Applying risk analytic techniques to the integrated assessment of climate policy benefits

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1. Introduction

Integrated assessment of climate policy aims to examine adaptation and mitigation in a single framework within which it is possible to assess how best to cope with climate change risks. This task is commonly undertaken in a modelling context wherein integrated assessment models (IAMs) link simplified representations of climate change and its impacts with similarly simple representative macro-economic structures designed to simulate the interactions between energy production and the economy. Most of the focus on IAMs has been to balance the short-term costs of mitigating climate change against simplified damage relationships linked to various levels of global warming distributed well into the future. More detailed examinations of the site-specific and path-dependent diversity of climate-related damages and therefore the benefits that can be attributed to climate policies have thus far received less attention.

The IAM community contains two main schools of thought on how climate change risks could be managed within the international policy environment. One school suggests that the decision on whether to act on climate change through the setting of targets be made on the basis of expert judgement by policymakers involving the use, to some degree, of the precautionary principle to set targets that are themselves defined by the thresholds of avoiding dangerous anthropogenic inference with the climate system. The other school believes that the decision on the timing and magnitude of measures should be based on economic efficiency, usually portrayed in terms of formalised cost-benefit analyses. Policy positions also reflect these schools of thought. Several countries have eschewed applying the precautionary principle to set targets and will not commit themselves to action until they are assured that the economic risks of acting are negligible.

Tol and Yohe (2006) argue that the relative applicability of these two approaches depends in large measure on the degree of uncertainty with which we view the future. The cost-benefit approach, more specifically, relies critically on the assumption that marginal costs and benefits, as well as absolute costs and benefits, are finite. When this condition cannot be guaranteed, and Tol (2003) suggests that it cannot if equity weights and Ramsey discounting are employed, then the appropriate context within which to examine climate policy involves some sort of risk-management approach, multiple policy tools as described in Yohe (2003), or both. In addition, Yohe (2006) points to the difficulty in summing local impacts, net of adaptation, across the diversity of locations across the globe – an essential requirement of representing the benefit side to mitigation. He concludes that this second source of profound uncertainty also points to the need to confront the combined issue of mitigation and adaptation from a risk-management perspective. Nonetheless, he emphasized that strict application of the precautionary approach is but one choice in the arsenal of risk-management tools.

It is equally important to note that both approaches rely on IAMs, although they use them somewhat differently. A precautionary tact incorporates a combination of direct and indirect costs, but assesses non-market impacts (e.g. species loss, risk of irreversible impacts, risk of large-scale singularities) separately. A cost-benefit calculation, meanwhile, seeks to incorporate all possible costs into a monetary framework in order to make an optimal, or at least rational, decision on climate change. The differences are mainly to do with the relative emphasis placed on risk. The first approach is most sensitive to longer-term impact risks and the latter to shorter-term economic risks. The major limitations in both approaches are, however, the same. Damages are not well developed in IAMs; nor are IAMs well structured to manage significant uncertainties within the process they represent. Therefore, improving uncertainty management and an understanding of how climate damages can be assessed will allow both points of view to be better investigated.

This paper builds on earlier work on managing climate change risks (Jones, 2004) that contributed to the first Benefits of Climate Policy project (Corfee-Morlot and Agrawal, 2004). This earlier work utilised risk assessment methods to show how impacts and adaptation, which are highly scale-dependent, might best be aggregated into a global benefits framework. Here we build on subsequent advances in risk assessment, including those from Downing et al. (2005) and Watkiss et al. (2005) on measuring the uncertainty in assessing the social cost of carbon, the uncertainty analysis of outcomes undertaken using IAMs by Hope (2006) and Tol (2005) combined with probabilistic approaches to measuring probability over threshold at a range of scales (Mastrandrea and Schneider, 2004; Wigley, 2004; Jones 2004a and others). Our intent is to offer a proof of concept paper designed to show how existing risk analysis tools can overcome the significant complexities that enormous diversity and dramatic uncertainty about abrupt climate change and/or abrupt climate impacts bring to bear on climate policy deliberations.

More specifically, we use guided sensitivity analysis to explore how marginal impact damages may relate to potential benefits within a risk management framework and explore how risk weighting might be applied to assess those damages and represent the derivative benefits of avoiding those damages. Our approach is adapted from the simple probabilistic model linking emissions to global warming described in Jones (2004a and 2004b). Relationships between greenhouse gas emissions, radiative forcing and global warming are linked to prior distributions of uncertainty for CO_2 emissions, non-CO_2 radiative forcing and climate sensitivity to produce a probability density function for global mean temperature in 2100. To this structure we add impact damage curves derived from the research literature, a tool designed to assess marginal differences between policy and reference scenarios, and another tool designed relate the resultant damage curves back to annual emissions to assess the cost of CO_2 emissions.

Section 2 begins our discussion with a quick review of the structure of climate risks and how integrated assessors have tried to cope with them. Section 3 refers to work by Downing et al. (2005) to argue that much of the real action in climate risk is still missing from their work. A fourth section describes representations of four economic and four biophysical contexts within which we will illustrate our application of risk-analytic tools. Section 5 describes how to compare these representations of damages to estimates of the probability of exceeding given levels of global warming by a specific point in time (the year 2100). We then compute risk-weighted marginal costs and risk-weighted marginal benefits for our range of representative damages in 2100 in Section 6 before testing the sensitivity of these metrics to a Kyoto-like reduction in emissions in Section 7. The concluding section of discussion tries to provide context for our approach both in the research enterprise and the decision-analytic world of climate policy deliberation.

2. The structure of climate change risks

Figure 1 from Jones (2004) shows how adaptation and mitigation deal with the different aspects of climate change risk. The right hand side of the figure relates the consequences of climate change to the likelihood of exceeding specific levels of global warming. Derived from Smith et al. (2001)’s construction of the Five Reasons for Concern, it shows that low levels of climate change are likely to be exceeded but that the impacts will be negative in only some cases. High levels of warming are less likely to be exceeded over the near to middle term, but negative consequences are likely to be more widespread and more severe. This conclusion was robust across a wide range of probability distribution of input uncertainties, but more recent work summarized in Warren (2006) has indicated that the thresholds of significant impacts are now thought to be lower than presented in 2001. Moreover, Schlesinger et al. (2006) suggest that the top entry on the right side, where extreme events are noted with low probability above 6°C warming, may now be extremely misleading. Their work shows that the likelihood of a collapse of the Atlantic thermohaline circulation could be as high as 50% with 2 degrees of additional warming from 1990 levels. Similar increases in sensitivity have been proposed for melting of the Greenland Ice-sheet.

The range of mean global warming under the non-greenhouse gas policy SRES scenarios is shown in the left-hand graph of Figure 1. Adaptation will be most beneficial to activities that are vulnerable to current climate and likely to be worsened under climate change and those that are likely to be affected under small to modest increases in global warming. Adaptations to larger warmings will be difficult and costly, needing to cover a larger number of activities and a larger range of change in any single activity. Adaptation for critical outcomes exceeded under larger warmings could only be contemplated if the benefits without climate change were large and/or the consequences of not adapting were severe. The most optimal range of warming for adaptation is the lower shaded zone; and it is up to mitigation to work to keep us in or close to that zone.

Regardless of the precise location of the boundaries of managing climate risk by mitigation and adaptation, the boundaries and time-scales of Figure 1 teach us that the complementary effects of adaptation and mitigation must be examined within a framework that can accommodate significant complexities of scale and scope. Mitigation and adaptation are, quite simply and fundamentally, different for a variety of reasons:

1. They manage different parts of the risk: mitigation reduces the likelihood and magnitude of specific climate-related hazards and their resultant impacts; adaptation reduces the consequences of those impacts.

2. They manage risk in different parts of the potential climate change envelope: mitigation reduces the likelihood of changes in the upper tails of the plausible ranges of change; adaptation manages experienced or likely changes and is most likely to be effective within the tails of the plausible ranges.

3. They are effective over different timescales: adaptations are put in place and will have an effect when the conditions they are designed for ensue, usually within a specific planning period and frequently as manifest in climate variability; the benefits of mitigation extend into the relatively distant future since climate change responses take decades to centuries to cascade through the biophysical earth systems.

4. They are effective at different spatial scales: mitigation reduces climate change at the global scale because greenhouse gases are well-mixed in the atmosphere and changes in radiative forcing are expressed globally; adaptation is usually locally specific in terms of climate, impacts, the activity in question and people engaging in/with that activity.

Despite these differences, mitigation can reduce uncertainty within the planning horizon of adaptation programs; and successful adaptation can ease the pressure within which decisions about how and when to adjust mitigation programs as the future unfolds. It follows that strong mechanisms exist for adaptation and mitigation to complement one another in a strict economic sense: more of one makes the other more productive.

These encouraging observations notwithstanding, the complexities depicted in Figure 1 have lead integrated assessment modellers to rely on a host of other assessments when they try to link the climate system with an economic system across differences in scale and scope; i.e., they turn to assessments that investigate a range of activities at their appropriate scale and try to span the differences with sets of simplified and usually empirically estimated relationships. Even if a fully integrated model of climate and the economy were available, though, it would be so involved that its handler could investigate only a limited set of possible futures. The analyst would, therefore, be incapable of addressing the enormous range of policy and scientific uncertainties that bedevil the climate change issue.

Researchers have generally tried to quantify this uncertainty and cope with this complexity in one of two ways. In the first, a specific model is run repeatedly using large set of initial conditions and underlying drivers of future activity to produces ranges of outcomes that are then aggregated in some manner. This has been the tact of, amongst others, Yohe and Schlesinger (1998), Webster et al. (2003), Hope (2006) and Tol (2003). This is the method can accommodate most integrated models of simple to intermediate complexity. The second approach samples a set of ranges of interesting state variables individually and links them to a range of climate futures using very simple but nonetheless robust relationships (e.g. Jones, 2004a and b; Wigley, 2004). To work properly the second method requires even simpler relationships than the first. As a result, individual outcomes have limited utility, and the results only make sense if all are viewed together.

3. Integrating risk approaches

A limited number of risk assessments that aim to balance the costs of mitigation with the benefits of avoiding climate change damages have been published. For example, Mastrandrea and Schneider (2004) used the RICE economic model to assess the costs of avoiding dangerous climate change as defined by assumptions drawn from the IPCC Third Assessment Report. Webster et al. (2003) used an integrated model of intermediate complexity to quantify the likelihood of global warming in 2100, beginning with projections of population, economy and energy use. Jones (2004a & b) and Wigley (2004) both presented frameworks that probabilistically relate CO_2 concentrations at stabilisation with equilibrium temperature, but treat neither the costs of mitigation nor the benefits of avoiding damages. Yohe et al. (2006) tracked the likelihood of a collapse of the Atlantic thermohaline circulation over the next one or two centuries under a variety of mitigation assumptions using three alternative representations of underlying uncertainty in climate sensitivity and a simple ocean model.

Downing, et al. (2005) presented a semi-quantitative framework that relates the uncertainty in climate change and its impacts with the uncertainty in valuing the social cost of carbon that takes into account the cost of those impacts. They reviewed how a range of uncertainties, including those mentioned above, influence the limitations and outcomes of integrated assessment modelling. Table 1 shows how IAMs have so far managed to cover the ranges of uncertainty across climate and valuation. We have altered the climate categories slightly from those proposed by Downing et al. (2005) because mean climate, climate variability and extremes, and system changes and singularities are directly related to the ease of quantifying uncertainty within both climate and its impacts and also to successively higher levels of cost (benefit). For example, while it is relatively straightforward to model climate as a regulated series of incremental changes in mean climate (so that the economic response is “smooth”), most of the economic response to climate change will, in reality, be due to changes in variability and extremes (including large-scale singularities) which are much more difficult to quantify.

As in Downing, et al. (2005), the substantive boxes of Table 1 inter-relate two key uncertainties of climate and its impacts with valuation uncertainties; they are intended to suggest how much is known and adequately represented in integrated assessments. Most studies have been restricted to the upper left corner, with some progress in both a vertical and horizontal direction from that corner. However, little work has been done to contribute insight into the boxes that run along the diagonal; and even less is known about existence and bequest values – the boxes that lie along the right-hand side. We have currently have inadequate representations of climate change variability, minimal representations of abrupt change and singularities, minimal coverage of non-market costs, and no coverage beyond that.

It is, therefore, not a large stretch to conclude that current attempts to evaluate the costs of climate change significantly under-estimates climate damages (e.g. Watkiss et al., 2005). Nor is it difficult to argue that decisions made solely on the basis of economic outcomes are derived from a subset of the total climate impacts and responses. It remains to be seen how the interactions that have not yet be examined will turn out, and we do not claim to make progress in meeting that need, here. Instead, we continue to use results that are limited in their scope while the concepts described in Table 1 allow us to speculate that our method will be able to accommodate new knowledge calibrated across multiple metrics. We are also able to suggest how more detailed knowledge that will someday fill the lower right portion of Table 1 may affect the results.

4. Representing damages from economic and biophysical perspectives

Two representative sets of damage curves are used; one was drawn from the economic sphere, and the other catalogues four bio-physical impacts. The economic damage curves were derived from assessments undertaken by Nordhaus and Boyer (2000) and Nordhaus (2006), but they were altered as shown in the left-hand panel of Figure 2 to allow for linear, quadratic, or cubic relationships, on the one hand, or the sudden impacts of a significant singularity, on the other. The key assumption in anchoring all of these curves is that a 3°C increase in global mean average temperature will result in a 3°C decrease in GDP so that the linearity or curvatures of different cost curves are fixed on that point. This point was obtained by Nordhaus (2006) from his application of a Ricardian approach to a 1° × 1° with a scenario of warming and mid-continental drying. The result is population rather than output weighted, so it has some allowance for equity. It is, though, restricted to market impacts only. Although the estimates of economic impact for warming < 3°C are larger than for other studies (e.g. Tol et al., 2002; Mendelsohn and Williams, 2004), these estimates are still restricted to the upper left-hand corner of Table 1; i.e., they do not include abrupt events and rates of change that push the limits beyond the climate-economy equilibrium (Nordhaus, 2006). The highest warming for which damage functions were estimated by Nordhaus and Boyer (2000) was 6°C for which a decrease in global GDP of 10.1% was assigned. Therefore the quadratic curve posits a more negative relationship beyond 3°C. The step function combines a sigmoidal curve mimicking a long term response to a single event superimposed on a quadratic curve, producing an almost straight line. The linear and quadratic lines reflect monotonic damage curves constructed from mean changes in climate, while the more non-linear curves are more representative of changes in variability and extremes as they may affect a range of sectors and locations.

The biophysical damage curves were developed by Sheehan et al. (submitted) from the published scientific literature, covering damage as a function of increase in global mean temperature for critical thresholds of coral reef bleaching, risk of species extinction, slowdown in North Atlantic thermohaline circulation and the commencement of irreversible melting of the Greenland ice-sheet. The right-hand panel of Figure 2 displays them graphically. The threshold for coral reef bleaching measures the proportion of the Great Barrier Reef affected by thermal bleaching in 50% of all years. The species extinction curve denotes the number of species at risk of extinction because their bioclimatic envelope is likely to be completely separate from their current range; the upper part of the curve beyond 3°C warming relates to two studies in Australia, so is likely to be too sensitive and can only be related to endemic vertebrates from which these data were derived. The THC curve relates to the slowdown in north Atlantic Thermohaline circulation from the range of climate models described in IPCC (2001; chapter 9). More recent estimates suggest that freshwater melt from the Greenland Ice-sheet and other ice, and freshwater from increased continental runoff may render THC more sensitive than estimated from AOGCMs, but these interactions have not been incorporated into the analysis at this stage. The Greenland Ice-sheet curve relates to different estimates in the literature as to when the Greenland ice-sheet is likely to commence irreversible melting – and the most recent estimates indicate a greater sensitivity than those published previously (e.g. Hansen, 2005; Joughin, 2006). In any case, complete melting would produce approximately 5 to 6 meters of sea level rise across the globe. The associated rates of sea level rise are uncertain, since they will depend on the speed of melting before and after crossing the threshold of irreversibility.

It is important to note that the biophysical damage curves are largely insensitive to human adaptation, except perhaps for the risk of species extinction which can be increased or decreased by human activities. This is, of course, not the case for the economic damages curves. They include unspecific rates of adaptation, since Nordhaus (2006) did factor in some level of adaptation.

5. The probability of exceeding a given level of damage

To produce distributions of climate change through 2100, we compared the probabilities of various degrees of warming projected using the marker scenarios of the Special Report of Emission Scenarios (SRES; Nakiçenovic and Swart, 2000). The marker scenarios from the A1 Family: A1B, A1FI and A1T are used to define three upper limits of “no policy” warming scenarios. The probability of warming in 2100 was created from two factors: GHG and sulphate aerosol forcing (F), and climate sensitivity. Sensitivity ($\boldsymbol{T_s}$) is represented by the factor λ which is multiplied with radiative forcing (F), using a method similar to that applied by Schneider (2001). GHG forcing is closely related to atmospheric CO_2, which was obtained from IPCC (2001), and originally derived using the MAGICC simple climate model (Wigley, 2000). A simple, linear regression was created to estimate λ as in Equation (1), producing an r^2 value of 0.88 and standard error of 0.036. Global warming (T) is projected using Equation (2).

$$\lambda = 0.1086\, T_s + 0.1871 \qquad (1)$$

$$T = F\,\lambda \qquad (2)$$

Climate sensitivity is randomly sampled according to a probability distribution developed by Murphy et al. (2004), which has a 5/50/95 percentile distribution of 2.4/3.5/5.4°C for 2×pCO_2. It is possible to run this sample for a range of recent published sensitivity distributions – the resultant values will change but not the patterns of response. Forcing in Wm^{-2} is sampled uniformly in the average range produced from the six IPCC marker scenarios (IPCC, 2001), with the upper limit of A1FI, A1B, and A1T and lower limit of B1. The results were compiled from >60,000 random samples. The results, superimposed on the damage curves from Figure 2 are shown in Figure 3.

The results show the likelihood of exceeding either economic and biophysical impacts thresholds or targets under different emission regimes. In particular, it shows how key biophysical vulnerabilities are likely to be exceeded by 2100, but that this is not necessarily evident in the economic analyses available in the literature. The step function occurring at >3°C warming may reflect accumulating damages due to sea level rise from melting of the Greenland ice-sheet and loss of key ecosystems such as coral reefs, but we do not think that the curves in the left-hand panels adequately reflect the impacts in the right-hand panels.

We have, evidently, created a common framework that expresses consistently the monetary and non-monetary impacts of climate change damage curves expressed as a function of global warming. The different curves for GDP and key vulnerabilities extend along both the first column and top row of Table 1 where the monetary curves cover direct and some indirect damages. The biophysical damages meanwhile denote aspects where non-market and existence values come into play. We are therefore in a position to contrast monetary and non-monetary damages using an internally consistent approach. There is, of course, nothing special about the year 2100; comparable results could be produced for any benchmark year in the near or distant future. Our comparison, of course, leaves open the question of whether it is desirable to continue to try to monetise everything, as proponents of cost-benefit analysis would have us do. We have argued elsewhere, in agreement with others like Jacoby (2004), that diverse impacts are not commensurate and that we have pushed the cost-benefit approach perhaps as far as it can go. Nonetheless, our approach is sufficiently flexible to handle economic and non-economic numeraires.

6. Risk-weighting damage functions

Risk weighting (i.e., multiplying likelihood times consequence) offers the potential to contrast monetary with non-monetary losses portrayed in Figure 3 over a range of projected warming at a given date. Panel A of Table 2 shows the results of multiplying the probability density function of warming and the damage curves depicted in Figure 3. The results are estimated risk-weighted average damages whose sensitivity to alternative emissions scenarios can be tracked. Economic damages are expressed in percentage decrease in GDP; biophysical impacts are expressed either as percentage lost (for coral reefs and species extinctions) or chance of loss (for Greenland ice sheet and THC collapse). On the economic side, A1F1 produces the largest reductions in GDP and A1T the smallest; no surprise there. It is, though, important to note that the increase in economic losses between A1B and A1F1 are exaggerated (relative to the differences between A1T and A1B) for all but the linear case. On the biophysical side, though, the temperature at which a particular impact becomes critical becomes more important in contrasting emissions scenarios. Curves that are critical at around 1–2°C (e.g. coral reefs and initiation of Greenland ice-sheet melting) show only minimal changes between A1FI and A1T, whereas species extinction risk and THC slowdown curves both show significant gains that are not as large, relatively speaking, in the A1B to A1F1 comparison as the economic estimates. This demonstrates a point at which a particular level of mitigation may have little utility in terms of avoided damage for some sensitive sectors. It also illustrates graphically a texture in biophysical impacts that is not captured by economic aggregates.

Panel B of Table 2 show net present value (NPV) calculations for each of the economic damage curves; all were calculated for 1990 values using the UK Treasury Greenbook long term discount curves m(which begin at 3.5% and decreased to 2.5% after 75 years). Counter intuitively, the linear relationship between warming and GDP produced higher discounted losses than the non-linear curves, but this is because the linear relationship showed larger near-term damages for lower temperatures. However, when temperatures exceed the break point of 3°C, the situation turns around and the non-linear curves become more significant.

Risk-weighting shows the benefits of reducing emissions on climate-related risks can be significant where they reduce strongly reduce non-linear components of that risk. This implies that small cuts in greenhouse gases can potentially deliver significant benefits, providing the mitigation actions themselves are not short-lived. The results also show that gaining a better understanding of climate-related damages is critical to integrated assessment modelling – and that using simple curves of damages, in situations where strongly non-linearities are expected, will produce misleading results. In particular, knowing where damages become non-linear and how non-linear those damages are, is crucial. These conclusions are consistent with findings by Mastrandrea and Schneider (2004).

7. Testing risk weighted marginal costs and benefits

We can use our framework to test the efficacy of Kyoto Protocol-like reductions in greenhouse gases across the range of economic and geophysical numeraires by reducing emissions by 1 Gt C per year between 2010 and 2100. This reduces radiative forcing by 0.23 Wm^{-2} for a mid-range climate sensitivity, resulting in a decrease in temperature of approximately 0.1–0.3°C by 2100, similar to that produce by enforcing the Kyoto Protocol to 2100 (see Wigley, 1998). Reductions in CO_2 emitted are 4.1%, 6.1% and 8.5% for the A1FI, A1B and A1T scenarios, respectively. Not surprisingly, gains from this modest mitigation are highest where the gradient of change with respect to climate change is highest.

Table 3 shows the changes from Table 2. It also shows that the benefits are greatest when reducing impacts from higher temperatures. The risk-weighted benefits to GDP in percentage change appear very modest but actually exceed 5% of the total loss for most of the non-linear monetary outcomes. However, significant benefits are gained for both current and future generations when net future value is taken into account (not shown). Benefits for the biophysical damages are less consistent because they rely on whether critical levels of damage have been substantially exceeded by the range of warming being assessed. Substantial benefits are found for species extinction risk and less so for THC slowdown, but critical levels of damages for coral reefs and Greenland have been exceeded by such a degree, this small level of change is insufficient to produce substantial benefits on its own. However, it does help to bring critical threshold closer to the reach of future mitigation efforts.

8. Discussion

Most analyses of climate risk produce one scenario at a time and, utilising a range of input uncertainties to produce a large number of results, then compare those results. This produces the situation where some estimates of impact damages are low, and some are high. This sends the message to many that a choice needs to be made, and if one is risk averse to causing damage to the economy through making the wrong policy choice, then it is best to wait until that choice can be made. The recommendation that a precautionary approach be taken to applying a social cost of carbon in policy application (e.g. Watkiss et al., 2005) has not found favour in all quarters.

Here, we have applied an approach that integrates a range of plausible outcomes for several metrics of damage that includes economic and biophysical damage functions tied to key vulnerabilities. By explicitly including the risk of large system changes that we believe would result in significant economic damages but have not yet been adequately costed, we show that appreciable benefits can be gained by a modest amount of mitigation.

It also shows that although damages will build up over time, layer by layer as climate changes, building in successively deeper mitigation efforts will peel away the upper layer of risk out into the future. This image refers back to Figure 1. Mitigation reduces the upper limit of potential future warming, and thus reduces the greatest risks. Accounting for these using risk-weighted methods shows considerable benefits for quite modest efforts, as illustrated by the example in the previous section.

The damages building up from the lower level of the global warming envelope will need to be adapted to, to minimise losses from climate change that cannot be avoided. Some of this climate change is already occurring due to past emissions and near term emissions that cannot be avoided will ensure that some damage will be experienced in the future.

In this paper we have developed proof of concept examples for assessing risk weighted marginal damages and marginal benefits for climate change as an alternative to formalised cost-benefit analysis. Our work has built on the work of others in ways that may have stretched their applicability, but not at the expensive of demonstrating the utility of our approach. We have ignored non-CO_2 emissions; this means that total costs of emissions and different lifetimes in the atmosphere have not been incorporated into the analysis, but they could be. In addition, the annual costs of carbon have been assessed by assuming that an emission in a given year contributes directly to the entire temperature increase in that year. In reality, this ignores the delay between emissions and increases in surface air temperature which may be up to several decades. It also assumes that all CO_2 is maintained in the atmosphere so that, in effect, each tonne of CO_2 remains in the atmosphere and that decay is constant. The assumption can be maintained because it assumes that CO_2 is dispersed into a global atmospheric pool and therefore individual rates of sequestration have no effect on the outcome.

In this paper we have shown that, using risk-weighted marginal costs of climate damage, that modest reductions in greenhouse gases can produce significant benefits in terms of risks avoided. The analysis also shows that knowing how damage curves relate to the magnitude and rate (though we did not address the latter here) of climate change is critical information that is just as important as knowing the costs of abatement and sequestration.

Conclusion

Not written yet

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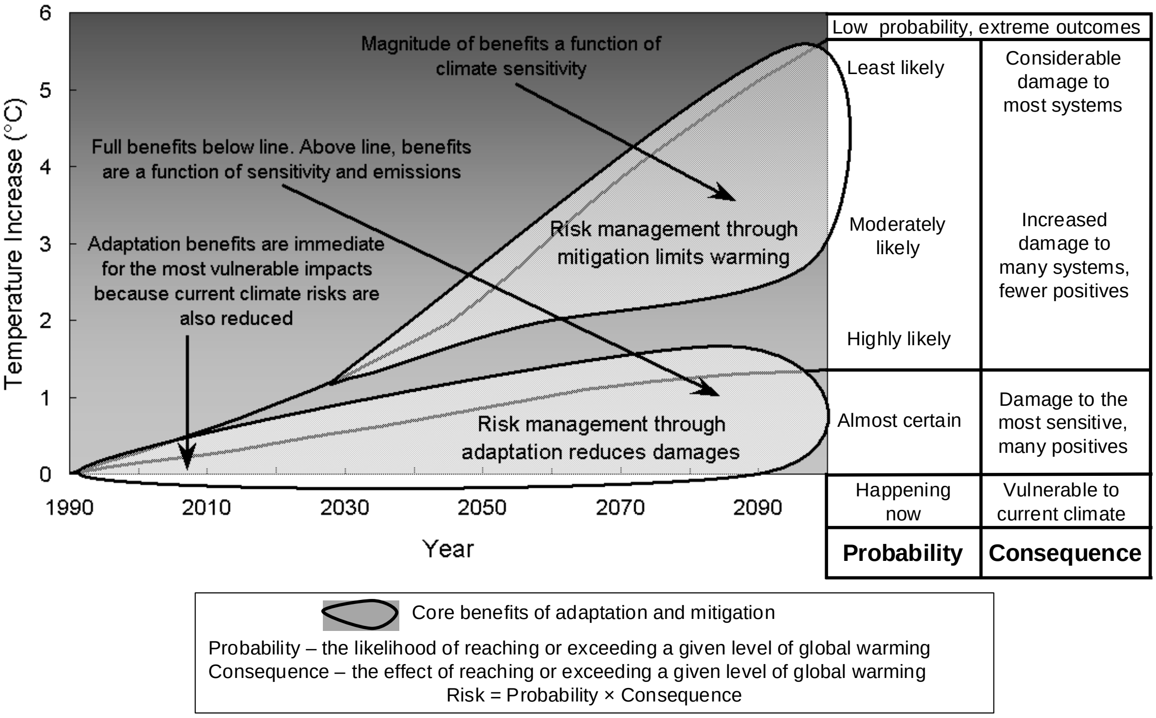

Probability	Consequence
Low probability, extreme outcomes	
Least likely Moderately likely Highly likely	Considerable damage to most systems Increased damage to many systems, fewer positives
Almost certain	Damage to the most sensitive, many positives
Happening now	Vulnerable to current climate

Core benefits of adaptation and mitigation

Probability – the likelihood of reaching or exceeding a given level of global warming
Consequence – the effect of reaching or exceeding a given level of global warming
Risk = Probability × Consequence

Figure 1. Synthesis of risk assessment approach to global warming. The left part of the figure shows global warming based on the six SRES greenhouse gas emission marker scenarios with the zones of maximum benefit for adaptation and mitigation. The right side shows likelihood based on threshold exceedance as a function of global warming and the consequences of global warming reaching that particular level based on the conclusions of IPCC WG II (Smith et al., 2001). Risk is a function of probability and consequence.

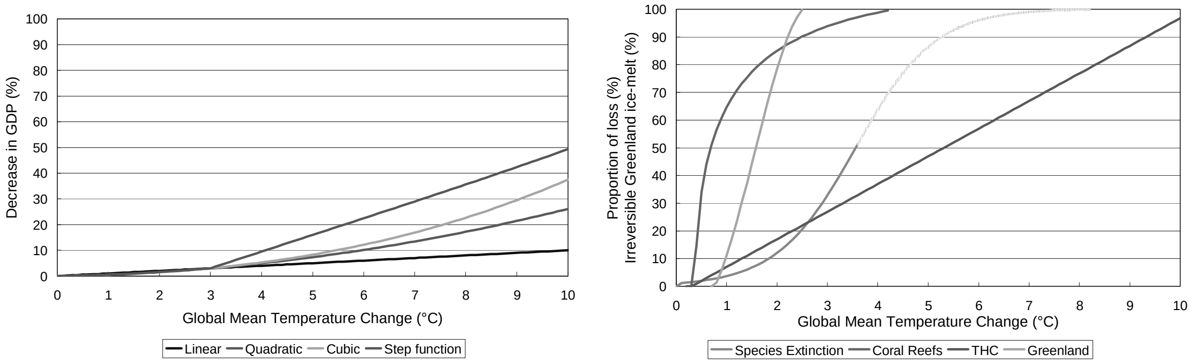

Figure 2. Damage curves as a function of global warming. Left panel: different conceptual damage curves for global impacts expressed as percentage decrease in global Gross Domestic Product (GDP). Right panel: damage curves for four key biophysical vulnerabilities: proportion of loss of coral reefs due to thermal bleaching, risk of species extinction, slowdown in North Atlantic thermohaline circulation and the probability if commencement of irreversible melting of the Greenland ice-sheet (from Sheehan et al., submitted).

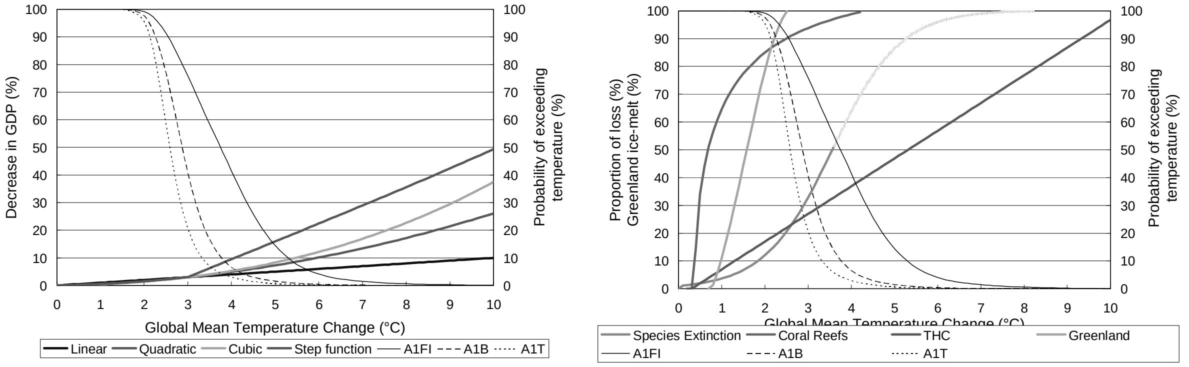

Figure 3. Likelihood of exceeding levels of mean global warming in 2100 assuming climate sensitivity from Murphy at al. (2004) and the SRES range of emissions scenarios with upper limits of A1FI, A1B and A1T superimposed on the damage curves from Figure 2.).

Table 1. Comparison of valuation and climate change uncertainties influencing the assessment of the social cost of carbon (adapted from Downing et al., 2005).

	Valuation uncertainties			
Climate change uncertainties		**Market (direct) value**	**Non-market (indirect use and options)**	**Existence and bequest value**
	Mean climate	Global studies	Some global studies (as WTP)	None
	Climate variability & extremes	Regional studies, some allowance in global studies	Some local and regional studies	None
	System changes & singularities	Few sensitivity studies	None	None

Table 2. Risk-weighted changes multiplying the risk of three ranges of warming for 2100 with upper limits of A1FI, A1B and A1T with four curves measuring economic loss to global GDP, and four curves measuring damages in biophysical systems. NPV in $1990 calculated from the A1 SRES GDP using the UK Treasury Greenbook long term discount curves.

Biophysical				
Scenario upper limit	Species	Coral Reefs	THC slow-down	Green-land ice sheet
	(% damage)			Chance of loss (%)
A1FI	54.6	97.3	36.1	99.3
A1B	31.2	94.5	27.2	98.3
A1T	25.1	92.3	24.3	96.7

Economic				
Scenario upper limit	Linear	Squared	Cubic	Step change
	(% decrease in GDP)			
A1FI	3.9	5.1	5.5	9.4
A1B	3.0	3.1	3.2	4.3
A1T	2.4	2.6	2.6	3.2
	(NPV $Trillion 1990)			
A1FI	68.3	53.1	74.2	131.6
A1B	49.2	35.1	46.2	57.1
A1T	43.6	30.1	38.8	44.8

Table 3. Benefits of a Kyoto Protocol-like reduction in greenhouse gases on risk-weighted damages for 2100 with upper limits of A1FI, A1B and A1T with four curves measuring economic loss to global GDP, and four curves measuring damages in biophysical systems. NPV in $1990 calculated from the A1 SRES GDP using the UK Treasury Greenbook long term discount curves.

Biophysical				
Scenario upper limit	Species	Coral Reefs	THC slow-down	Green-land ice sheet
	(% damage)			Chance of loss (%)
A1FI	-3.0	-0.4	-1.3	-0.4
A1B	-3.3	-0.8	-1.4	-1.1
A1T	-2.8	-0.9	-1.3	-2.0

Economic				
Scenario upper limit	Linear	Squared	Cubic	Step change
	(% decrease in GDP)			
A1FI	-0.1	-0.3	-0.4	-0.7
A1B	-0.1	-0.2	-0.3	-0.5
A1T	-0.1	-0.2	-0.2	-0.4
	(NPV $Trillion 1990)			
A1FI	-2.8	-2.7	-4.2	-11.6
A1B	-2.7	-2.3	-3.5	-5.6
A1T	-2.7	-2.3	-3.5	-5.6