] The intervals varies between \$100/tC in the tails and \$0.1/tC in the inner reaches (−\$25/tC to \$125/tC). The PDFs are truncated at −\$5000/tC and \$100,000/tC.

[4] These means are calculated using the composite PDFs. The means reported above are calculated using only the best estimates of the respective studies. As some of the PDFs are asymmetric, the results differ.

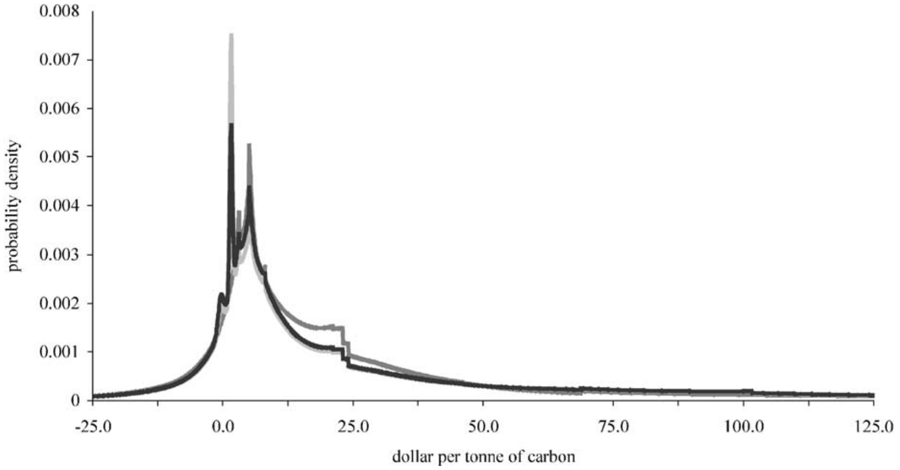

Fig. 2. The composite probability density function of the marginal costs of carbon dioxide using author weights (light gray), quality weights (black), and quality weights including peer-reviewed studies only (dark gray).

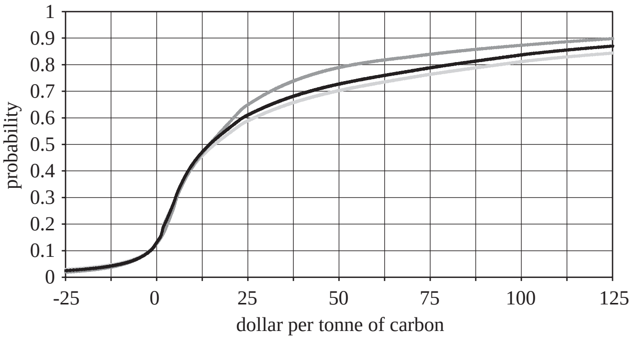

Fig. 3. The composite cumulative density function of the marginal costs of carbon dioxide, from bottom to top, using author weights (light gray), quality weights (black), and quality weights including peer-reviewed studies only.

Table 3
The probability characteristics of the marginal costs of carbon dioxide emissions ($/tC)

	Mode	Mean	5%	10%	Median	90%	95%
Base	1.5	93	−10	−2	14	165	350
Author-weights	1.5	129	−11	−2	16	220	635
Peer-reviewed only	5.0	50	−9	−2	14	125	245
CoV = 0.5	5.0	92	−1	2	17	160	345
CoV = 1.5	1.5	94	−25	−8	14	170	375
No equity weights	1.5	90	−8	−2	10	119	300
Equity weights	−0.5	101	−20	−2	54	250	395
PRTP = 3% only	1.5	16	−6	−2	7	35	62
PRTP = 1% only	4.7	51	−14	−2	33	125	165
PRTP ⩽ 0% only	6.9	261	−24	−2	39	755	1610

composite probability density function is robust against such variations.

5. Interpretation

Figs. 1 and 2 show an enormous uncertainty. Much of this uncertainty is in fact due to two assumptions, viz.

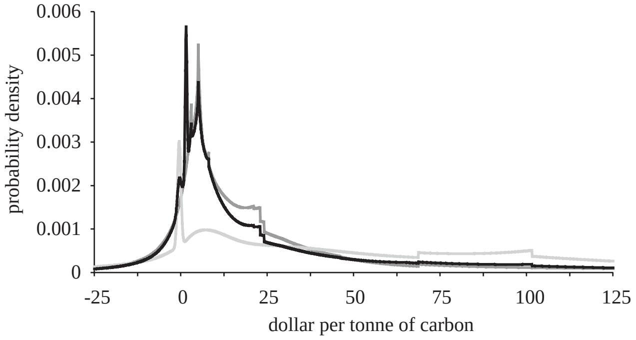

Fig. 4. Composite probability density function, author weighted, for all studies (black), for all studies using equity weights (light gray, early peak, fat tail) and for all studies without equity weighting (dark gray, shallow tail).

the discount rate and the aggregation of monetized impacts over countries. Azar and Sterner (1996) and Tol (1999) report extensive sensitivity analyses about this. Limiting our sample to these two studies, we estimate the following relationship:

$$MC = \underset{(126)}{-405} + \underset{(62)}{187}\,PRTP - \underset{(0.03)}{0.10}\,PRTP \times TH + \underset{(0.05)}{0.22}\,TH + \underset{(31)}{106}\,EW; R^2 = 0.67; N = 31 \quad (1)$$

where MC is marginal damage costs, $PRTP$ is pure rate of time preference, TH is time horizon and EW is a dummy for equity weighting. All parameter estimates deviate significantly from zero at the 5% level. With a time horizon of 2100, the marginal damage cost estimate falls by $23/tC for every 1% increase in $PRTP$. Equity weighting adds some $106/tC to the marginal damage cost estimate. This is only valid for a limited sample of the data, though. Let us look at all data.

Fig. 4 shows the probability density functions of the marginal damage costs of carbon dioxide emissions for those studies with and those studies without equity

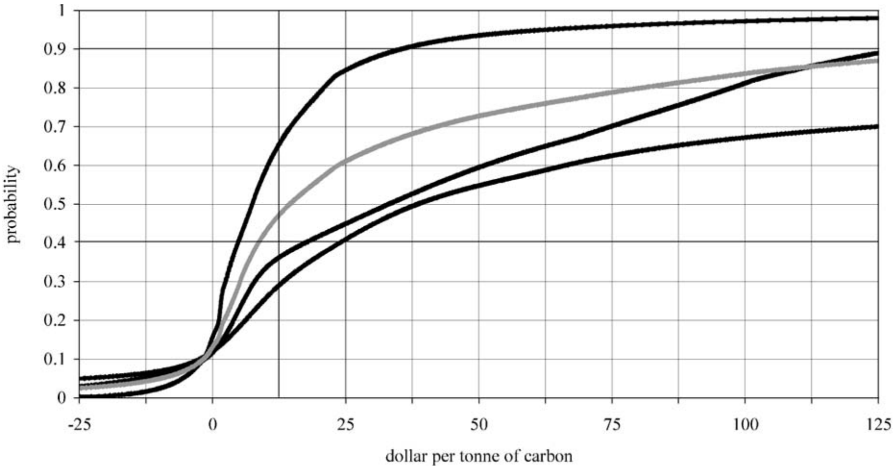

Fig. 5. Composite cumulative density function, author weighted, for all studies (gray) and for those studies that use a 3%, 1%, and 0% pure rate of time preference (black, in order of decreasing steepness).

weighting. Although the mode and expectation do not differ much, the studies with equity weighting clearly put a lot more weight on high marginal damage costs (cf. Table 3). The 90-percentile marginal damage cost, for instance, is \$395/tC with equity weighting but \$300/tC without.

Fig. 5 shows the cumulative density functions of the marginal damage costs for those studies with a 3% pure rate of time preference (or a 5% consumption discount rate), a 1% pure rate of time preference, and a 0% (or less) pure rate of time preference.[5] The effect is striking. Not only the expected value and the mode are lower for lower discount rates (the mode is \$2/tC for 3%, \$5/tC for 1%, and \$7/tC for 0% or less; cf. Table 3), but also the uncertainty is much reduced. The 90-percentile marginal damage cost, for instance, is \$62/tC for a 3% pure rate of time preference, \$165/tC for 1%, and \$1610/tC for 0% or less. In fact, both Fig. 5 and Table 3 show that the uncertainty about the marginal damage costs is largely driven by the discount rate, and the composite probability density functions (for all time preferences) behave as if the utility discount rate is somewhere in between 0 and 1%.

6. Conclusion

Actively working in the area of external costs of energy in general and climate change in particular, I am often confronted with people who argue that climate change is too uncertain to say anything about the marginal damage costs of carbon dioxide emissions. The uncertainties are indeed substantial, but not as large as these people think. This paper has made the following conclusions possible. First, there are no less than 28 studies of the marginal damage costs of carbon dioxide, authored by 18 independent (teams of) scholars, 12 of whom report original work on the underlying estimates of the economic impacts of climate change. These studies contain a total of 103 estimates, including a wide array of sensitivity analysis. There is therefore an empirical basis, albeit a small one.

If we take all studies without discriminating between them, the best guess for the marginal damage costs of carbon dioxide emissions is $5/tC, but the mean is $104/tC. This difference reflects the large uncertainty combined with the notion that negative surprises are more likely than positive ones.

However, there are good reasons to discriminate between studies, and this has a systematic effect on the combined marginal damage cost estimate. It appears that studies with better methods yield lower estimates with smaller uncertainties than do studies with worse methods. If one excludes the studies in the gray literature, the combined marginal damage cost estimate falls further, and so does its uncertainty. It seems as if the most pessimistic estimates of climate change impacts do not withstand a quality test. Alternatively, referees may have blocked publication of results that are too far out of the consensus range. There are two "ethical" parameters that flow into a marginal damage cost estimate. The first is the aggregation over time (the discount rate). The second is the aggregation over countries (equity weighing). Equity weighing leads to a higher estimate of the marginal damage costs and particularly to greater uncertainty (Tol, 2003; Yohe, 2003). Although equity weighing is theoretically sound (Fankhauser et al., 1997, 1998), it does pose an idealized worldview on the estimates. In reality, the rich do not reveal as much concern for the poor as is implied by the equity weights used in the various models.

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[5] Recently, it has been argued that the pure rate of time preference should fall over time (Gollier, 2002a,b; Weitzman, 1998). This argument has been taken up by only 2 of the marginal damage costs studies, viz. Nordhaus and Boyer (2000) and Newell and Pizer (2003, 2004).

The discount rate has an even starker influence on the central estimate but particularly on the uncertainty. If we use a pure rate of time preference of 3%—corresponding to a social rate of discount of 4–5%, close to what most western governments use for most long term investments—the combined mean estimate is \$16/tC, not exceeding \$62/tC with a probability of 95%. Lower social rates of discount lead to higher estimates but particularly to greater uncertainty, but even for a 1% pure rate to time preference the combined mean is \$51/tC. Even lower discount rates may be morally preferable, but are clearly out of line with common practice.

One can therefore safely say that, for all practical purposes, climate change impacts may be very uncertain but is unlikely that the marginal damage costs of carbon dioxide emissions exceed \$50/tC and are likely to be substantially smaller than that.

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