IAJ The Integrated Assessment Journal
Bridging Sciences & Policy
Vol. 8, Iss. 1 (2008), Pp. 123–149

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

Roger Jones
CSIRO Marine and Atmospheric Research, PMB1 Aspendale, 3195, Australia *

Gary Yohe
Woodhouse/Sysco Professor of Economics, Wesleyan University, 238 Church St., Middletown, CT 06459 USA †

Abstract

The two main flavours of integrated climate change assessment (formal cost benefit analysis and the precautionary approach to assessing dangerous anthropogenic interference with the climate system) also reflect the major controversies in applying climate policy. In this assessment, we present an approach to using risk weighting that endeavours to bridge the gap between these two approaches. The likelihood of damage in 2100 to four representative economic damage curves and four biophysical damage curves according to global mean warming in 2100 is assessed for a range of emissions futures. We show that no matter which future is followed, the application of climate policy through mitigation will reduce the most damaging outcomes first. By accounting for the range of plausible risks, the benefit of mitigation can be substantial for even small reductions in emissions. Disparate impacts calibrated across multiple metrics can be displayed in a common format, allowing monetary and non-monetary impacts and benefits to be assessed within a single framework. The applicability of the framework over a wide range of climate scenarios, and its ability to function with a range of different input information (e.g. climate sensitivity) also shows that it can be used to incorporate new or updated information without losing its basic integrity.

Keywords: Integrated assessment, climate change, risk assessment, modelling

1 Introduction

Many integrated assessments of climate policy have focused on creating a single framework within which it is possible to assess how best to cope with the risks

*Corresponding Author. E-mail: Roger.Jones@csiro.au
†E-mail: gyohe@wesleyan.edu

associated with climate change. Integrated assessment models (IAMs) have been designed for this purpose. They typically link simplified representations of the climate system with similarly simplified representations of macro-economic structures. The former are intended to capture the essential characteristics of how increasing concentrations of greenhouse gases impact the planet; the latter are designed to simulate the interactions between energy production and the economy. When exercised together, these two components allow integrated assessors to explore how one might balance the short-term costs of mitigating climate change against the longer term but potentially serious damages associated with various levels of global warming. These damages are, of course, the implications of "dangerous anthropogenic interference with the climate system" which the United Nations Framework Convention on Climate Change (UNFCCC) aims to avoid, but the state of the art has not progressed to the point where the details of the spatial, temporal and path dependent aspects of climate-related damages can be included in the models. Because the devil is in the details, it follows that integrated assessments fall well short in their attempts to account fully for the benefits that could be attributed to climate policies.

The community of integrated assessors is not, however, discouraged by this shortcoming; progress is being made in both expanding global coverage and developing decision criteria that can cope with missing data. Nor is the IA community completely homogeneous. At least two main schools of thought on how climate change risks should be managed within the international policy environment can be identified. One school suggests that the decision on whether to act on climate change should be made on the basis of expert judgement by policymakers who, to some degree, apply some variant of the precautionary principle to set concentration or temperature targets—the thresholds that define the "dangerous anthropogenic inference" that must be avoided. The other school believes that the decision on the timing and magnitude of measures should be based on economic efficiency; the precise definition of what is or is not "dangerous interference" is, for them, still decades away. While proponents of the precautionary approach have not shied away from setting specific thresholds (and frequently apply cost-effectiveness criteria to their attempts to avoid them), proponents of the efficiency approach have typically relied on formal cost-benefit calculations in their work.

The policy positions of various actors on the international negotiating stage also reflect these schools of thought, of course. Several countries, like the United States and Australia, have eschewed applying the precautionary principle to climate risks; their position is that they will not commit themselves to near-term action until they are assured that the economic risks of acting are negligible or that the risks of not acting are large. Other countries and sub-national units, like some members of the European Union, California, and the New England states, have looked with alarm at the risks associated with abrupt change and an observed increase in the frequency of extreme events. They have responded to these perceived risks by agreeing to design climate policy targeted at specific temperature thresholds; and in their negotiations with one another, the economic cost presents the lesser risk.

(Tol & Yohe, 2007) argue that the relative applicability of these two approaches to the climate problem depends in large measure on the degree of uncertainty with which we view the future as well as the degree to which we are comfortable with the compensation assumptions underlying cost-benefit calculations. The cost-benefit approach 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. This is, of course, an essential requirement of representing the benefit side to mitigation, and so he points to the need to confront the combined issue of mitigation and adaptation from a risk-management perspective. Nonetheless, he emphasizes that strict application of the precautionary approach is but one extreme version of risk-management; it is also an extreme version of cost-benefit analysis with a maximin criterion. Other versions, anchored squarely on first principles of economic efficiency, exist in other fields; and it is becoming increasing clear that their applicability to the climate arena should be explored.

It is equally important to note that IAMs support the application of both approaches. A precautionary tack incorporates a combination of direct and indirect costs, but assesses non-market impacts and impacts calibrated in alternative metrics separately; of course, representations of both are derived from IAMs. A cost-benefit calculation, meanwhile, seeks to incorporate all possible costs and benefits drawn from IAMs into a monetary framework in order to make an optimal, or at least rational, decision on climate change. The precautionary approach is therefore more sensitive to longer-term impact risks while the cost-benefit approach, given its reliance on discounting, attaches more significance to shorter-term economic risks. Action using a cost-benefit approach is delayed until knowledge of the optimal path outweighs the risk of acting before the optimal pathway becomes known, whereas the precautionary principal is exercised to keep climate impacts at "safe" levels, measured using a range of criteria drawn from Article 2 of the UNFCCC (Jones & Preston, 2006). Neither strategy is acceptable to staunch advocates of the opposing strategy.

Both approaches are, however, also challenged by the same limitations in their application of IAMs. The details underlying damage calculations derived from vulnerabilities that depend on specific exposures and sensitivities are not well developed in IAMs; nor are they well structured to manage significant uncertainties and abrupt changes in the processes they represent. It follows immediately that improving uncertainty management and our understanding of how climate damages can be assessed would improve the abilities of both points of view to confront the climate problem; but this is another long term research agenda in and of itself.

Figure 1 offers a simple portrait of the context within which this diversity of views plays itself out and suggests why it is important. The left axis calibrates the cost of mitigation (from low to high as you move up the axis) while the bottom axis does the same for the likelihood of dangerous anthropogenic inference (DAI). Two aspects of this diagram are important: one is that if both the costs of mitigation and the levels of impact damages were known (subject to future emission rates), a range of 'rational' strategies establishing a balance between the two could be proposed. However, due to the large uncertainties associated with both axes, the perception of different risks dominates the policy debate.

Decision-makers who are averse to economic risk with high economic discount rates (so future risks associated with climate change impacts do not loom large in the decision calculus) would place higher weight on the cost of mitigation in their deliberations. Decision-makers who are averse to climate risk with low discount rates (so future risks associated with climate change do loom large in the decision calculus) would place higher weight on potential damaging impacts in their considerations.

If both costs of mitigation and damages were low, the lower left region near the origin of Figure 1 would be a comfortable location that could sustain productive conversation between practitioners from both camps even now. There would be time to wait from either perspective. Research would be encouraged without apology; and only modest, economically benign mitigation would be warranted. Unfortunately, there is no guarantee that either "mother Nature" or Adam Smith's "invisible hand" has placed us in the comfort zone where Strategy I would be appropriate. Outside that zone, however, conversation between the camps is severely hampered by the absence of a common language with which to express competing concerns about the economic consequences of climate change and climate policy, on the one hand, and the environmental consequences of climate change (calibrated in a multiplicity of non-currency metrics), on the other. Indeed, policy deliberations in the competing views zone require an analytical approach capable of supporting comparable portraits of the economic and non-economic components of climate risks that are so important to the application of the two decision criteria.

This paper offers a small step towards such an integrating approach. It builds on earlier work by Jones (2004*b*) that exercised risk assessment methods to show how impacts and adaptation, which are highly scale-dependent, might best be aggregated into a global benefits framework. It builds, as well, on subsequent advances in risk assessment by Downing & Watkiss (2003), Downing et al. (2005) and Watkiss et al. (2005) (who contributed to measuring the uncertainty in assessing the social cost of carbon), by Hope (2006) and Tol (2005) (who used updated IAMs to conduct new rounds of uncertainty analyses), and by Mastandrea & Schneider (2004*b*,*a*), Wigley (2004), Jones (2004*a*) and others (who applied probabilistic approaches to measuring the likelihoods of crossing critical thresholds at various scales). 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 of impact metrics and dramatic uncertainty about abrupt climate change and/or abrupt climate impacts bring to bear on climate policy deliberations. Our purpose is therefore to construct a common framework within which the sensitivities of a wide range of vulner-

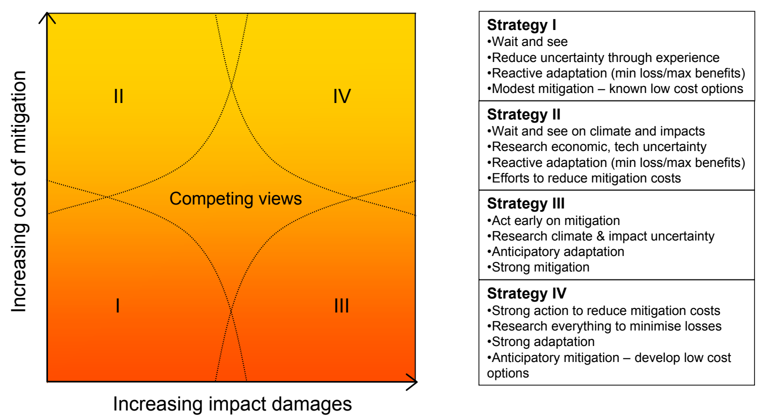


Figure 1: A schematic portrait of alternative risks. This matrix suggests how the costs of mitigation play against increasing impact damages. The axes represent two aspects of risk: increasing costs of mitigation as opposed to increasing impact damages. Risks along both axes are understood through formal assessment, which are highly uncertain, and the perception of risk. Competing views surround such perceptions, the extremes being those who are risk averse towards economic damage and have a fast rate of time preference, and those who are risk averse to environmental damage and have a slow rate of time preference. The former tend to perveive risks to the economy as being high and the later perceive the risk to the environment as being high. The strategies on the right are what a balanced assessment of economic costs and the benefits of avoided damage would suggest. Presently, most of this matrix is highly contested.

abilities when underlying exposure is contingent on various levels of mitigation (from no action to dramatic emissions reductions in the near term) can be clearly portrayed and easily compared.

More specifically, we use sensitivity analysis to explore how risk weighting might be applied to assess climate risks and represent the benefits of avoiding their associated damages. Our approach is adapted from the simple probabilistic model linking emissions to global warming described in Jones (2004*a*,*b*). 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. We add impact damage curves derived from the research literature to this structure so that differences between policy and reference scenarios can be assessed regardless of the metric and the units by which damages are measured.

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 agrees with Downing & Watkiss (2003) in arguing that much of the real action in climate risk is still missing from integrated assessments. Section 4 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 (taken to be the year 2100 for the sake of illustration). We then compute risk-weighted costs and risk-weighted 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. Section 8 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 2 (taken from Jones (2004*b*)) 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 the Intergovernmental Panel on Climate Change (2001*b*, Chapter 19) 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.

The range of mean global warming under the non-greenhouse gas policy SRES scenarios is shown in the left-hand graph of Figure 2. Adaptation to

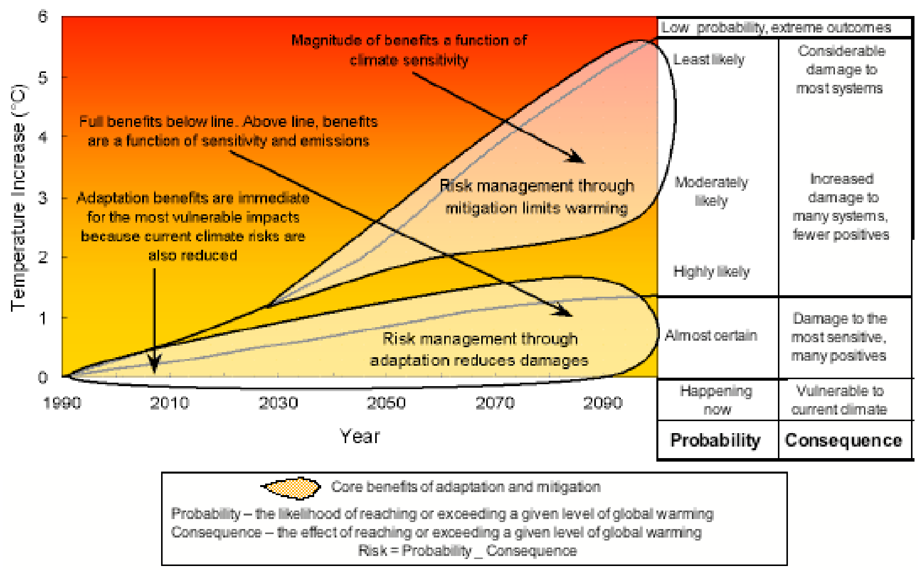


Figure 2: Synthesis of risk assessment approach to global warming. The left part of the figure shows global warming based on the six SRES greenhouse gas emission marker scenarios with the zones of maximum benefit for adaptation and mitigation. The right side shows likelihood based on threshold exceedance as a function of global warming and the consequences of global warming reaching that particular level based on the conclusions of Intergovernmental Panel on Climate Change (2001*b*, Chapter 19). Risk is a function of probability and consequence (Jones, 2004*b*).

climate risk 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 (Intergovernmental Panel on Climate Change, 2001*b*, 2007*b*). Trying to adapt to critical outcomes driven by larger warmings could only be attempted if the benefits without climate change were otherwise large and/or the consequences of not adapting to specific risks were severe. The least troublesome 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 2 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 sensitivity and perhaps exposure to 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 lower 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 (and others noted in Klein et al. (2005), Füssel & Klein (2006) and Tol (2005)), 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 what 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 2 have led integrated assessment modellers to rely on a host of other assessments when they try to link a representation of the climate system with a model of an economic system; 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. See, for a recent example, Warren (2006) in support of Stern (2007). 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 hard-pressed to address 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 approach of, amongst others, Yohe & Schlesinger (1998), Webster et al. (2003), Hope (2006) and Tol (2003). This 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 experimentally robust[1] relationships; see, for example, Jones (2004*a*,*b*) or Wigley (2004), so, the second method requires even simpler relationships than the first. This shifts the emphasis from showing results of single scenarios to displaying a probability distribution produced from a range of underlying probability distributions that ideally, incorporate the most important sources of contributing uncertainty.

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, Mastandrea & Schneider (2004*b*) used the DICE 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 (2004*a*,*b*); 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 (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

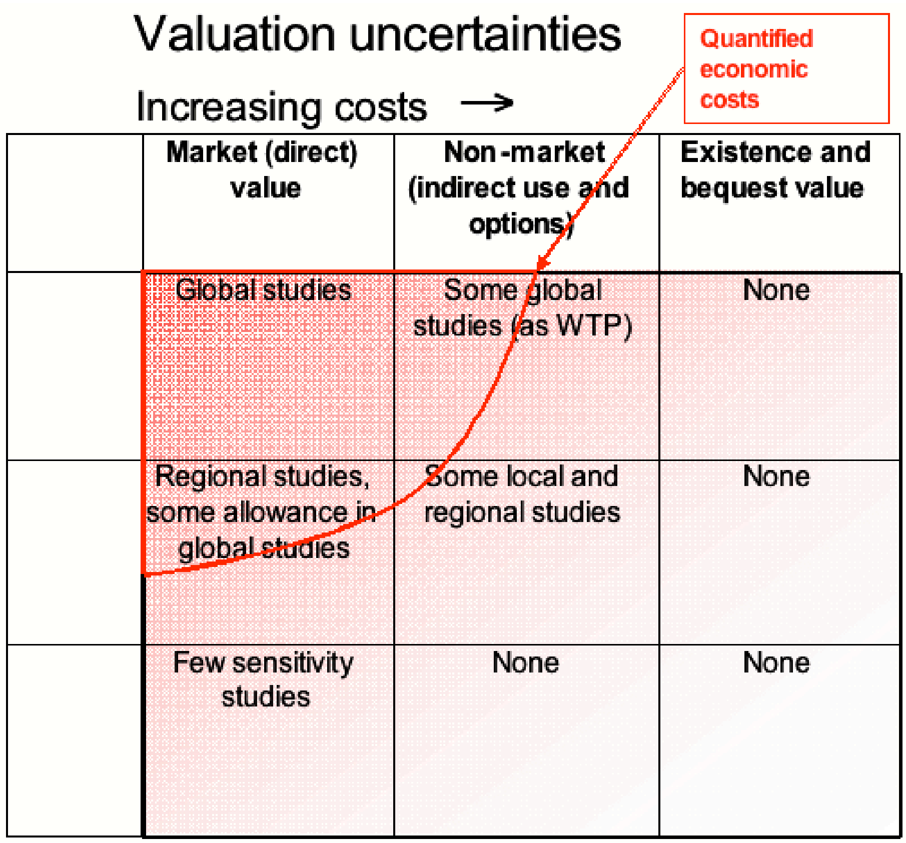
[1]Here robust refers to an outcome that is not overly sensitive to underlying uncertainties, producing a similar response across a plausible range of inputs.

climate sensitivity and a simple ocean model.

Downing & Watkiss (2003) 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 (i.e, the marginal cost of carbon emissions) 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 & Watkiss (2003) 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"), Smit & Pilifosova (2001) note that most economic and other responses to climate change will, in reality, be due to changes in variability and extremes (including large-scale singularities). These are, of course, much more difficult to quantify but evidence that extreme events relative to a threshold defined by the ability to cope are likely to increase in type, magnitude and location under climate change, suggest that economic damages can be substantially higher than those assessed using smooth functions (Hallegatte et al., 2006).

As in Downing & Watkiss (2003), the substantive boxes of Table 1 interrelate 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. At the global scale, we have currently have inadequate representations of climate change variability, minimal representations of abrupt change and singularities (Goodess et al., 2003), 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. 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.



Valuation uncertainties

Increasing costs →

Quantified economic costs

	Market (direct) value	Non-market (indirect use and options)	Existence and bequest value
	Global studies	Some global studies (as WTP)	None
	Regional studies, some allowance in global studies	Some local and regional studies	None
	Few sensitivity studies	None	None

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

4 Representing damages from economic and biophysical perspectives

Even casual review of the right column and lowest row of Table 1 makes it clear that potential damages from climate change can be calibrated in terms of multiple numeraires, as recommended by several studies on the benefits of avoided damages (Schneider, 2004; Jacoby, 2004). To explore how one might try to convert this multiplicity into comparable metrics of risk, we consider two representative sets of damages. One set was drawn from the economic sphere, and the other set catalogues four biophysical impacts. The economic damage curves were based on assessments undertaken by Nordhaus & Boyer (2000) and Nordhaus (2006), but altered as shown in the top panel of Figure 3 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 from 1990 will result in a 3% decrease in global 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°grid with a scenario of warming and mid-continental drying[2]. 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 such as Tol (2002) or Mendelsohn & 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. The highest warming for which damage functions were estimated by Nordhaus & Boyer (2000) was 6°C for which a decrease in global GDP of 10.1% was assigned[3]. Therefore the quadratic curve posits a more negative relationship beyond 3°C, the cubic curve even more so. 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 higher anticipated damages due to changing climate variability and extremes affecting an increasing number of sectors and locations.

In one sense, these curves represent the historical development of damage approaches in the literature. The earliest examples tested were linear followed by the development of quadratic damage curves (e.g., Nordhaus & Boyer, 2000). Over time, the non-linearity of damages with temperature has become more

[2]Note that Nordhaus (2006) later revised this figure to 2.4% for a 3°C warming. These damage curves accommodate most of the range published in the literature. Note however, there is no consensus on what the real level of economic damages and estimates, whether low or high, are hotly debated.

[3]Note that most of the published damages date from ∼1900 and represent change from pre-industrial times, whereas all warming and consequent damages in this paper date from 1990.

apparent, although this does not fit all examples (e.g., Mendelsohn & Williams, 2004), and includes estimates that represent net benefits at low temperatures before coming negative (e.g., Tol, 2002). From Table 1, most of these approaches under-estimate true costs, a case taken up by Stern (2007). The increasing non-linearity is consistent with the evolution of costing methods that early on accounted for mean changes in temperature only, with other climate variables, climate variability and extremes being added later and, according to Downing et al. (2005), incompletely. Our contention is that, based on many local studies of climate impacts that carry through to costs, the inclusion of all these factors tends to increase those costs. The incompatibility between bottom-up or local assessments and top-down global assessments has meant that by and large, these larger costs have not carried through into global assessments. Thus the application of all four curves allows different assumptions to be tested according to a sensitivity assessment.

Biophysical damage curves were developed by Sheehan et al. (2006) from the published scientific literature. They reflect 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 bottom panel of Figure 3 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 Intergovernmental Panel on Climate Change (2001*a*, Chapter9). 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)[4]. In any case, complete melting would produce up to 7 meters of sea level rise across the globe, taking centuries to millennia. 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

[4]The recently released IPCC Working Group I Summary For Policymakers (Intergovernmental Panel on Climate Change, 2007*a*) suggests that negative mass balance would be achieved with a warming of 1.3 to 4.0°C from 1990 and that a negative mass balance for a millennium would result in 7 m sea level rise.

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) method assumes perfect adaptation carried out instantaneously.

5 The probability of exceeding a given level of damage

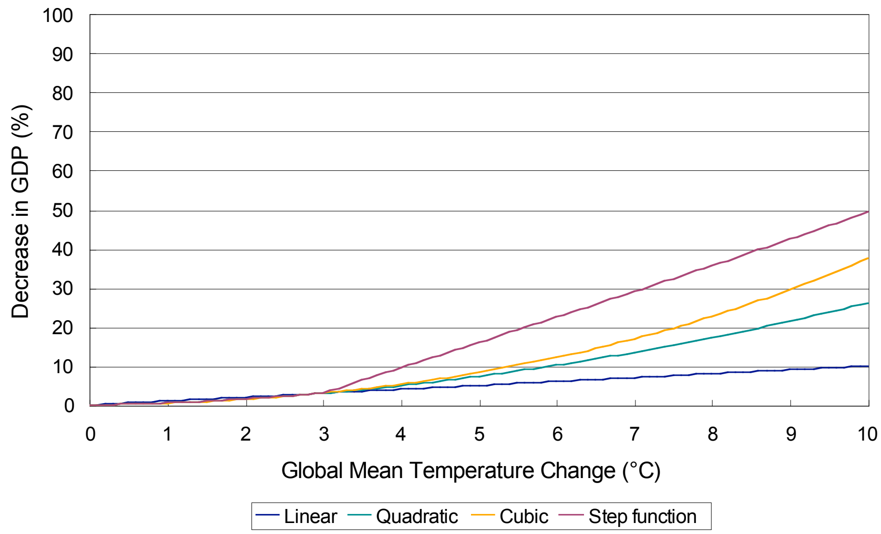
To produce distributions of climate change through 2100, we compared the probabilities of various degrees of warming projected using the marker scenarios of the Special Report of Emission Scenarios (SRES Nakiçenovic & Swart, 2000). The marker scenarios from the A1 Family (A1B, A1FI and A1T) are used 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 (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 Intergovernmental Panel on Climate Change (2001*a*), and originally derived using the MAGICC simple climate model (Wigley, 2000). MAGICC was run again using the same GCM settings as used in Intergovernmental Panel on Climate Change (2001*a*) allowing a simple, linear regression 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.

$$\lambda = 0.1086T_s + 0.1871 \quad (1)$$

$$T = F\lambda \quad (2)$$

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. This distribution is pessimistic with regard to the recent IPCC conclusions on the likely range of uncertainty (a 5/50/95 percentile distribution of 2.0/3.0/4.5°C; Intergovernmental Panel on Climate Change 2007*a*). When sampled for a range of alternative sensitivity distributions the resultant values will change but not the patterns of response themselves. Forcing in Wm^{-2} is sampled uniformly across the range produced from the six IPCC marker scenarios (IPCC, 2001), with the upper limit of A1FI, A1B, and A1T respectively, and lower limit of B1. The results were compiled from >60,000 random samples. The resulting probability distributions for global warming in 2100, superimposed on the damage curves from Figure 3 are shown in Figure 4.

Combining the two sets of curves, Figure 5 displays cumulative distributions of the likelihoods of exceeding economic or biophysical impacts thresholds or



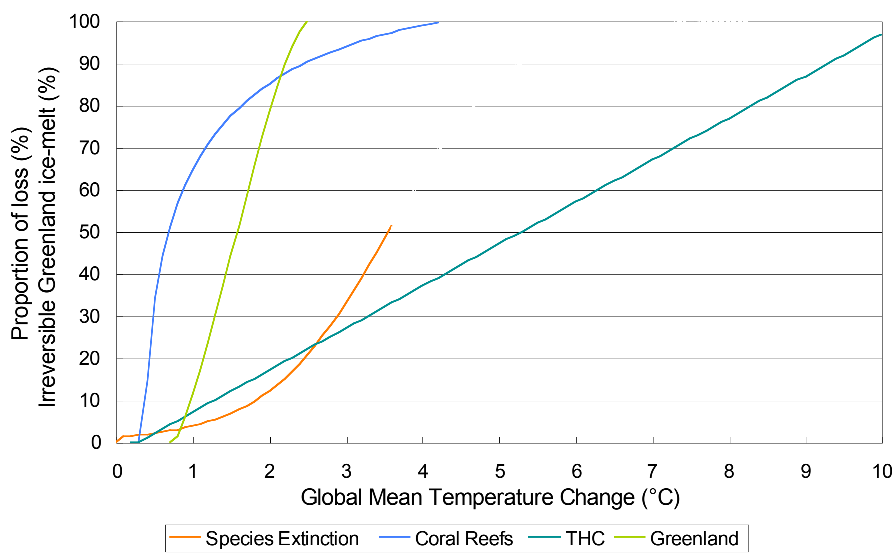


Figure 3: Damage curves as a function of global warming. Panel A: different conceptual damage curves for global impacts expressed as percentage decrease in global Gross Domestic Product (GDP) derived from Nordhaus and Boyer (2000). Panel B: damage curves for four key biophysical vulnerabilities: proportion 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., 2006).

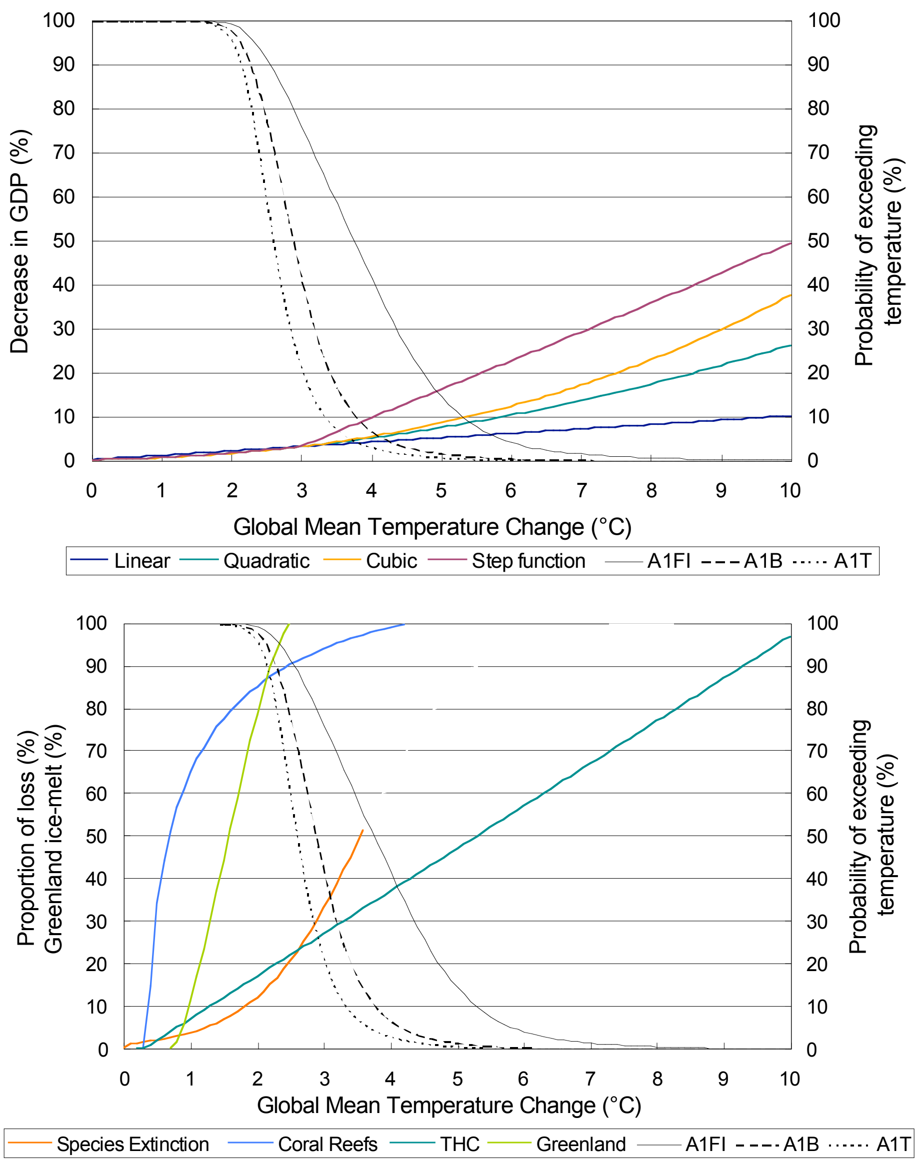
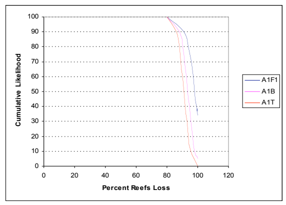
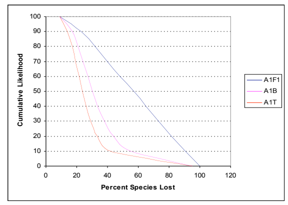


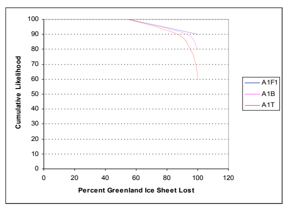
Figure 4: The likelihood of exceeding levels of mean global warming in 2100. Climate sensitivities from Murphy & et al. (2004) are assumed for the SRES range of emissions scenarios with upper limits of A1FI, A1B and A1T superimposed on the damage curves from Figure 2.



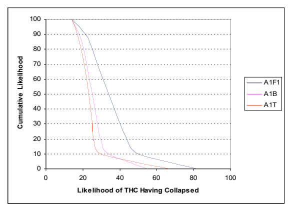
Panel A: Percentage coral reefs lost



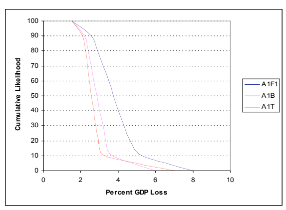
Panel B: Percentage species at risk of extinction



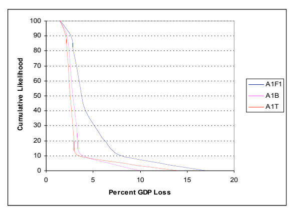
Panel C: Likelihood of initiating melting of the Greenland ice sheet.



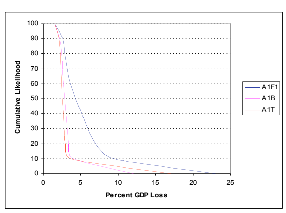
Panel D: Likelihood of THC having collapsed



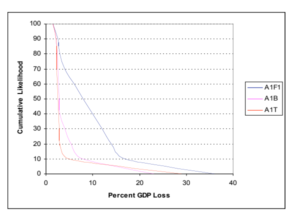
Panel E: Linear damages



Panel F: Quadratic damages



Panel G: Cubic damages



Panel H: Step damages

Figure 5: Cumulative distributions of impacts in 2100. Panels A and B show cumulative distributions in terms of proportion of lost reefs and species extinction, respectively; Panel C, in terms of likelihood of a collapse of the THC; Panel D, and in terms of percentage of Greenland ice sheet lost. Panels E through H show cumulative distributions in terms of percentage of global GDP lost along linear, quadratic, cubic, and step damage functions.

targets under different emission regimes. Because Figure 5 displays economic and biophysical risks within the shared context of mean global warming, we can compare vulnerabilities directly. Notice, for example, that panels A through D show that key biophysical vulnerabilities are likely to be exceeded by 2100. Panel A, for example, suggests that it is nearly certain that >80% of the reefs will be lost by 2100 regardless of emissions path adopted unless emissions fall below the SRES lower limit. Panel C shows that >50% likelihood that melting of the Greenland ice sheet will have been initiated. Indeed, the likelihood of initiating melting by 2100 ranges from 90% for A1F1 down to 60% for A1T.

Panels E through H of Figure 5 do the same for the four economic damage curves. Notice that their horizontal scales are different, with the step damage case showing a 10% chance of around 15% GDP loss along A1F1. These economic distributions are, however, similarly shaped; but this common silhouette is reminiscent of only the shapes of the distributions for species extinction and THC collapse in Panels A through D. It follows, therefore, that economic metrics (even with a step in damages at 3°C warming) would not necessarily capture the scope of biophysical impacts like those depicted in Panels A and C for reefs and the Greenland ice sheet, respectively. The step function 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 economic curves reflect the severity of all impacts calibrated to biophysical numeraires. Put another way, profound asymmetry in vulnerabilities across biophysical systems is not seen in the aggregation of economic measures, especially if those measures omit the direct and indirect costs incurred.

We have, though, created a common framework that overcomes this problem by expressing consistently the monetary and non-monetary impacts of climate change damage curves 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 generated 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.

6 Risk-weighting damage functions

Risk weighting (i.e., multiplying likelihood times consequence) offers the potential of contrast monetary with non-monetary losses portrayed in Figure 3 through Figure 5 with an different aggregate index. In this case, weighted damage is calculated by multiplying the probability distribution of temperature (which adds up to 1) by the damage function. Depending on the slope of the impact at higher temperatures, the weighted damage may be slightly to substantially above the outcome where median temperature is multiplied with the damage function.

Table 2: Risk-weighted Damages. Aggregate metrics computed by multiplying the likelihoods of warming through 2100 with upper limits of A1FI, A1B and A1T times economic losses to global GDP or the likelihoods of damage in biophysical systems. NPV in $1990 calculated from the A1 SRES GDP using the UK Treasury Greenbook long term discount curves.

Panel A: 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
Panel B: 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	65.9	64.2	65.4	92.7
A1B	49.2	47.9	46.2	57.1
A1T	49.5	48.6	46.5	50.7

Panel A of Table 2 shows the results of multiplying the probability density function of warming and the damage curves depicted in Figure 3; they are the means of the cumulative distributions displayed in Figure 5. 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 loss (for coral reefs, species extinctions, and Greenland ice sheet) or chance of loss (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, the temperature at which a particular impact becomes critical (i.e., beyond a tolerable level of harm) is more important when contrasting emissions scenarios. Curves subject to critical critical levels at around ∼2°C warming (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 anchoring all of the damage curves at 3% for 3°C warming meant that 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, but it is likely that this will not be known before the fact for many impacts. These conclusions are consistent with findings by Mastandrea & Schneider (2004*b*).

Table 3: Risk-weighted Benefits of a Kyoto-like Reduction in Greenhouse Gas Emissions. Aggregate metrics computed by multiplying the likelihoods of warming through 2100 with upper limits of A1FI, A1B and A1T times economic losses to global GDP or the likelihoods of damage in biophysical systems. NPV in \$1990 calculated from the A1 SRES GDP using the UK Treasury Greenbook long term discount curves.

Panel A: Biophysical				
Scenario upper limit	Species	Coral Reefs (% damage)	THC slow-down	Green-land ice sheet 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

Panel B: 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	-3.1	-3.2	-3.7	-6.9
A1B	-2.7	-3.2	-3.5	-5.6
A1T	-2.6	-3.3	-3.5	-4.2

7 Testing risk weighted 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}, resulting in a decrease in temperature of approximately 0.10.3°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 shows that the benefits are greatest when reducing impacts from higher temperatures. The risk-weighted benefits to GDP in percentage change appear to be small but actually reduce the total loss for the non-linear monetary damage curves by >5%. In percentage GDP terms the benefits of avoided damage in 2100 range between 0.1% and 0.7% of GDP, or between \$2.6 to \$6.9 trillion for the SRES A1 economy. Without a method to estimate costs within the same framework we are dependent on comparison with estimates from the literature. Using a much smaller economy (~\$100 trillion in 2100) Nordhaus & Boyer (1999) estimated an increase in global temperature from pre-industrial levels of 2.3°C in 2100 (approximately 1.9°C from 1990) in the reference scenario, with Kyoto producing a temperature benefit of 0.13°C. The minimum estimated cost in 1990 dollars of a Kyoto-like mitigation using maximum efficiency was \$0.11 trillion; compliance using Kyoto rules ranged from \$0.8 to \$1.5 trillion. Estimated damages reduced from \$1.83 to \$1.72 trillion in 2200. Note that the temperature increase and climate sensitivity (2.5°C) is at the low end of those applied here. A later estimate of Kyoto-like reduction "forever" applied with maximum efficiency is \$0.036 trillion (Nordhaus, 2005). Manne & Richels (1999), applying a Kyoto forever scenario (much more stringent than that modelled here), estimated costs of approximately \$1 trillion in 2100, discounted at a rate of 5% to net present value in 1990. These costs cannot be directly compared with our risk-weighted economic benefits, because of the different economies and assumptions used. However, it is clear that a number of previous estimates have contrasted compliance costs of Kyoto using comparatively low values of climate sensitivity (~2.5°C is typical), thus have contrasted the costs of Kyoto against comparatively low damage estimates. When we balance assumptions of cost-effective Kyoto-like mitigation against the risk-weighted benefits of avoided economic damages, the benefits may well be positive because the most damaging economic impacts have been avoided. Again, the point needs to be made that assumptions surrounding discounting and equity are critical to such considerations.

The same principal applies for the biophysical damages. However, the benefits are more variable 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 a THC collapse. On the other hand, critical levels of damages for coral reefs and Greenland have already been exceeded by such a degree that this small level of change is insufficient to produce substantial benefits on its own even though it does help to bring critical threshold closer to the reach of future mitigation efforts.

8 Discussion and concluding remarks

In this paper we have developed proof of concept examples for assessing risk-weighted damages from climate impacts and risk-weighted benefits from climate policy; and we offer it as an alternative to formalized cost-benefit analysis. We have, in fact, demonstrated a method by which disparate impacts calibrated across multiple metrics can be displayed in a common format and therefore compared directly. To be clear, though, these risk portraits cannot be aggregated directly; they are designed to present synthesized information that will inform the decision-making process about relative risks and the robustness of policy across multiple domains. 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 appeal of our approach.

A similar but not identical approach of risk-weighting was used in Stern

(2007), There, emission futures were weighted probabilistically and all climate impacts were expressed in economic terms. Damages were then expressed in terms of a certainty-equivalent per capita consumption metric computed so that it sustains discounted utility at the level of expected discounted utilty across all possible futures. It is important to note that this metric does not measure lost GDP in any given year. In the controversy over the way in which Stern aggregated costs and applied discount rates, however, the advantages of risk-weighting have been overlooked. We believe separating the economic from non-economic damages is appropriate given the large uncertainties involved and the possibility that the monetary and non-monetary values ascribed to those damages may be incommensurable (e.g., Jacoby, 2004). The ability to examine risk-weighting separately across scientific uncertainties (e.g., the radiative forcing–climate sensitivity–warming process) and socio-economic uncertainties (e.g., population–technology–energy use–emissions process) is also instructive.

In our illustrative examples, we have made a range of simplifying assumptions so that attention can be focused on the approach. We have, for example, 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.

Notwithstanding these deficiencies in our illustrations, we have shown that risk-weighted costs of climate damage can be employed to consider the value of mitigation in a way that captures the diversity of scale and scope in climate impacts. For our small set of impacts, in fact, we see the potential for even modest reductions in greenhouse gases to produce significant benefits in terms of risks avoided; and the distribution of these benefits across multiple impacts is seen comparing changes in associated risk profiles the cumulative distributions of the sort portrayed in Figure 5. 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.

9 Bibliography

Downing, A. D., Butterfield, R., Ceronsky, m., Grubb, M., Guo, J., Hepburn, C., Hope, C., Hunt, A., Li, A., Markandya, A., Nyong, A., Tol, R. S. J. & Watkiss, P. (2005), Scoping uncertainty in the social cost of carbon, Final project report. social cost of carbon: A closer look at uncertainty, Department of Environment, Food and Rural Affairs. 126, 133, 135

Downing, T. & Watkiss, P. (2003), The marginal social costs of carbon in policy making: Applications, uncertainty and a possible risk based approach, *in* 'DEFRA International Seminar on the Social Costs of Carbon'. 126, 128, 132

Füssel, H.-M. & Klein, R. J. T. (2006), 'Climate change vulnerability assessments: An evolution of conceptual thinking', *Climatic Change* **75**, 301–329. 130

Goodess, C. M., Hanson, C., Hulme, M. & Osborn, T. J. (2003), 'Representing climate and extreme weather events in integrated assessment models: A review of existing methods and options for development', *Integrated Assessment* **4**, 145–171. 132

Hallegatte, S., Hourcade, J. C. & Dumas, P. (2006), 'Why economic dynamics matter in the assessment of climate change damages: illustration extreme events', *Ecological Economics*. doi:10.1016/j.ecolecon.2006.06.006. 132

Hansen, J. E. (2005), 'A slippery slope: How much global warming constitutes 'dangerous anthropogenic interference'?', *Climatic Change* **68**, 269–279. 135

Hope, C. (2006), 'The marginal impact of CO_2 from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern', *The Integrated Assessment Journal* **6**, 19–56. 126, 131

Intergovernmental Panel on Climate Change (2001*a*), Climate change 2001a: The scientific basis, Technical report, Cambridge University Press. 135, 136

Intergovernmental Panel on Climate Change (2001*b*), Climate change 2001b: Impacts, adaptation and vulnerability, Technical report, Cambridge University Press. 128, 129, 130

Intergovernmental Panel on Climate Change (2007*a*), Summary for policymakers—climate change 2001a: The scientific basis, Technical report, Cambridge University Press. 135, 136

Intergovernmental Panel on Climate Change (2007*b*), Summary for policymakers—climate change 2001b: Impacts, adaptation and vulnerability, Technical report, Cambridge University Press. 130

Jacoby, H. (2004), 'Informing climate policy given incommensurable benefits estimates', *Global Environmental Change*. 134, 145

Jones, R. N. (2004*a*), 'Incorporating agency into climate change risk assessments', *Climatic Change* **67**, 13–36. 126, 128, 131

Jones, R. N. (2004*b*), Managing climate change risks, *in* S. Agrawal & J. Corfee-Morlot, eds, 'The benefits of climate change policies: Analytical and framework issues', OECD, Paris, pp. 249–298. 126, 128, 129, 131

Jones, R. N. & Preston, B. L. (2006), *Climate change impacts, rist and the benefits of mitigation: A report for the Energy Futures Forum*, CSIRO, Melbourne. 125

Joughin, I. (2006), 'Greenland rumbles louder as glaciers accelerate', *Science*. 135

Klein, R. J. T., Schipper, E. L. F. & Dessai, S. (2005), 'Integrating mitigation and adaptation into climate development policy: Three research questions', *Environmental Science and Policy* **8**, 579–588. 130

Manne, A. S. & Richels, R. G. (1999), 'The Kyoto protocol: A cost-effective strategy for meeting environmental objectives?', *The Energy Journal* **20**, 1–24. 144

Mastandrea, M. D. & Schneider, S. H. (2004*a*), Probabilistic assessment of 'dangerous' climate change and emissions scenarios: Stakeholder metrics and overshoot pathways, *in* H. J. Schnellnhuber, W. Cramer, N. Nakicenovic, T. Wigley & G. Yohe, eds, 'Avoiding dangerous climate change', Cambridge University Press, Cambridge. Chapter 27. 126

Mastandrea, M. D. & Schneider, S. H. (2004*b*), 'Probabilistic integrated assessment of "dangerous" climate change', *Science* **304**, 571–575. 126, 131, 142

Mendelsohn, R. & Williams, L. (2004), 'Comparing forecasts of the global impacts of climate change', *Mitigation and Adaptation Strategies for Global Change* **9**, 315–355. 134, 135

Murphy, J. M. & et al. (2004), 'Quantifying uncertainties in climate change from a large ensemble of general circulation model predictions', *Nature* **430**, 768–772. 136, 138

Nakiçenovic, N. & Swart, R. (2000), *Special Report on Emissions Scenarios*, Cambridge University Press, Cambridge. 136

Nordhaus, W. D. (2005), Economic analyses of Kyoto Protocol: Is there life after Kyoto?, *in* 'Global warming: Looking beyond Kyoto', Yale University, New Haven, CT. 144

Nordhaus, W. D. (2006), 'Geography and macroeconomics: New data and new findings', *Proceedings of the National Academy of Science* **103**, 3510–3517. 134, 136

Nordhaus, W. D. & Boyer, J. (1999), 'Requiem for Kyoto: An economic analysis of the Kyoto Protocol', *The Energy Journal* **20**, 93–130. 144

Nordhaus, W. D. & Boyer, J. (2000), *Warming the world: Economic models of global warming*, MIT Press, Cambridge. 134

Schneider, S. H. (2001), 'What is 'dangerous' climate change?', *Nature* **411**, 17–19. 136

Schneider, S. H. (2004), 'Abrupt non-linear climate change, irreversibility and surprise', *Global Environmental Change—Human and Policy Dimensions* **14**, 245–258. 134

Sheehan, P., Jones, R. N., Jolley, A., Preston, B. L., Clark, M., Durack, P. J., Islam, S., Sun, F. & Whetton, P. H. (2006), Climate change and the global knowledge economy: an immediate challenge, Cses climate change working paper no. 11, Centre for Strategic Economic Studies, Victoria University. 135, 137

Smit, B. & Pilifosova, O. (2001), Adaptation to climate change in the context of sustainable development and equity, *in* J. McCarthy, O. Canziani, N. Leary, D. Dokken & K. White, eds, 'Climate Change 2001: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change', Cambridge University Press, Cambridge, pp. 877–912. 132

Stern, N. (2007), *The economics of climate change: The Stern Review*, Cambridge University Press, Cambridge and New York. 131, 135, 144

Tol, R. S. J. (2002), 'New estimates of the damage costs of climate change. part II: Dynamic estimates', *Environmental and Resource Economics* **21**, 135–160. 134, 135

Tol, R. S. J. (2003), 'Is the incertainty about climate change too large for expected cost-benefit analysis', *Climatic Change* **56**, 265–289. 125, 131

Tol, R. S. J. (2005), 'The marginal damage costs of carbon dioxide emissions: An assessment of the uncertainties', *Energy Policy* **33**, 2064–2074. 126, 130

Tol, R. S. J. & Yohe, G. (2007), 'The weakest link hypothesis for adaptive capacity: An empirical test', *Global Environmental Change* **17**, 218–227. 125

Warren, R. (2006), Impacts of global climate change at different annual mean global temperature increases, *in* H. J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley & G. Yohe, eds, 'Avoiding Dangerous Climate Change', Cambridge University Press, Cambridge. 128, 131

Watkiss, P., Anthoff, D., Downing, T., Hepburn, C., Hope, C., Hunt, A. & Tol, R. S. J. (2005), *The social cost of carbon (SCC) review—Methodological approaches for using SCC estimates in policy assessemnt*, Department of Environment, Food and Rural Affairs, London. 126

Webster, M. D., Forest, C. E., Reilly, J., Babiker, M., Kicklighter, D., Mayer, M., Prinn, R., Sarofim, M., Sokolov, A. P., Stone, P. & Wang, C. (2003), 'Uncertainty analysis of climate change and policy responses', *Climatic Change* **61**, 295–320. 131

Wigley, T. M. L. (1998), 'The Kyoto Protocol: Co_2, ch_4 and climate implications', *Geophysical Research Letters* **25**, 2285–2288. 143

Wigley, T. M. L. (2000), *Updated version of and results from the simple climate model MAGICC*, National Center for Atmospheric Pressure, Boulder, CO. 136

Wigley, T. M. L. (2004), Modelling climate change under policy and no-policy pathways, *in* S. Agrawal & J. Corfee-Morlot, eds, 'The Benefits of Climate Change Policies: Analytical and Framework Issues', OECD, Paris, pp. 221–248. 126, 131

Yohe, G. (2006), 'Representing dynamic uncertainty in climate policy deliberations', *Ambio* **35**, 36–38. 125, 131

Yohe, G. & Schlesinger, M. (1998), 'Sea level change: The expected economic cost of protection or abandonment in the United States', *Climatic Change* **38**, 447–472. 131

Yohe, G. W. (2003), 'More trouble for cost-benefit analysis', *Climatic Change* **56**, 235–244. 125