Climatic Change (2009) 95:325–339
DOI 10.1007/s10584-009-9614-2

Toward an integrated framework derived from a risk-management approach to climate change

An editorial comment

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Received: 5 May 2009 / Accepted: 7 May 2009 / Published online: 9 July 2009

Ackerman et al. (2009) criticize optimization applications of integrated assessment models of climate change on several grounds. First, they focus attention on contestable assumptions about the appropriate discount rate. Second, they worry that integrated assessment models base their damage estimates on incomplete information and questionable estimates of the value of human life and/or ecosystem services. Thirdly, they suggest that mitigation costs are systematically overestimated because they ignore technological innovation. So what good is economics in the climate arena? The authors suggest only one opportunity—investigate how the cost of achieving politically or hedging-based climate targets might be minimized.

Their contribution provides a concise and internally consistent presentation of several sources of concern, but none is really new in their fundamental arguments. Antecedents of the points that they raise (and many others, for that matter) can be found in the established literature from the past 5 or 10 years; see, for example, Yohe (2003), Weitzman (2009) or Yohe and Tol (2008). This is not really a problem or a criticism for present purposes, though, because their discussion is so tightly articulated that it can be an effective springboard for discussions how improving economic analyses of climate change can do more than elaborate cost-minimizing strategies more thoroughly. On the one hand, dynamic cost–benefit frameworks cannot be discarded on the basis of what Ackerman, et al. or others say because official government agencies have not yet been convinced. Indeed, despite the now obvious concerns about the bases of estimates of the social cost of carbon derived from integrated assessment models, for example, such estimates are essential in bringing climate change to bear on a wide range of other policies and regulations. We cannot dismiss them, therefore; we must improve them and let practitioners know about their deficiencies. On the other hand, focusing on the economic underpinnings of risk-management techniques makes it clear that cost minimization is but of many roles for efficiency-based economic analysis.

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The Synthesis Report of the Fourth Assessment Report {AR4, IPCC 2007c} that was approved by the Intergovernmental Panel on Climate Change in November of 2007 is perhaps the easiest place to look to see that the climate community has moved well beyond standard optimization approaches that caught the attention of Ackerman, et al. Based on an assessment of published literature, the IPCC convinced governments to accept risk as the unifying theme for future assessments. Indeed, because they unanimously approved the Summary for Policymakers *word by word*, *all* governments agreed that risk (and not just impacts or associated vulnerability) matters most to them as they consider how to respond to the climate problem; in their words:

> Responding to climate change involves an *iterative risk management* process that includes both adaptation and mitigation, and takes into account climate change damages, co-benefits, sustainability, equity and attitudes to risk {IPCC (2007c), pg 22; my emphasis}.

Careful, deliberate, and extensive negotiations during the final plenary of the Fourth Assessment Report process therefore made it clear that governments now understand that the risk associated with any possible event depends both on its likelihood and its potential consequences. This is the definition of risk that their finance ministers have been using for decades, so it was no surprise that many governments' delegations understood the concept well. Perhaps the only surprise is that it took so long for governments to articulate an imperative to move beyond standard inter-temporal optimization.

To spring forward from Ackerman, et al. in response to governments' change in perspective, we must begin to ponder what this fundamental synthetic result means for the application of economics to climate change. Comparisons of costs and benefits of various policies will still be made within government agencies, so we are really asking questions about how risk-based approaches can complement those calculations and perhaps emerge as a deciding factor in many areas. How, more generally and perhaps most fundamentally, can climate risk be framed in an internally consistent way to inform the interaction between mitigation and adaptation? This essay will touch on these questions—not with the expectation of providing complete answers, but rather with the hope of offering some observations and suggestions that might push the discussion forward an iota or two.

1 Applying optimization techniques to climate change

The application of the optimization approach to climate change can trace its roots from Nordhaus (1991). In applying this approach in integrated assessment exercises, researchers track economic damages that would be associated with climate change and costs that would be associated by climate policy over time scales that extend many decades if not centuries into the future. They calibrate these damages and costs along scenarios of economic development and resource availability that display ever-growing ranges of possible futures. Both metrics are disaggregated to the extent possible across countries and regions, and both are then discounted back to present values. In this final step, estimates of the present value of benefits and costs are highly sensitive to natural parameters (like climate sensitivity) and policy parameters (like the assumed discount rate which is, in turn, extremely sensitive to attitudes toward risk, attitudes toward inequity, and inter-temporal impatience). When optimization is the goal (but only then), these calculations allow the researcher to describe trajectories for which the marginal discounted benefits of a mitigation pathway (from reduced or delayed damages) are equal to its marginal discounted cost.

Even though many authors and commentators have become increasingly critical of this approach, practitioners are still being instructed to calculate discounted costs and benefits (as in the United States for example by Circular A-4 or its much anticipated replacement[1]). These practitioners have begun to track benefits and costs in terms of alternative, non-economic metrics; but it is not yet clear what to do next. As Ackerman, et al. correctly argue, assigning economic values to these metrics is controversial, at best. Practitioners have also recognized problems with specifying appropriate discount rates, coping with enormous, pervasive and persistent uncertainty, and accommodating the profound distributional consequences of climate change; but it is not yet clear what to do with the ranges of estimates that emerge from the confluence of truly uncertain natural parameters (like climate sensitivity) and other parameters that reflect the normative perspectives of individual decision-makers (like the pure rate of time preference or degrees of aversion to inequality or risk).

At the same time, though, pressure to assign numerical values to benefits of reducing greenhouse gas emissions has grown; i.e., they cannot simply respond to the Ackerman, et al. critique by dismissing the entire integrated assessment approach. The 9th Circuit ruling about proposed CAFÉ standards in early 2008 asked, for example, that benefit–cost analyses of stricter standards include estimates of associated climate change benefits derived from reduced carbon emissions. The court's decision was apparently based in large measure on the belief that zero was not the correct price for carbon; but it seems that the court was not informed by Tol (2005). If it were, it would have known that not all of the published estimates of the social cost of carbon are positive. The ruling begged the question of how to include benefits that could not be monetized in the policy deliberations. And the court gave no instruction about whether the appropriate price of carbon should reflect economic costs of climate change that would be felt outside the boundaries of the United States.

Executive Order 13497, signed by President Obama on January 30, 2009, opened the door for a review of these issues by directing the Director of the Office of Management and Budget to provide input, with advice from regulatory agencies, for a new Executive Order on Federal regulatory review. As suggested above, the

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[1] Circular A-4 [White House (2003)] was distributed by the Office of Management and Budget to update long-standing instructions that defined the standards for "good regulatory analysis"—exercises that work from statements of need and explorations of alternative approaches to produce evaluations of the "benefits and costs—quantitative and qualitative—of the proposed action and the main alternatives…" The Circular suggests how to identify areas where government action may be required, but it warns against unwarranted intervention in the marketplace by leading with an explicit "presumption against economic regulation." Most of the text, though, is dedicated to illuminating "best practices" for circumstance in which this presumptive hurdle has been overcome. It begins by highlighting benefit–cost and cost-effectiveness analyses as the "systematic frameworks" within which to identify and to evaluate the likely outcomes of alternative regulatory choices. The Congressional Budget Office (2005) amplified these points. Critiques of relying too heavily on limited benefit–cost analyses include Tol (2003) and Yohe (2004 and 2006).

issues are so complicated that the 100 day deadline for recommendations could prove to be completely infeasible in terms of provide support for such an Order. It is clear that the president has set in motion a process through which non-quantified costs and/or benefits calibrated in multiple metrics including reduced risk could become important components of regulatory design analyses and perhaps even emerge as the determining criteria. It is also clear that cost–benefit calculations set the stage and must be included—warts and all (identified, but included)

2 Investing in a complementary risk-management approach

It follows that the risk-management approach to confronting climate change described by the IPCC (2007c) is gaining traction as a *complementary* analytic tool designed explicitly to ameliorate or at least account for many (but by no means all) of these thorny issues.[2] Its most straightforward applications begin with the statistical definition of risk (the probability of an event multiplied by some measure of its consequence). In a world full of people who are averse to risk (that is to say, people who are willing to invest in instruments that eliminate or at least reduce risk associated with uncertain outcomes across a range of decision alternatives), the concept of statistical risk teaches us about the value of diversification and the value of hedging against the chance of high-consequence outcomes. Moreover, these lessons are derived from the same economic efficiency criteria that provide the theoretical underpinnings for benefit–cost analysis; indeed, benefit–cost analysis is a special case in which the decision-maker is risk-neutral (and so will not pay anything to reduce uncertainty). Wider applications of risk-management have also illuminated the value of enacting robust policies and other responses that work reasonably well across a wide range of possible futures even if they do not work optimally for any single outcome). In short, some risk-based analyses rely heavily on information about the relative likelihoods of possible events (or at least subjective views about those likelihoods). Others, including the ones that relate to identifying robust strategies, can be built directly from catalogues of possible futures even if they cannot be characterized in terms of their relative likelihoods.

The rigorous economic underpinnings of risk-management techniques is a fine and reasonable conclusion in the abstract, but what do we really know about how to apply all of this knowledge to the climate arena? According to the IPCC (2007a), we know “unequivocally” that the planet is warming. We are now “virtually certain”, to use IPCC parlance, that the climate is changing at an accelerating rate. We also know with “very high confidence” that anthropogenic emissions are the principal cause. We even know now from Stott et al. (2004) and IPCC (2007b) that anthropogenic climate change is the strongest contributor to the conditions that created the 2003 heat-wave across central Europe that caused tens of thousands of premature deaths. In short, we know that we see many risks when we contemplate our capacities to cope with climate variabilities whose future ranges will be determined by dynamic climate change. Even though substantial uncertainties persist about specific vulnerabilities,

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[2] The foundations for the results that follow can be found in Raiffa and Schlaiffer (2000).

the existence of these macro-scale risks is sufficient to establish the need to respond in the near-term in ways that will reduce future emissions and thereby ameliorate the pace of future change. Indeed, looking at uncertainty through a risk-management lens makes the case for near-term action through hedging against all sorts of climate risks—risks that can be denominated in terms of economic damages, of course, but also in terms of other indicators like billions of additional people facing hunger, water stress, or hazard from coastal storms. It then follows from simple economics that this near-term action should begin immediately if we are to minimize the expected cost of meeting any long-term objective.

3 "Thick tails" and "tipping points"—lessons from the conduct of monetary policy in the United States

What can be said about applying risk-management to situations that could be dominated by the dark, thick tails of climate distributions and/or associated possibilities of crossing "tipping points"? Can a risk-based economic approach support hedging even when we cannot calibrate those tails and cannot identify the triggers of potentially irreversible impacts of potentially extraordinary consequence? The conduct of economic policy-makers in other areas suggests that the answer here is "yes". It is sufficient in this regard to remember that the conduct of monetary policy frequently represents a real-world illustration of how hedging strategies have been employed at a macro scale against large risks whose likelihoods and/or consequences cannot be estimated. Opening remarks offered by Alan Greenspan, Chairman of the Federal Reserve Board, at a symposium on "Monetary Policy and Uncertainty: Adapting to a Changing Economy" that was sponsored by the Federal Reserve Bank of Kansas City in August of 2003 are a great place to start to make this point. In his attempt to motivate 3 days of intense conversation among policy experts, Chairman Greenspan observed:

> "For example, policy A might be judged as best advancing the policymakers' objectives, conditional on a particular model of the economy, but might also be seen as having relatively severe adverse consequences if the true structure of the economy turns out to be other than the one assumed. On the other hand, policy B might be somewhat less effective under the assumed baseline model … but might be relatively benign in the event that the structure of the economy turns out to differ from the baseline. *These considerations have inclined the Federal Reserve policymakers toward policies that limit the risk of deflation even though the baseline forecasts from most conventional models would not project such an event.*" {Greenspan (2003); pg. 4; emphasis by the current author}

Why did the FED worry about deflation? Because the effects of nearly every American citizen paying back existing personal debt with dollars that would be worth more (potentially much more) than anticipated when their loans were taken included the seeds of catastrophic economic recession. The resulting contraction in economic activity would depress asset prices (e.g., homes and businesses), increase bankruptcy filings, and thereby undermine the supply of lendable funds. Sound familiar?

To continue, the Chairman expanded on this illustration in his presentation to the American Economic Association (AEA) at their 2004 annual meeting in San Diego:

> "...the conduct of monetary policy in the United States has come to involve, at its core, crucial elements of risk management. This conceptual framework emphasizes understanding as much as possible the many sources of risk and uncertainty that policymakers face, quantifying those risks *when possible*, and assessing the costs associated with each of the risks. ... ... This framework also entails, in light of those risks, a strategy for policy directed at maximizing the probabilities of achieving over time our goals ... ... As this episode illustrates (the deflation hedge recorded above), policy practitioners under a risk-management paradigm may, at times, be led to undertake actions intended to provide *insurance against especially adverse outcomes*" {Greenspan (2004); pg. 37; emphasis by the current author}

Clearly, these views are consistent with an approach that would expend some resources over the near-term to avoid a significant risk (despite a low probability) in the future. It is perhaps most important to remember that none of the models that informed FED policy in real time put any probability weight on the chance of deflation. The Board simply knew that this critical probability *was not zero* and it understood that the *potential consequences were too large to ignore*. Stated more succinctly, the FED understood that this low-probability but high-consequence event represented an *enormous risk*.

It is reassuring that our current understanding of the climate system can support at least preliminary applications of a similar approach. Even though its coverage cannot be comprehensive, it can, at the very least, provide some information about consequences of climate change that we would like to avoid and some insight into the sensitivity of their likelihood to mitigation. Indeed, many authors have recently provided insights to some or all of the requisite components. Some have, for example, applied the principles of risk assessments directly in comparisons of the costs of mitigation with the corresponding changes in climate risks. Mastrandrea and Schneider (2004) used the DICE economic model from Nordhaus and Boyer (2000) to assess the costs of avoiding dangerous climate change as defined by assumptions drawn from the IPCC (2001a, b). 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. Others researchers, like Jones (2004a, b) and Wigley (2004), have done part of the work by presenting frameworks that probabilistically relate CO_2 concentrations at stabilization with equilibrium temperature even though they stopped short of relating their results to either the costs of mitigation or the benefits of avoiding damages. Still others have begun to consider the role of learning in informing risk assessment. Brian O'Neill edited an entire volume of papers designed to explore the role of learning in setting long-term mitigation strategies; see O'Neill (2008) for his overview paper. Schlesinger et al. (2006) adopted a more focused approach by tracking the likelihood of a collapse of the Atlantic thermohaline circulation (the THC) over the next one or two centuries under a variety of mitigation assumptions using three alternative representations of underlying uncertainty in climate sensitivity and in three fundamental parameters of a simple, reduced-form ocean model. Zickfeld and Bruckner (2008) followed with an investigation of the implications of alternative emissions corridors on the same THC risk profile using an alternative ocean model. Taken together, these studies show progress in tracking the potential efficacy of mitigation in reducing the likelihood of serious consequences even when information about likelihood is more fully developed than evidence about consequence.

In addition, of course, our understanding of the science of climate change provides “not-implausible” descriptions of why a variety of “tipping points” could easily exist. Collapsing land-based ice-sheets, collapsing ocean currents, runaway methane emissions from melting tundra, collapsing livelihood support generating humanitarian crises that could put enormous pressure on unfriendly international boundaries all come to mind. Greenspan offers evidence of an economic reason to respond; and again, simple economics instructs us to act as soon as possible.

4 Integrated assessment and risk-based metrics

Can integrated assessment models do anything to continue to complement a risk-based approach to climate? Again, the answer is “yes”, particularly when it comes to providing an appropriate range of prices for carbon for other analyses. To see how, it is sufficient to recognize the notion of certainty equivalence, a fundamental concept derived from risk analysis that has successfully been exploited to inform mitigation decisions in cases where underlying model developments have been able to provide the requisite reflections of the relative likelihoods of possible futures.[3] Stern et al. (2006 and 2007) are primary examples of this approach. Climate damages that were expressed there in terms of losses in certainty equivalent per capita consumption discounted over 200 year futures. To be more specific, Stern et al. (2006) accommodated enormous variability in per capita consumption across 1,000 climate scenarios tracked through the year 2200 (for multiple regions that together spanned the globe) by computing mean expected discounted utility without and with climate change (for three different damage calibrations). The certainty equivalent for each was then computed; i.e., the authors calculated the initial level of per-capita consumption which, if it were to grow with certainty at 1.3% per year (an assumed “natural growth rate”), would achieve a level of discounted utility exactly equal to the expected discounted utilities just defined. The economic values of global damage attributable to climate change damages under alternative calibrations were then taken to be the differences between certainty equivalents with and without climate change—differences expressed in terms of an extremely aggregated, single valued and utility-based metric of risk. In their simplest form, these computed differences in indices are simply estimates of the fraction of current per capita consumption that the representative citizen would be willing to pay to eliminate all of the climate risk captured by the underlying analysis.

Stern et al. (2006) did not report any comparable results from their full modeling exercise for any specific mitigation trajectories. As a result, they provided no infor-

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[3] The certainty equivalent of a risky situation is implicitly defined as the outcome that would, if it could be guaranteed, achieve a level of welfare or utility that is equal to the *expected welfare* or *utility* calculated across all possibilities. The difference between a certainty equivalent and an *expected outcome* therefore represents an estimate of what people would be willing to pay to avoid the risky situation altogether. In addition, differences in certainty equivalents for two distributions of outcomes can be used to track what people would be willing to pay to reduce uncertainty.

mation about what their representative citizen would be willing to pay for various levels of emission reductions. Tol and Yohe (2009) worked to fill this gap using a much simpler model; Table 1 shows their results. Notice in the first row that the unregulated path is calibrated to match the Stern baseline—a 5.3% reduction in certainty equivalent per capita consumption from climate change. Corresponding levels of residual damage, expressed comparably in terms of certainty equivalence along cost-minimizing mitigation pathways, are then reported for concentration thresholds ranging all the way down to 400 ppm. It is important to recognize that none of these concentration limits eliminate damages completely, so none of them obviates the need for adaptation. It is also important to remember that even Stern et al. (2006) does not include economic metrics of socially contingent impacts. Still, as indicated in Anthoff et al. (2009a, b), calculating certainty equivalents to quantifying climate damages (the ones that can be quantified in currency, at least) can support new estimates of the social cost of carbon. These new estimates are designed explicitly to reflect uncertainties; they thereby suggest why attitudes toward risk and inequity, choice of baseline, and the income elasticity of damages can be just as important as time preference in producing relatively high (or low) values for policy analyses that need to price carbon.

5 The beginnings of an integrating framework based on risk-management

It cannot be asserted, though, that dynamic optimization is not without its comparative advantages. Its necessity in assigning a value for carbon reductions, however flawed, has already been noted. Moreover, dynamic optimization inspired by the original Nordhaus (1991) framing of the question are born of a rigorously developed and internally consistent framework within which it is possible to assess, with admittedly incomplete information, tradeoffs on the margin in a world constrained by scarce resources. The same cannot (yet) be said for the risk-based approach. The seeds of such a framework have been sown, however, and Fig. 1 offers a cartoon of some early thoughts.

The left-hand side offers a schematic of three Annex I act then learn (about non-Annex I participation) then act scenarios. The idea here is that developed countries understand that their initial response is necessary but not sufficient to meet any but the most lenient long-range concentration targets. The emissions trajectory arrows are illustrative at best, but it is important to note that the upper arrows for each

Table 1 Estimates of residual economic damage along least-cost mitigation pathways from the Stern et al. (2006) baseline expressed in terms of certainty equivalent per capita consumption; source: Tol and Yohe (2009)

Atmospheric concentration	Δ Certainty equivalent per capita consumption
Unregulated	−5.3%
750 ppm	−3.8%
700 ppm	−3.4%
650 ppm	−3.0%
600 ppm	−2.6%
550 ppm	−2.2%
500 ppm	−1.7%
450 ppm	−1.3%
400 ppm	−0.8%

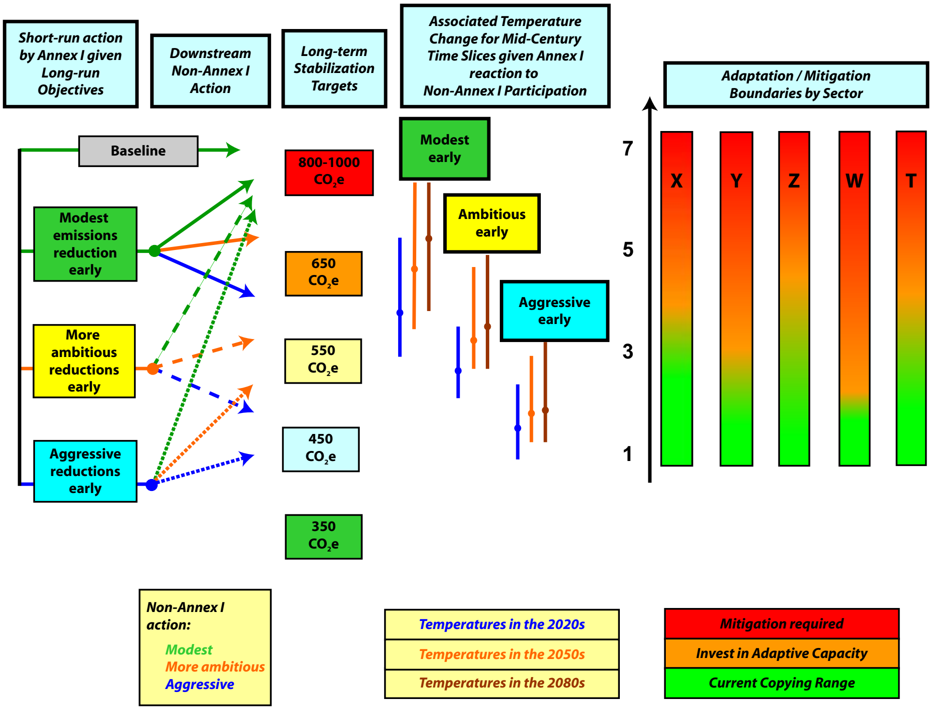

Fig. 1 A schematic portrait of an integrating risk-based framework for evaluating iterative mitigation and adaptation responses to climate change. The left hand portion illustrates an "act then learn then act again" approach to near-term mitigation decisions. Annex I starts the process with the understanding that adjustments will be made as they observe how non-Annex I nations will respond; i.e., they may slow or increase the pace of their emissions reductions if they see non-Annex I countries delaying or accelerating their participation in global mitigation strategies. The results, over the longer-term, produce trajectories of atmospheric concentrations that move toward values in 2100 ranging from 350 ppm CO_2e to perhaps 1000 ppm CO_2e. The middle panel translates these trajectories into time slice portraits of the distribution of global mean temperature change (in the 2020's, the 2050's and the 2080's). The *right-hand side* summarizes vulnerabilities in key sectors and their sensitivity to the aggregate temperature change index of climate change; they are calibrated in terms of current coping ranges for climate variability superimposed on dynamic climate change, the extent to which investment in adaptive capacity might expand those ranges, and levels above which even those investments would be "overwhelmed". Source: personal communication with Leon Clarke, Linda Mearns, Richard Moss, Richard Richels, Tom Wilbanks, and John Weyant. The figure was produced by M. Yohe

(limited no non-Annex I participation) end up very near the baseline. While Annex I emissions started this problem, reducing Annex I emissions over a decade or two will have little effect on ultimate concentrations.

The middle part of the figure depicts temperature distributions along the three Annex I mitigation alternatives; their ranges are determined not only by profound scientific uncertainties like climate sensitivity, but also uncertainty about what non-Annex I countries will do. No emissions scenario produces deterministic temperature trajectory, though; this is the fundamental reason why climate is a risk management problem.

The right-hand side mimics the contribution of the authors of Chapter 11 (Australia and New Zealand) to IPCC (2007b, Figure 11.4). There, the sensitivity of current coping ranges and the potential of investment adaptive capacity to accommodate climate variability in a dynamic climate were assessed for a range of key sectors. Even though the specific vulnerabilities for specific sectors might depend on something other than global mean temperature (like changes in precipitation, storm tracks, humidity, day and/or night temperatures, etc…), the authors found it useful to correlate these sources of stress to global mean temperature.[4] Uncertainty in these associations means that the boundaries should be blurred. The aggregation involved in surveying each sector across time and space and economic development pathway is another reason for the blurring. Notwithstanding the blurring, the result is a visual portrait of when adaptive capacity is overwhelmed and mitigation is the only choice with which society might ameliorate specific risks.

Problems with the framework are obvious, especially in light of discussions of similar aggregate indicators of vulnerability calibrated to temperature change. Vulnerabilities are local and driven by many different manifestations of climate change (i.e., not just temperature change). It is also difficult to produce credible within-century time slice distributions for temperature change that are tied to alternative mitigation pathways that envision staggered participation by both Annex I and non-Annex I countries. Adaptive capacity is one primary source of diversity in vulnerability over space and time, and this path dependence certainly depends on mitigation decisions. Put another way, the climate problem is not as linear as it is portrayed. Finally, iteration in mitigation will depend on more than whether or not global participation is achieved in a timely manner. Those observations are important to track progress toward announced mitigation objectives, but those objectives might also change with new information about the climate system, climate impacts associated with climate variability, the identification of major "tipping points" for catastrophic impacts, the relative success of investment in adaptive capacity, and the like.

In light of these and other concerns, it must be emphasized that frameworks of the sort portrayed in Fig. 1 should not be the foundation upon which policy can be built. Figure 1 offers only a schematic into which information might flow with the purpose of informing policy deliberations—not yet ready to suggest actual responses, but nonetheless capable of rigorously identifying the locations of key, high-risk vulnerabilities. The result of organizing thoughts and research efforts to fill in schematics of the sort displayed in Fig. 1 can, quite simply, focus more detailed analyses of when and how best to intervene, how to adjust the long-term objectives of iterative mitigation policies, and the degree to which a wide range of risks would be sensitive to alternative mitigation strategies. As an example of how a more textured analysis might be conducted, consider the vulnerability of New York City to severe coastal storms as a proof of concept. Despite the simplicity and limited scope, some interesting hypotheses will also be advanced.

Developed coastlines are, of course, among the most vulnerable places on the planet to the various manifestations of climate change. Indeed, if one were to list "hot-spots" of vulnerability to climate change across North America or around the

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[4] Much like the "burning embers" that were developed by the authors of Chapter 19 in IPCC (2001a), highlighted by the governments that approved the Third Assessment Report in IPCC (2001b) and updated in Smith et al. (2009) on the basis of new information derived from IPCC (2007a), IPCC (2007b) and summarized in IPCC (2007c) and subsequent literature.

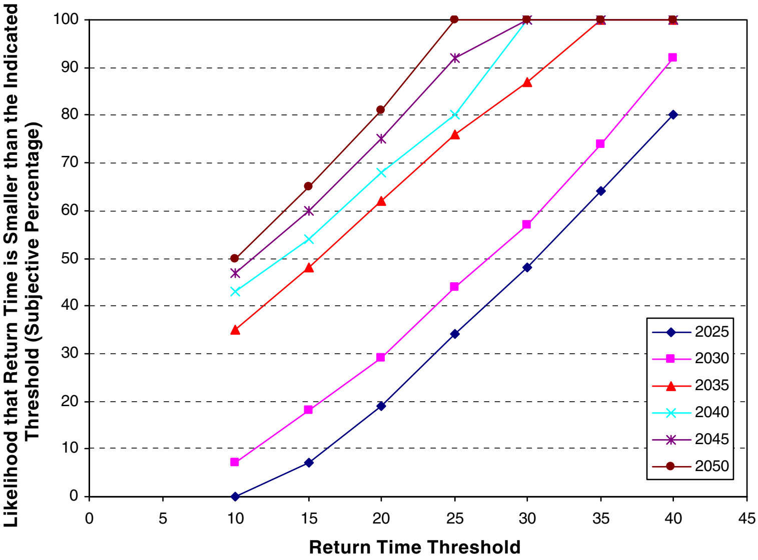

Fig. 2 The relative likelihoods that the return time of the 2005 calibrated 100-year anomaly will be smaller than specified planning horizon in selected years. Any point on any locus indicates, with its vertical location and for the identified year, the likelihood that the return time of the 100-year storm will be smaller than the value identified by its horizontal location. So, for example, third triangle point up the red locus shows that it is more than 60% likely that the return time will be less than 20 years

world, coastal cities would surely be well represented. In this example, the 100-year anomaly for New York City (as last judged by FEMA in the 1980's) is chosen to represent how such vulnerability might be experienced. It builds directly on recent work by Kirshen et al. (2008) in which return times of the current "100-year" flooding event are correlated with prospective levels of sea level rise. It is important to note that these return times are not a function of any presumption that the intensities or frequencies of coastal storms along the New York coastline will change with climate. They are, instead, simply the result of rising sea levels on surges associated with storms so that what now looks like the 25- or 50-year storm in terms of flooding will, sometime in the future, look like the current 100-year storm. The question, therefore, is "when will the current 20-year storm be transformed into the analog of the 100-year storm?" The answer, as always, is "It depends", which begs the question "On what?"

To explore that question, alternative trajectories of future sea level rise around New York City were derived from four alternative emissions scenarios reported, along with subjective probabilities of their relative likelihoods, in Yohe et al. (1999) across nine alternative climate sensitivities.[5] Figure 2 shows the results of superimposing the resulting probabilistically weighted sea level rise scenarios on the Kirshen results. Given this information, a decision-making planner who reported that a 40-year return time was the lower bound of his or her comfort zone could see an

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[5] The climate sensitivity distribution applied here is drawn from Yohe et al. (2004); it is a discrete representation of the distributed reported in Andronova and Schlesinger (2001).

80% chance that this threshold would be breached within a 2025 planning horizon with virtual certainty beyond 2035. This realization could easily trigger any number of adaptative responses that could range from significant investment in protection to planned retreat from the sea (highly unlikely in downtown Manhattan, but more likely for some more residential and exposed communities). If, however, our planner were comfortable after having taken some preliminary protective action, with a lower return time like 20 years for the current 100-year anomaly, then the likelihood of falling below this lower threshold would be a more tolerable 20% in 2025 and 30% in 2030. The subjective likelihood of crossing the critical return time threshold would, though, jump to more than 60% by 2035. It follows that the original urgency of the more risk-averse planner would be diminished, but not by much. More generally, it would appear that some serious risks appear in the middle of the distribution of possible climate futures; put another way for conjectural hypothesis number 1—worrying about the dark tails is not always necessary.

Turning now to questions about the sensitivity of adaptation decisions to various mitigation strategies, consider Fig. 3. It displays some evidence about the sensitivity of the return time of the 100 year flooding anomaly to alternative mitigation pathways for the year 2050. The unabated plot adds some detail to the 2050 distribution recorded in Fig. 2. The IPCC(450) mitigation scenario adds about 10 years to the median return time—roughly equivalent, according to Fig. 2, to a 10 or 15 year delay in crossing the 50–50 risk threshold. Perhaps more importantly for the policy community at large, however, notice that the more cost effective WRE {see Wigley et al. (1996)} mitigation pathway does not expand the return time associated with any likelihood threshold for the 100-year storm anomaly as vigorously as the more aggressive near-term IPCC mitigation trajectory. While it is difficult to draw general insight from a single example (indeed, a single year for a single example), this result strongly supports a second hypothesis—the timing of mitigation efforts can matter in ways that could easily influence the urgency with which adaptation might be pursued. If true, we could add a corollary—the timing of mitigation could alter the set of acceptable adaptation options under consideration. This simple hypothesis,

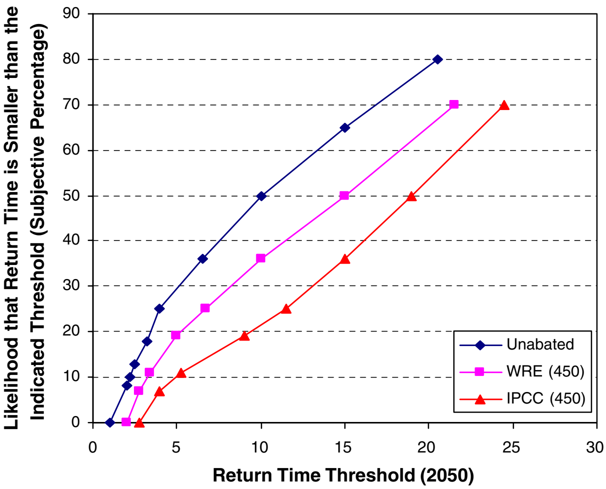

Fig. 3 The relative likelihoods that the return time of the 2005 calibrated 100-year anomaly will be smaller than specified planning horizon in 2050. These loci indicate the likelihood that the return time of the 100-year storm along unabated and two mitigation trajectories; both hold concentrations of greenhouse gases below 450 ppmv in CO_2 equivalents along two different emissions trajectories. The slower pace of early reductions along the more cost-effective WRE trajectory reduces the efficacy of mitigation to slow the reduction in return times

if supported by other detailed analyses from other sectors and other locations, is certainly consistent with earlier critiques of cost-effectiveness analyses like WRE that argues that cost-effectiveness expressed only in terms of mitigation costs would not adequately account for the timing of impacts and their associated costs. A third hypothesis can now be articulated—the most efficient timing of investment in adaptation and/or adaptive capacity depends on the timing of mitigation.

6 Concluding remarks

Research and policy communities are beginning to come to grips with the obvious point that nobody will be setting climate policy in 2009 for the entire 21st century. Indeed, the first adjective in the IPCC (2007c) synthetic conclusion highlighted at the top is "iterative". It follows that perhaps the most important contribution of a framework like the one portrayed in Fig. 1 will involve clarifying what iteration might mean by, in the first instance, highlighting what should be monitored over time to inform mid-course adjustments and to make their implementation as transparent as possible.

The left-hand side, for example, tells us to keep track of emissions trajectories and their distribution across nations. How emissions are moving relative to the short-term targets that set the course for achieving long-term objectives? Are they higher or lower than expected, and how might their allocations be adjusted.

The right-hand side can focus attention on how to identify key vulnerabilities, on how our knowledge about their underlying sensitivities and exposures is evolving, and on the degree to which investment in adaptive capacity in critical areas and sectors is expanding current coping ranges. The right-hand side can also highlight the thresholds above which adaptative capacity would be overwhelmed by progressing climate change—i.e., providing information on what might be considered "dangerous anthropogenic interference with the climate system".

The middle portion shows dramatically why climate change is a risk problem because it shows that no concentration limit can guarantee any temperature limit. Indeed, many uncertainties are so profound that they will never be resolved in a timely fashion. The poster child in this regard is climate sensitivity—the increase in global mean temperature that is associated with a doubling of greenhouse gas concentrations from pre-industrial levels. Current understanding puts the range of this critical parameter between 1.5°C and more than 5°C, but it is now widely accepted that substantial and timely reductions in this uncertainty are quite unlikely.[6]

In conclusion, the existence of profound uncertainties means that a policy proposal which works to delay immediate action in favor of waiting for the results of a

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[6] IPCC (2007a) reports, for example, that "the equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is not a projection but is defined as the global average surface warming following a doubling of carbon dioxide concentrations. It is *likely* to be in the range 2°C to 4.5°C with a best estimate of about 3°C, and is *very unlikely* to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values." Roe and Baker (2007) show, for example, that "the probability of large temperature increases" is "relatively insensitive to decreases in uncertainties associatedwith the underlying climate processes". Allen and Frame (2007) responded by arguing that it was pointless for policy makers to count on narrowing this fundamental uncertainty.

"crash research program" to narrow their ranges is not viable. Moreover, since we should not anticipate that we will be able to set long term policies in concrete at any time in the foreseeable future, policy proposals that claim to be the result of long-term dynamic optimization efforts should be viewed with skepticism (for reasons that are far more fundamental than the points made by Ackerman, et al.). To support the requisite "iterative risk-based process involving mitigation and adaptation" we must begin to devise an analytic framework that will help us construct a process in which interim targets and objectives will be informed by long-term goals in ways that make appropriate adjustments as efficient and as transparent as possible. This is a simple conclusion that makes enormous sense, but its promise cannot be overstated. No policy intervention at this point can guarantee that climate catastrophes will not happen—but properly framed interventions can lower their likelihoods.

References

Ackerman F, DeCanio SJ, Howarth RB, Sheeran K (2009) Limitations of integrated assessment models of climate change. Clim Change. doi:10.1007/s10584-009-9570-x

Allen M, Frame D (2007) Abandon the quest. Science 328:582–583

Andronova NG, Schlesinger ME (2001) Objective estimation of the probability density function for climate sensitivity. J Geophys Res 106:605–622

Anthoff D, Tol RSJ, Yohe G (2009a) Risk aversion, time preference, and the social cost of carbon. Environmental Research Letters 4:024002. Available at IDEAS/RePEc http://ideas.repec.org/p/esr/wpaper/wp252.html as well as http://stacks.iop.org/1748-9326/4/024002

Anthoff D, Tol RSJ, Yohe GW (2009b) Discounting for climate change. Economics: The Open-Access, Open-Assessment E-Journal 3:2009–4

Congressional Budget Office (Congress of the United States) (2005) Uncertainty in analyzing climate change: policy implications. Washington, D.C. 36 p

Greenspan A (2003) Opening remarks, monetary policy and uncertainty: adapting to a changing economy. In Monetary Policy and Uncertainty: Adapting to a Changing Economy, Federal Reserve Bank of Kansas City, pp 1–7

Greenspan A (2004) Risk and uncertainty in monetary policy. Am Econ Rev 94:33–40

Intergovernmental Panel on Climate Change (IPCC) (2001a) Climate Change 2001: impacts, adaptation, and vulnerability. Cambridge University Press, New York, 2000 pp

Intergovernmental Panel on Climate Change (IPCC) (2001b) Climate Change 2001: synthesis report. A contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, 398 pp

Intergovernmental Panel on Climate Change (IPCC) (2007a) Climate Change 2007: the physical science basis. Cambridge University Press, Cambridge

Intergovernmental Panel on Climate Change (IPCC) (2007b) Climate Change 2007: impacts, adaptation and vulnerability. Cambridge University Press, Cambridge

Intergovernmental Panel on Climate Change (IPCC) (2007c) Climate Change 2007: synthesis report. Cambridge University Press, Cambridge

Jones RN (2004a) Managing climate change risks. In: Agrawal S, Corfee-Morlot J (eds) The benefits of climate change policies: analytical and framework issues. OECD, Paris, pp 249–298

Jones RN (2004b) Incorporating agency into climate change risk assessments. Clim Change 67:13–36

Kirshen P, Watson C, Douglas E, Gontz A, Lee J, Tian Y (2008) Coastal flooding in the northeastern United States due to climate change. Mitig Adapt Strategies Glob Chang 13:437–451

Mastrandrea MD, Schneider SH (2004) Probabilistic integrated assessment of "dangerous" climate change. Science 304:571–575

Nordhaus W (1991) To sow or not to slow: the economics of the greenhouse effect. Econ J 101:920–937

Nordhaus W, Boyer J (2000) Warming the world—economic models of global warming. MIT Press, Cambridge, 232 p

O'Neill B (2008) Learning and climate change: an introduction and overview. Clim Change 89:1–6

Raiffa H, Schlaiffer R (2000) Applied statistical decision theory. Wiley, New York

Roe G, Baker M (2007) Why is climate sensitivity so unpredictable? Science 328:629–632

Schlesinger M, Yohe G, Yin J, Andronova N, Malyshev S, Li B (2006) Assessing the risk of a collapse of the Atlantic thermohaline circulation. In: Schellnhuber HJ, Cramer W, Nakicenovic N, Wigley T, Yohe G (eds) Avoiding dangerous climate change. Cambridge University Press, Cambridge

Smith JB, Schneider SH, Oppenheimer M, Yohe GW, Hare W, Mastrandrea MD, Patwardhan A, Burton I, Corfee-Morlot J, Magadza CHD, Fussel H-M, Pittock AB, Rahman A, Suarez A, van Ypserselen J-P (2009) Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) 'reasons for concern. Proc Natl Acad Sci U S A 106:4133–4137. 17 March 2009 available through open access at www.pnas.org_cgi_doi_10.1073_pnas.0812355106

Stern NH, Peters S, Bakhshi V, Bowen A, Cameron C, Catovsky S, Crane D, Cruickshank S, Dietz S, Edmonson N, Garbett S-L, Hamid L, Hoffman G, Ingram D, Jones B, Patmore N, Radcliffe H, Sathiyarajah R, Stock M, Taylor C, Vernon T, Wanjie H, Zenghelis D (2006) Stern review: the economics of climate change. Cambridge University Press, Cambridge

Stern N, Peters S, Bakhshi V, Bowen A, Cameron C, Catovsky S, Crane D, Cruickshank S, Dietz S, Edmonson N, Garbett S-L, Hamid L, Hoffman G, Ingram D, Jones B, Patmore N, Radcliffe H, Sathiyarajah R, Stock M, Taylor C, Vernon T, Wanjie H, Zenghelis D (2007) Postscript. HM Treasury, London

Stott PA, Stone DA, Allen MR (2004) Human contribution to the European heatwave of 2003. Nature 432:610–614

Tol RSJ (2003) Is the uncertainty about climate change too large for expected cost–benefit analysis? Clim Change 56:265–289

Tol RSJ (2005) The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties. Energy Policy 33:2064–2074

Tol RSJ, Yohe G (2009) The stern review: a deconstruction. Energy Policy (in press)

Webster MD, Forest CE, Reilly J, Babiker M, Kicklighter D, Mayer M, Prinn R, Sarofim M, Sokolov AP, Stone P, Wang C (2003) Uncertainty analysis of climate change and policy responses. Clim Change 61:295–320

Weitzman ML (2009) On modeling and interpreting the economics of catastrophic climate change. Rev Econ Stat 91:1–19

White House (2003) OMB Circular No. A-4, "Regulatory Analysis". Available at http://www.whitehouse.gov/omb/memoranda/m03-21.html

Wigley TML (2004) Modelling climate change under policy and no-policy pathways. In: Agrawal S, Corfee-Morlot J (eds) The benefits of climate change policies: analytical and framework issues. OECD, Paris, pp 221–248

Wigley T, Richels R, Edmonds J (1996) Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. Nature 379:240–243

Yohe GW (2003) More trouble for cost–benefit analysis. Clim Change 56:235–244

Yohe G (2004) Some thoughts on perspective. Glob Environ Change 14:283–286

Yohe G, Tol RSJ (2008) Precaution and a dismal theorem: implications for climate policy and climate research. Chapter 7. In: Geman H (ed) Risk management in commodity markets. Wiley, Chichester, pp 91–99

Yohe G, Jacobsen M, Gapotochenko T (1999) Spanning 'not implausible' futures to assess relative vulnerability to climate change and climate variability. Glob Environ Change 9:233–249

Yohe G, Andronova N, Schlesinger M (2004) To hedge or not against an uncertain climate future. Science 306:415–417

Zickfeld K, Bruckner T (2008) Reducing the risk of Atlantic thermohaline circulation collapse: sensitivity analysis of emissions corridors. Clim Change 91:291–316