Addressing Climate Change through a Risk Management Lens

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Abstract

In the Summary for Policymakers of the Synthesis Report for its Fourth Assessment, the Intergovernmental Panel on Climate Change (IPCC) achieved unanimous agreement from signatory countries of the Framework Convention that, "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; emphasis added). By accepting this key sentence, governments recognized for the first time, that their negotiations and associated policy deliberations must, individually and collectively, be informed by views of the climate problem drawn through the lens of reducing risk.

As new as this perspective might be for climate policy negotiators, risk-management is already widely used by policymakers in other decision making processes, such as designing social safety net programs, monetary policy, and foreign policy. Even though governments and some segments of the policy community are comfortable with the risk management paradigm, however, the climate change research and assessment community had heretofore been slow to catch on. This paper presents a first attempt to deconstruct the application of a risk-based paradigm to climate change by considering the critical phrases that are highlighted above, offering insights into what we do and do not know in each case.

Perhaps most importantly, the typical cost-benefit analysis used to make decisions in establishing regulations may not be fully appropriate for the climate problem because, to a large degree, many damages cannot be expressed monetarily and because uncertainty is so pervasive. To avoid being hamstrung by these fundamental complications, traditional policy analyses need to be supplemented by risk-based explorations that can more appropriately handle low-probability events and more easily handle large consequences calibrated in non-monetary metrics. In short, adopting a risk-based perspective will bring new clarity to our understanding of the diversity and complexity of the climate problem.

Introduction

Since the Synthesis Report of the Fourth Assessment Report (IPCC, 2007c) was approved by the Intergovernmental Panel on Climate Change in November 2007, much of the world's attention has focused on the economic costs of mitigation, species extinctions, extreme weather events, and other impacts that were highlighted in the previously approved report of Working Groups II and III (IPCC, 2007a & 2007b). Although these are important examples of the society and nature's vulnerability to climate change, the key policy development of the Fourth Assessment has received little attention: in a few paragraphs that appear toward the end of the Summary for Policymakers of the Synthesis Report, governments accepted ***risk*** as the unifying theme of this and future assessments. Because the world's governments unanimously approved the Summary for Policymakers word by word, they have all agreed that risk—not just impacts or their derivative vulnerabilities—matters most to them as they consider how to respond to the climate problem. As an expression of this paradigm shift, governments embraced a fundamental insight of the Fourth Assessment:

> *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; emphasis added)

Governments are beginning to 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 finance ministers have been using for decades, so it is not surprising that many governments' delegations understand the concept. Perhaps the only surprise was that it took so long for governments to recognize that they should look at climate change through the same lens through which they view social safety-net programs, monetary policy, and foreign policy.

Although governments and some segments of the policy community may be comfortable with the risk management paradigm, the climate change research and assessment community has heretofore failed to catch on. If researchers are to contribute further to the assessments that are the foundations of global policy deliberations, they must make rapid progress in providing policy-relevant, rigorous, scientific insight into how to make sense of the IPCC's conclusion quoted above.

This paper presents a first attempt to deconstruct the paradigm by taking each italicized phrase in turn and offering insights into what we do and do not know in each case. We know quite a bit about some of these critical phrases, and future research agendas will focus on applying, extending, and communicating that knowledge. For others, however, research into new approaches is required. Section 1 begins with a brief discussion of how *iterative* processes might be applied to the climate arena. Section 2 focuses attention on the need for supplementing traditional cost-benefit approaches with *risk-management* techniques. The insights offered here are amplified in Sections 3 and 4 by underscoring the roles of *both adaptation and mitigation* in a risk-reduction portfolio and by highlighting the boundaries of our understanding of the *benefits and co-benefits* of such a portfolio. Section 5 offers some preliminary thoughts about the roles of *sustainability, equity, and attitudes toward risk* in evaluating and synthesizing the value and costs of future iterative policy decisions. Finally, the concluding section reviews what we do and do not know about how to apply analytic techniques to the synthetic conclusion.

1. "Iterative"

Although climate change is a long-term problem that will require sustained policy action for a century or longer, it is unlikely that we will be able to set climate policy today for the entire 21st century. Many uncertainties are so profound that they will not be resolved soon and, in some cases, may only be resolved in hindsight. A classic example of this conundrum is climate sensitivity—the increase in global mean temperature that is caused by a doubling of carbon dioxide concentrations from pre-industrial levels. Current understanding, as reported in IPCC (2007a, pg 65), puts the likely range of this critical parameter at 2 – 4.5 ^{o}C, but higher values are possible and it is widely accepted that timely reductions in this uncertainty are unlikely.[1] As reported in Roe and Baker (2007), for example, "the probability of large temperature increases" is "relatively insensitive to decreases in uncertainties associated with 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. As a result, a policy response that delays immediate action in favor of waiting for the results of a crash research program to narrow the range is not viable. Moreover, we should not anticipate that we will be able to set long-term policies in concrete at any time in the foreseeable future. It follows that we must begin to construct a process by which *interim targets and objectives* will be informed by *long-term goals* in ways that necessary adjustments can be made in an efficient manner (e.g., Yohe et al., 2004). This is a simple and logical conclusion, but difficult to make operational.

Domestic and international banking and financial systems provide some evidence that iterative policy-making can be accomplished on a macro scale (e.g., Stiglitz and Walsh, 2005; chapters 32 and 33). For example, central banks frequently set trajectories for growth in the money supply when they expect normal economic activity over a foreseeable future; they work within an announced time period that defines precisely when they expect to make the next round of policy decisions. Since they do not have exact control over the money supply, however, central banks also reserve the right to intervene

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[1] IPCC (2007a) describes "the equilibrium climate sensitivity [as] 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."

earlier than anticipated if the money supply climbs above or falls below clearly described thresholds that define acceptable levels of variability. Central banks can also monitor exchange rates in exactly the same way. In both cases, actors across the economy know exactly how the central bank will conduct its analyses in anticipation of making scheduled policy adjustments; that is, they can anticipate much of what will happen during those adjustments and begin to make appropriate changes in their own behaviors in advance of the policy change. These actors also understand what the banks will do if unanticipated adjustments are initiated by crossing the trigger threshold; that is, they can also detect early warning signs so that they can begin to respond in advance of these more unexpected events. In other words, transparency in the process can lessen the costs of planned or unplanned policy adjustments.

The experiences of these monetary structures suggest at least three evaluative criteria that can be applied to the climate arena: (1) keep long-term target options available for as long as possible by adopting hedging strategies to inform near-term actions and identifying downstream adjustment thresholds, (2) minimize the adjustment costs of regularly implemented adjustments, and (3) minimize administrative complexity in both by making them as transparent and as predictable as possible.

Events in the financial markets that marked the second half of 2008 clearly indicate that difficulties can still arise, especially when policy levers and well understood monitoring mechanisms break down. Central banks may have been monitoring the money supply, inflation rates, and exchange rate fluctuation in the early part of 2008, but it would seem that they were not keeping track of complexity in financial instruments that spread enormous risk across a range of unsuspecting and otherwise debt-burdened citizens and institutions.

Potentially unforeseen difficulties are perhaps even more ubiquitous and dangerous in the climate arena. The enormous uncertainty that still clouds our understanding of the climate system means that climate policy must be implemented while simultaneously monitoring impacts and vulnerability of human and natural systems. Even when we understand specific climate processes very well, persistent and potentially profound uncertainties about impacts can produce fuzzy thresholds of dangerous interference across key vulnerabilities that cannot all be calibrated in dollars. Some are best left in terms of “millions of people at risk from coastal storms” or changes in the return-times of the current 100-year flood. In other words, risks are potentially large and the possibility of a “bail-out” might be quite low. Insights drawn from our experience with monetary policy show us, however, that this complexity should not be a source of paralysis. Instead, they show the fundamental need for iterative policies that are designed both to hedge against potential calamities (i.e. lower their likelihoods with full understanding that there are no guarantees) and to adjust efficiently in response to new information about the climate and economic systems as well as performance against near-term goals.

2. "Risk management process"

Having recognized that pervasive uncertainty in our understanding of both the climate system and future political-social-economic development pathways requires iterative climate responses, we must now turn to framing the underlying analysis in ways that can inform such an approach. Here we contrast conventional benefit-cost techniques designed to determine the "optimal" policy with broader risk-management techniques designed to hedge against uncertain but potentially high-consequence outcomes and allow for mid-course adjustments as needed.

Beginning perhaps with Nordhaus (1991), the dynamic long-term version of the standard benefit-cost paradigm has been the mainstay of economic analyses of climate policy (particularly on the mitigation side). In applying this approach, researchers track economic damages that would be associated with climate change and costs that would be associated with climate policy over time scales that extend decades or centuries into the future. They calibrate these damages and costs along scenarios of economic development and resource availability that represent a range of possible (but unpredictable) futures. The damages and costs are disaggregated across countries and regions to varying degrees by different researchers, and both are discounted back to present values. In this final step, estimates of the present value of benefits and costs are highly sensitive to uncertain natural parameters (e.g., climate sensitivity) and uncertain policy parameters (e.g., the assumed discount rate, which is extremely sensitive to attitudes toward risk, attitudes toward inequity, and inter-temporal impatience, as discussed below).

Pointing out that some benefits (and even some costs) cannot be monetized, many researchers and commentators have become increasingly critical of this approach.[2] In response, practitioners have opened the door to tracking benefits and costs in terms of alternative, non-economic metrics, although such metrics have yet to be applied to regulatory policy.[3] They have also recognized problems with specifying appropriate discount rates, coping with uncertainty, and accommodating the profound distributional consequences of climate change.[4] Early in 2009, President Obama signed Executive Order 13497 instructing the Director of the Office of Management and Budget to review these issues with advice from regulatory agencies. While progress has been slow at the federal level, this action opens the door further to non-quantified costs and benefits expressed in

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[2] Critiques of relying too heavily on limited benefit-cost analyses include Tol (2003), Yohe (2004, 2006), and Ackerman et al. (this volume).

[3] For example, Circular A-4 [White House (2003)] was issued 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 leads with an explicit "presumption against economic regulation." Most of the text, though, is dedicated to illuminating "best practices" for circumstances in which intervention is deemed warranted. 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.

[4] See the paper by Rose in this volume.

non-monetary terms, including maintaining risk thresholds, being considered for regulatory design. Indeed, City of New York adopted this approach when it started to think about how to protect its enormous public and private infrastructure from growing climate risk; see NPCC (2009) for details.

As suggested by the IPCC (2007c), risk-management techniques can explicitly accommodate many (but not all) of these thorny issues.[5] Its most straightforward applications to climate change begin, as elsewhere, with the statistical definition of risk – the probability of an event multiplied by its consequence. In benefit-cost approaches, all consequences are calibrated directly as anticipated economic outcomes that are expressed in units of currency. In these applications, any dollar lost or gained in one possible outcome is worth the same as any other dollar lost or gained in any other outcome. It follows that decision-makers need only worry about expected dollar gains or losses regardless of how good or bad any particular outcome might be.[6] Risk management approaches expand the range of analytic applicability by allowing consequences to be calibrated in terms of more general welfare metrics. These metrics may depend on the same outcomes as before, but they make it clear that one dollar in one possible outcome is not necessarily worth the same as one dollar in another possible outcome. Metrics that reflect aversion to risk, for example, hold that an extra dollar gained in a good outcome is worth less, in terms of welfare, than an extra dollar lost in a bad outcome. It follows that the extremes of possible outcomes matter in these cases, and it is in these contexts that people buy insurance and/or adopt hedging strategies against especially bad outcomes—even if such strategies fail in a benefit-cost analysis. They do so because hedging increases expected welfare (computed over the welfare implications of the full range of possible outcomes) even though it reduces the expected dollar value of the associated outcomes.[7]

What do we know about how to apply this insight in the climate arena? According to the IPCC (2007a), we know "unequivocally" that the planet is warming. We are now "virtually

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

[6] To be precise, let the range of possible outcomes be calibrated by $\{X_1 , \ldots, X_n \}$ where the subscripts indicate financial values in n possible future states of the world. A benefit-cost approach looks only to calculating the expected outcome across these futures. That is, if $\{\pi_1 , \ldots, \pi_n \}$ represent the subjective likelihoods of each possible outcome, then expected benefit-cost calculations would focus attention exclusively on $E\{x\} \square \Sigma \pi_i \cdot X_i$.

[7] To continue with the notation of footnote 5, risk-analysis lets the consequences be calibrated in terms of welfare and not just outcomes. It follows that the relevant measure of the range of consequences is $\{U(X_1), \ldots, U(X_n)\}$ where U(-) is the welfare metric. In this case, decision makers worry about expected welfare and not expected outcome; i.e., they would focus attention on $E\{U(X)\} \square \Sigma \pi_i \cdot U(X_i)$. If they are averse to risk (so U(-) increases with X at a decreasing rate), then they would buy insurance even though the premiums they pay lowers every possible outcome. Why? Because insurance guarantees that they will be compensated to some degree should a really bad outcome (a really low value for X_i) materializes. In other words, they willingly sacrifice expected economic value calculated across all possible outcomes to reduce the pain that they would feel in the (potentially unlikely) event that a single bad outcome might occur; and they are so willing because doing so increases their expected welfare. Hedging is a variant on the same theme in which decision-makers sacrifice expected economic value to invest in some action that works to reduce the likelihood that a bad extreme event might occur. Both results can be derived directly from the observation that risk aversion means that $E\{U(X)\} < U(E\{X\})$.

certain" that the climate is changing at accelerating rates. We also know with "very high confidence" that anthropogenic emissions are the principal cause. We even have evidence that anthropogenic climate change was the strongest contributor to the conditions that created the 2003 heat wave across central Europe that caused tens of thousands of premature deaths (Stott et al., 2004; IPCC, 2007b). We also know from the dire consequences of the 2003 European heat wave, the 2004 Asian Tsunami, and Hurricane Katrina in 2005,[8] that both developing and developed countries are susceptible to the types of events that are expected to occur more often and with greater intensity in the future because of climate change. This knowledge alone is sufficient to establish the serious risks of climate change and the need to respond in the near-term in ways that will reduce future emissions and thereby ameliorate the pace and extent 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 as well as other indicators, including more widespread hunger, water stress, or greater hazards from coastal storms. It then follows from simple economics that action should begin immediately in order to minimize the expected cost of meeting any long-term objective.

As discussed previously, monetary policy provides a real-world illustration of how hedging strategies have been employed at a macro scale. At a 2003 symposium on "Monetary Policy and Uncertainty: Adapting to a Changing Economy,"[9] Chairman of the Federal Reserve Board Alan Greenspan, illustrated the point:

> *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 that 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 added)

Indeed, none of the models that informed Federal Reserve policy would even put a probability on the chance of deflation. The Board simply knew that it was not zero and that they did not want the economy to endure the consequences. The Chairman expanded on

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[8] Note that these events need not be linked to climate change to expose the underlying vulnerabilities to similar events that would be linked to climate change in the future. For example, although the Asian tsunami was caused by an earthquake, it simulated a storm surge that might be associated with a strong tropical cyclone.

[9] Monetary Policy and Uncertainty: Adapting to a Changing Economy: A symposium sponsored by the Federal Reserve Bank of Kansas City, Jackson Hole, Wyoming, August 28 - 30, 2003.

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…* (Greenspan, 2004, pg. 37; emphasis added)

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. Indeed, the Chairman used some familiar language when he summarized his position:

> *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 added)

Can our current understanding of the climate system support a similar approach to managing the risks of climate change? At the very least, we need some information about consequences of climate change that we would like to avoid and some insight into the sensitivity of their likelihood to mitigation. These are fundamental questions that must be addressed before proceeding.

Many authors have provided insights to some or all of the requisite components, i.e., estimates of probabilities of specific outcomes and quantifications or the associated vulnerabilities. Some have, for example, compared the costs of mitigation with the corresponding changes in climate risks:

- Mastrandrea and Schneider (2004) used the simplified integrated assessment model DICE to assess the costs of avoiding dangerous climate change as defined by assumptions drawn from the IPCC Third Assessment Report (IPCC, 2001a, 2001b).[10]
- Webster et al. (2003) used an integrated model of intermediate complexity to quantify the likelihoods of global warming futures in 2100, beginning with projections of population, economy and energy use.
- Jones (2004a, 2004b), Wigley (2004) and Jones and Yohe (2008), present frameworks that probabilistically relate stabilized CO_2 concentrations with equilibrium temperature, although these studies stopped short of relating their results to either the costs of mitigation or the benefits of avoiding damages.

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[10] For background on integrated assessment models, see the paper by Mastrandrea in this volume.

- Others have begun to consider the role of future 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 (O'Neill, 2008).
- Schlesinger *et al.* (2006) adopted a more focused approach by tracking the likelihood of a collapse of the Atlantic thermohaline circulation (THC) over the next one or two centuries under a variety of mitigation assumptions using three alternative representations of uncertainty in climate sensitivity. 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 very negative outcomes.

The concept of certainty equivalence is used in risk analysis to convert consequences calibrated in welfare terms into financial terms. Essentially, certainty equivalence accounts for risk aversion by providing an estimate of how much people would be willing to pay to avoid the risky situation.[11] It has also been employed to inform climate change mitigation decisions in cases where the relative likelihoods of various possible futures can be analyzed. Stern *et al.* (2006 and 2007) expressed damages in terms of losses in certainty equivalent per capita consumption discounted over 200-years. Using the uncertainty analysis capabilities of the simplified integrated assessment[12] model PAGE2002, the authors accommodated enormous variability in per capita consumption across 1000 model runs by computing mean expected discounted utility without and with climate change for three different damage calibrations. Certainty equivalents with and without climate change were then computed for each calibration; i.e., the authors calculated the level of per-capita consumption which, if it were to grow with certainty at 1.3 percent 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 for the three calibrations. In their simplest form, these computed differences 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) estimated what their representative citizen would be willing to pay to avoid all damages associated with three damage calibrations, but they provided no

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[11] 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. Returning to the notation of footnotes 5 and 6, the certainty equivalent outcome X_{ce} is defined implicitly as the solution to the equation $U(X_{ce}) \square E\{U(X)\}$. Since $X_{ce} < E\{X\}$ for risk-averse decision-makers, the difference between a certainty equivalent and an *expected outcome* (i.e., $E\{X\} - X_{ce}$) 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. For a recent application of this approach, see Newbold and Daigneault in this volume.

[12] For background on integrated assessment models, see the paper by Mastrandrea in this volume.

information about what their representative citizen would be willing to pay for various levels of emission reductions and their associated reductions in damages. 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 percent 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. Since all of these residuals are positive, none of the considered mitigation targets obviates the need for adaptation.

Table 1: Estimates of residual economic damage along least-cost mitigation pathways from the Stern et al. (2006) baseline expressed in terms of percentage changes in certainty equivalent per capita consumption relative to scenarios along which climate does not change. *(Source: Tol and Yohe, 2009)*

Atmospheric Concentration	Δ Certainty Equivalent Per Capita Consumption
unregulated	-5.3 percent
750 ppm	-3.8 percent
700 ppm	-3.4 percent
650 ppm	-3.0 percent
600 ppm	-2.6 percent
550 ppm	-2.2 percent
500 ppm	-1.7 percent
450 ppm	-1.3 percent
400 ppm	-0.8 percent

To summarize, we know that humanity's greenhouse gas emissions are changing the climate in ways that are likely to be detrimental to society and that some of the consequences could be catastrophic. We also know that the timing and severity of these changes are imprecisely associated with particular socioeconomic and emissions pathways. To be brutally honest, pervasive uncertainty about the physical and economic consequences of climate change undermines the credibility of economically optimal policies that emerge from traditional benefit-cost calculations. Since there is good evidence to suggest that getting the "optimal policy" wrong could be extremely expensive, it follows from straightforward economics that a complementary approach aimed at managing/reducing risk is required. It is important to recognize that hedging policies that emerge from the risk management approach would sacrifice a little in expected utility, but the payoff would be reductions in the likelihoods of unacceptable declines in general welfare – declines that would result if the optimal policy should fail.

3. "Both Adaptation and Mitigation"

The discussion has thus far framed mitigation as a mechanism by which climate risks can be reduced. This initial focus is appropriate because adaptive capacity can be overwhelmed even within the middle range of projected warming in developed and developing countries alike (IPCC, 2007b, Chapter 20). However, adaptation to unavoidable change is also required since we would be committed to another 0.6°C of warming even if greenhouse gas emissions had fallen permanently to zero in the year 2000 (IPCC, 2007b). It is therefore essential to consider the roles of both adaptation and mitigation in setting long-range climate stabilization goals and translating those goals into short-term objectives (in terms of, for example, emissions peaking points and the timing of adaptation investments). To make the synthetic statement of the IPCC (2007c) operational, we must also show how adaptation can be engaged in an iterative process designed to manage risk and how the need for adaptation can be influenced by investment in mitigation.

Since these issues have not yet received much attention, we will offer a simple applied example that focuses attention on the vulnerability of New York City to severe coastal storms as a proof of concept. In this example, the 100-year coastal flooding anomaly for New York City (as judged by FEMA in 2005) 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 the effects of changing intensities or frequencies of coastal storms were not considered. Only the effect of rising sea levels on storm surges associated with storms that now occur more frequently were considered (for example, the current 25- or 50-year anomalies that will, with rising sea level, portray inundation patterns now associated with the 100-year anomaly).

Alternative trajectories of future sea level rise around New York City were derived from 4 alternative emissions scenarios reported, along with subjective probabilities of their relative likelihoods, in Yohe et al. (1996) across 9 alternative climate sensitivities.[13] Figure 1 shows the results of superimposing the resulting probability-weighted sea level rise scenarios on the Kirshen results for flood return intervals. 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 80 percent 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 adaptive 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 percent in 2025 and 30 percent in 2030. The subjective likelihood of crossing the critical return time threshold would, though, jump to more than 60 percent by 2035. It follows that the original urgency of the more risk-averse planner would be diminished, but

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

not by much; put another way, adaptation might work for a short while, but it would not be sufficient over the long-term.

Figure 2, drawn from Yohe (2009) 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 Figure 1. The IPCC (450) mitigation scenario adds about 10 years to the median return time – roughly equivalent, according to Figure 1, to a 10 or 15 year delay in crossing the 50-50 risk threshold. Notice, however, that the more cost-effective WRE mitigation pathway (see Wigley et al., 1996), which allows emissions to peak later at the expense of sharper reductions thereafter, results in a smaller time delay than the earlier-acting IPCC scenario. Two insights from these results are that (1) slowing emissions buys more time for planning, financing, and implementing adaptation, and (2) the timing of emissions reductions (i.e. earlier vs. later peaking) for given stabilization concentration (e.g., 450 ppm CO_2-e) affects how much time the mitigation effort buys. Hence, the timing of mitigation efforts can influence the urgency with which adaptation might be pursued. Different levels of mitigation effort could even alter which adaptation options would be feasible

It should be clear from this preliminary work that risk profiles can portray a wide range of vulnerabilities over time even if those vulnerabilities cannot be expressed in terms of a single (monetary) metric. They can, therefore, be enormously valuable in considering and prioritizing investments in adaptation across multiple sectors and/or multiple locations. They can also be used to display the sensitivity of risks, with and without adaptation, to various mitigation pathways, although integrating the content of many individual risk profiles and scaling them up to the macro scale at which mitigation decisions are made remains problematic. A collection of vulnerability studies drawn from a wide sample of key vulnerabilities can nonetheless provide those decisions with information that is hidden in simple calculations of aggregate economic benefits. Such collections could thereby inform political deliberations about what might constitute “dangerous anthropogenic interference with the climate system” more fully.

Figure 1: The Relative Likelihoods that the Return Time of the 2005-calibrated 100-Year Anomaly Will Be Smaller than the Specified Planning Horizon in Selected Years. Any point on any line indicates, with its vertical location and for the identified year in the future, the likelihood that the return time of the 100-year storm will be smaller than the value identified by its horizontal location. For example, the third triangle up the red line shows that by 2035 it is more than 60 percent likely that the return time will be less than 20 years.

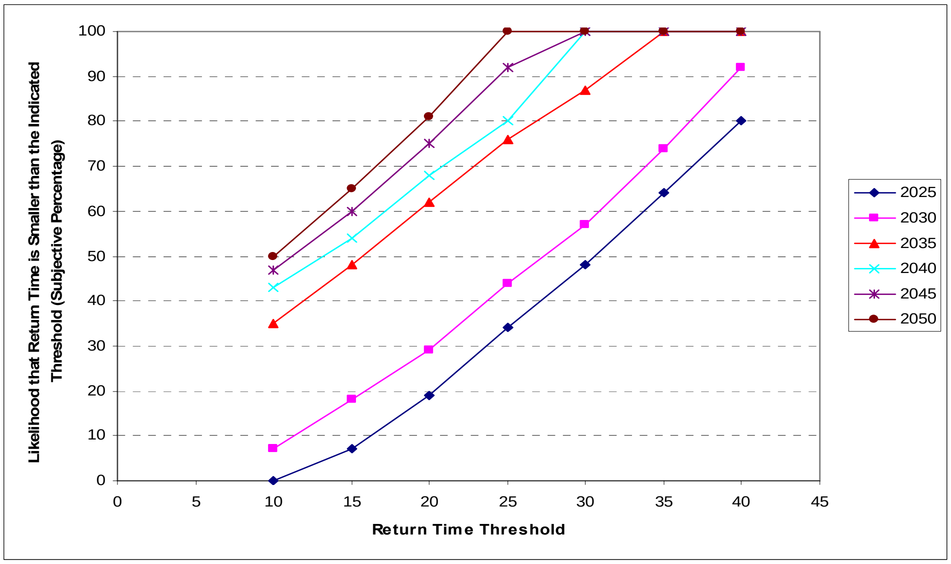
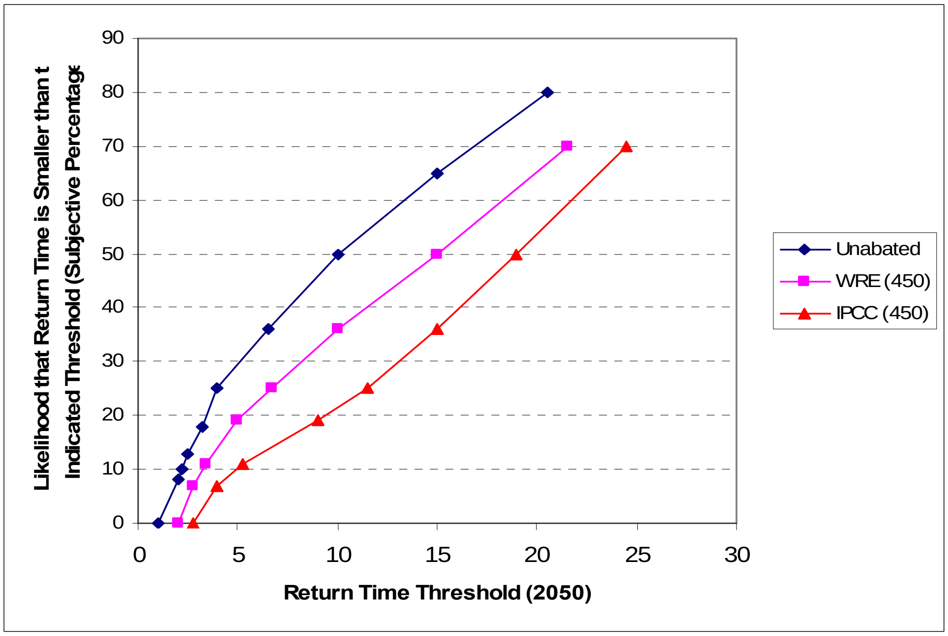


Figure 2: The Relative Likelihoods that the Return Time of the current 100-Year Anomaly Will Be Smaller than the Planning Horizon in 2050. The lines indicate the likelihood that the return time of the 100-year storm along unabated and two mitigation trajectories will be smaller than the indicated threshold in 2050; both stabilize concentrations of greenhouse gases at 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.



4. “Damages and co-benefits”

We turn now to consider metrics by which the damages of climate change, the costs of mitigation, and the potential for co-benefits across the two have been expressed. The first subsection indicates that existing estimates of economic damages from climate change have failed to address many of the dimensions of possible non-marginal climate impacts (that is, impacts that involve large and/or sudden changes). The second describes the “key vulnerabilities” identified from the current literature in Fourth assessment Report of the IPCC (2007b); the point here is that many of these vulnerabilities cannot be monetized (that is, they can only be calibrated in non-monetary metrics). A final subsection discusses the latest contribution by Martin Weitzman to the debate – a theoretical result that questions our ability to accommodate profound uncertainties that stretch the underlying probability distributions into regions where extreme and ambiguous consequences might occur.

4.1 Missing impacts

The matrix displayed in Figure 3, derived from a similar figure in Downing and Watkiss (2003), summarizes the state of the art in analyzing the economic impact of climate change and therefore the economic benefit of climate policy; it also appears in Yohe and Tirpak (2008) from which much of this subsection is drawn. The columns are divided vertically by the degree to which the complication of uncertainty in climate change science is captured by benefits analysis. They begin with coverage of projections of relatively smooth climate change trends (e.g., average temperature, sea level rise), move on to considerations of the bounded risks of extreme weather events (e.g., large-scale precipitation events and droughts) and climate variability along those trends, and end with representations of possible abrupt change and/or abrupt impacts. The rows are divided horizontally by the degree to which the corresponding impacts can be calibrated in monetary terms. They begin on the left with coverage of market impacts, move on to considerations of non-market impacts, and end with evaluations of socially contingent impacts (e.g. multiple stresses leading to famine and migration) across multiple metrics that cannot always be quantified in economic terms.[14]

Taken as a whole, the diagram suggests that much of the existing research has focused on market impacts along relatively smooth scenarios of climate change; i.e., most of our knowledge about the economic costs of climate change has emerged from *area 1* alone. In this context, researchers have noted the importance of site-specificity, the path dependence of climate impacts and the adaptive capacity of various systems. While coverage is greatest

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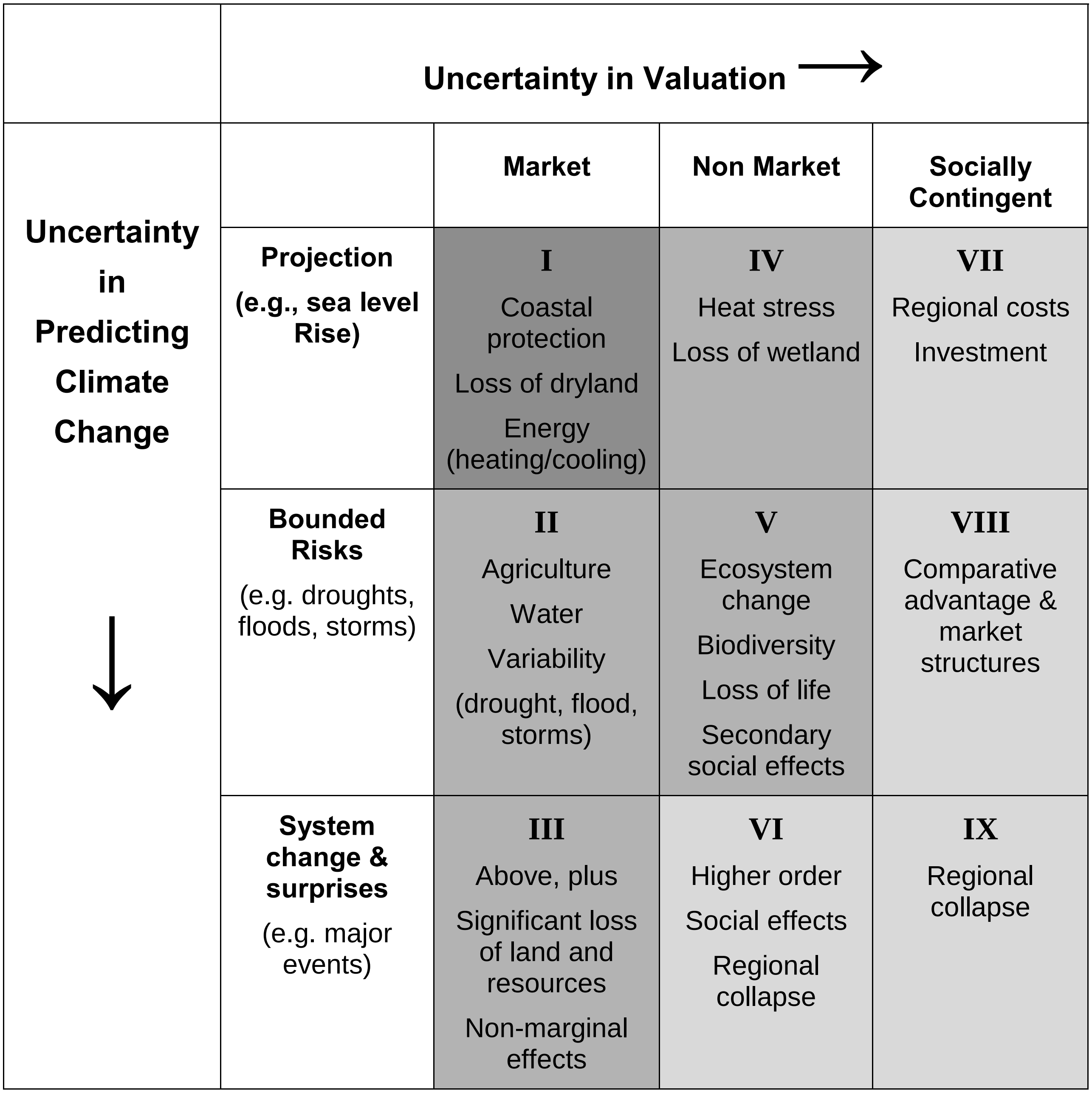
[14] The entries in the matrix are meant to be illustrative; and they are not meant to suggest the exclusive location of particular sectors like agriculture and forestry. There are, for example, impacts in those sectors derived from projections of long-term trends. They are shown in the bounded risk category to demonstrate additional and perhaps dominate sensitivity to climate driven variability and extreme weather events.

in *area 1*, this diversity of context means that coverage of even market-sector impacts is far from comprehensive.

Figure 3: Coverage of Existing Economic Analysis of the Impacts of Climate Change Related Risks. Most existing studies have been limited to market-based sectors, though a few have moved beyond region I to include non-market impacts along projected trends (region IV), bounded risks in market and non-market sectors (regions II and V) and abrupt change to selected market sectors (region III).



		Uncertainty in Valuation →		
		Market	**Non Market**	**Socially Contingent**
Uncertainty in Predicting Climate Change ↓	**Projection (e.g., sea level Rise)**	**I** Coastal protection Loss of dryland Energy (heating/cooling)	**IV** Heat stress Loss of wetland	**VII** Regional costs Investment
	Bounded Risks (e.g. droughts, floods, storms)	**II** Agriculture Water Variability (drought, flood, storms)	**V** Ecosystem change Biodiversity Loss of life Secondary social effects	**VIII** Comparative advantage & market structures
	System change & surprises (e.g. major events)	**III** Above, plus Significant loss of land and resources Non-marginal effects	**VI** Higher order Social effects Regional collapse	**IX** Regional collapse

Source: Yohe and Tirpak (2008), derived from Downing and Watkiss (2003).

Although a limited literature exists for economic impacts in areas II – V, no study has attempted a comprehensive analysis, either for lack of data or for the inability to monetize damages for certain categories of impacts.[15] The existing literature has almost nothing to say about impacts and vulnerability calibrated in the non-market impacts of abrupt change in and the multiple metrics of socially contingent impacts (*areas VI – IX*). Through these socially contingent vulnerabilities, climate impacts in one place (e.g., the developing countries) can be felt elsewhere (e.g., in the United States or the rest of the developed world). All calculations of the potential benefits of climate policy completely ignore these elements of climate risk. It does not necessarily follow, however, that attempts to calibrate these vulnerabilities in terms of economic damages should be the focus of new research. Indeed, it is here, perhaps most critically, that multiple metrics of climate-related risk must be accommodated so that our policy discussions are more fully informed about what might happen.

Despite these shortcomings in the coverage of our impacts analysis and concerns about our understanding of the climate system, researchers and, policy makers are now required to use the results of analyses that emanate largely from *area I* of Figure 3 to conduct assessments of optimal climate policies and to compute estimates of the social cost of CO_2 and other greenhouse gases. These social costs are estimated by tracking the damage caused over time by releasing an additional ton of a greenhouse gas like CO_2 into the atmosphere and discounting those estimates back to the year of its emission. That is to say, the social cost of carbon represents the "marginal cost" of carbon emissions; alternatively, it represents the "marginal benefit" of a unit of carbon emissions reduction.

Estimates of the social cost of carbon that are currently available in the published literature vary widely. IPCC (2007b) was informed by an early survey conducted by Tol (2005), which reported that fully 12 percent of then available published estimates were below $0 (i.e. the impacts of climate change were estimated to produce a net positive economic benefit). Their median was $13 per ton of carbon, and their mean was $85 per ton. Tol (2007) offers an updated survey of more than 200 estimates. His new results show a median for peer-reviewed estimates with a 3 percent pure rate of time preference and without equity weights (i.e. no recognition that a dollar of harm effects the poor more than the rich) of $20 per ton of carbon with a mean of $23 per ton of carbon. Moreover, he reports a 1 percent probability that the social cost of carbon could be higher than $78 per ton given the same assumptions; and he notes that the estimates increase rapidly with lower discount rates—one of the primary reasons why the range of estimates of the social cost of carbon is so large.

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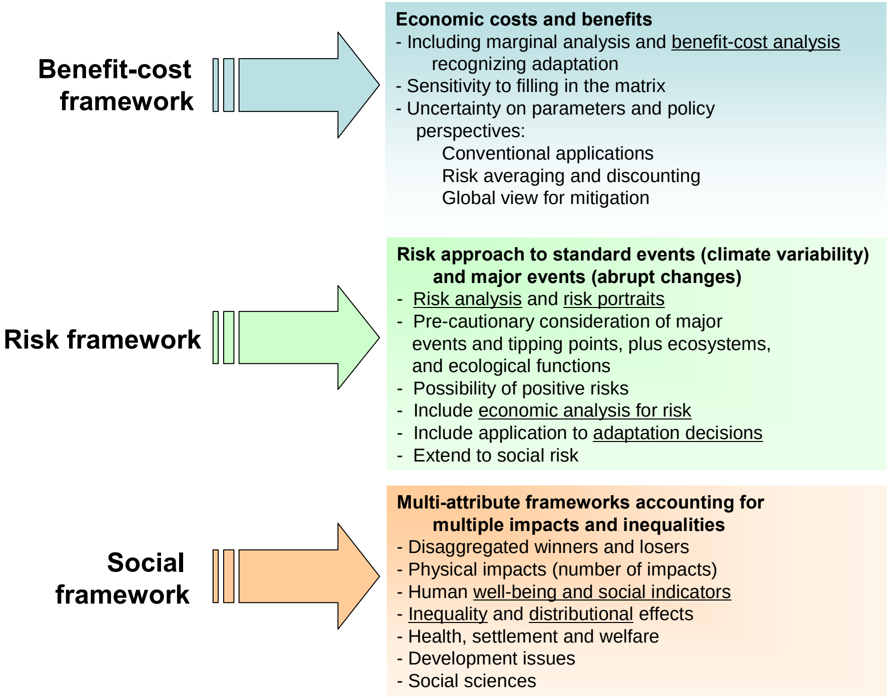
[15] For further discussion of damage estimates for *areas II – V* in Figure 3, see the appendix at the end of this paper and the paper by Mastrandrea in this volume.

Figure 4: Multiple Analytic Frameworks for Climate Policy Research. Characteristics of various analytical approaches are highlighted. General applicability increases from top to bottom with the prospect of supporting analyses of damages and co-benefits that would, were they available, begin to populate the lower right side of the matrix depicted in Figure 3 and thereby improve our understanding of the full range of issues. *(Source: Jones and Yohe, 2008).*



Economic costs and benefits

- Including marginal analysis and benefit-cost analysis recognizing adaptation
- Sensitivity to filling in the matrix
- Uncertainty on parameters and policy perspectives:
  - Conventional applications
  - Risk averaging and discounting
  - Global view for mitigation

Risk approach to standard events (climate variability) and major events (abrupt changes)

- Risk analysis and risk portraits
- Pre-cautionary consideration of major events and tipping points, plus ecosystems, and ecological functions
- Possibility of positive risks
- Include economic analysis for risk
- Include application to adaptation decisions
- Extend to social risk

Multi-attribute frameworks accounting for multiple impacts and inequalities

- Disaggregated winners and losers
- Physical impacts (number of impacts)
- Human well-being and social indicators
- Inequality and distributional effects
- Health, settlement and welfare
- Development issues
- Social sciences

The estimates above largely exclude impacts populating areas II-IX in Figure 3, yet Tol's survey provides evidence that assumptions about how to include even partial coverage of non-market damages can dominate estimates of market damages. Assumptions about what might emerge from more thorough investigations of *areas IV* through *VI* of Figure 3 are therefore critical, even if inference from a limited number of studies is suspect. Perhaps even more troubling is the observation that few if any of the estimates recognize abrupt change (*areas III, VI,* and *IX*); and none venture into anything contained in the right-hand column (*areas VII* through *IX*). Our current inability to populate the lightly shaded regions of Figure 3 with credible analyses undermines our ability to compute the social cost of carbon, and thus the economic benefit of climate policy, with any confidence.

Figure 4 offers some insight into how some of the light shaded areas in Figure 3 might be accommodated analytically. After characterizing traditional benefit-cost and risk-based approaches in its first two rows, the last row draws attention to a third type of analysis: multi-criteria approaches designed to illuminate vulnerabilities across the socially contingent impacts called out by the right column of Figure 3. Although practical approaches have yet to be developed, it is likely that much of this analysis would identify thresholds of socially unacceptable climate change or climate stress. To the extent that this is true, the risk profiles described above for the risk management perspective could be applied. Multiple and potentially non-monetary metrics have already been accommodated, and many have been expressed in terms of the likelihood of crossing critical thresholds set by natural systems. Putting humans into the business of defining comparable thresholds based on their values, institutions, and state of knowledge adds complication to the analysis, but risk profiles can accommodate these metrics, as well.

4.2 Key Vulnerabilities and Multiple Metrics

The authors of Chapter 19 of IPCC (2007b) seized on the content of Figure 3 (as portrayed in Chapter 20) to underscore the need for multiple impact metrics as they examined and identified "key vulnerabilities" to climate change.[16] They began their work by arguing how key vulnerabilities could be identified on the basis of a number of criteria that could be found in the literature: magnitude, timing, persistence/reversibility, the potential for adaptation, or lack thereof, distributional aspects, likelihood and 'importance' of the impacts. Leaving the last criterion, "importance", to the eye of the decision-making beholder, they offered an illustrative list based on not only their expert assessments of the literature, but also the insights offered by the authors of the sectoral and regional chapters of IPCC (2007b).

The content of their work has been most effectively communicated through changes in five aggregate "reasons for concern" first developed for and presented in the IPCC's Third Assessment Report (IPCC, 2001a, 2001b). These metrics, only two of which are calibrated predominantly (but no longer exclusively) in terms of economic measures, include:

- *Risk to unique and threatened systems* speaks to the potential for increased damage to or irreversible loss of unique and threatened systems such as coral reefs, tropical glaciers, endangered species, unique ecosystems, biodiversity hotspots, small island states, and indigenous communities. There is new and stronger evidence of observed impacts of climate change on unique and vulnerable systems (such as polar and high mountain communities and ecosystems), with increasing levels of adverse impacts as temperatures increase further. An increasing risk of species extinction and coral reef damage is projected with higher confidence now than in the Third Assessment Report (IPCC, 2001b) as warming proceeds.
- *Risk of extreme weather events* tracks increases in extreme events with substantial consequences for societies and natural systems. Examples include increase in the frequency, intensity, or consequences of heat waves, floods, droughts, wildfires or tropical cyclones. There is now new and stronger evidence of the likelihood and likely impacts of such changes, such as the IPCC (2007b) conclusion that it is now "more likely than not" that human activity has

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[16] Vulnerabilities, here, are defined as is now most usual in terms of exposure to anticipated impacts and associated sensitivities that can be ameliorated by exercising available adaptive capacity. Since all three of these components of the vulnerability (exposure, sensitivity and adaptive capacity) are site-specific and path-dependent, an ability to accommodate the diversity noted in subsection 2.1 remains critical.

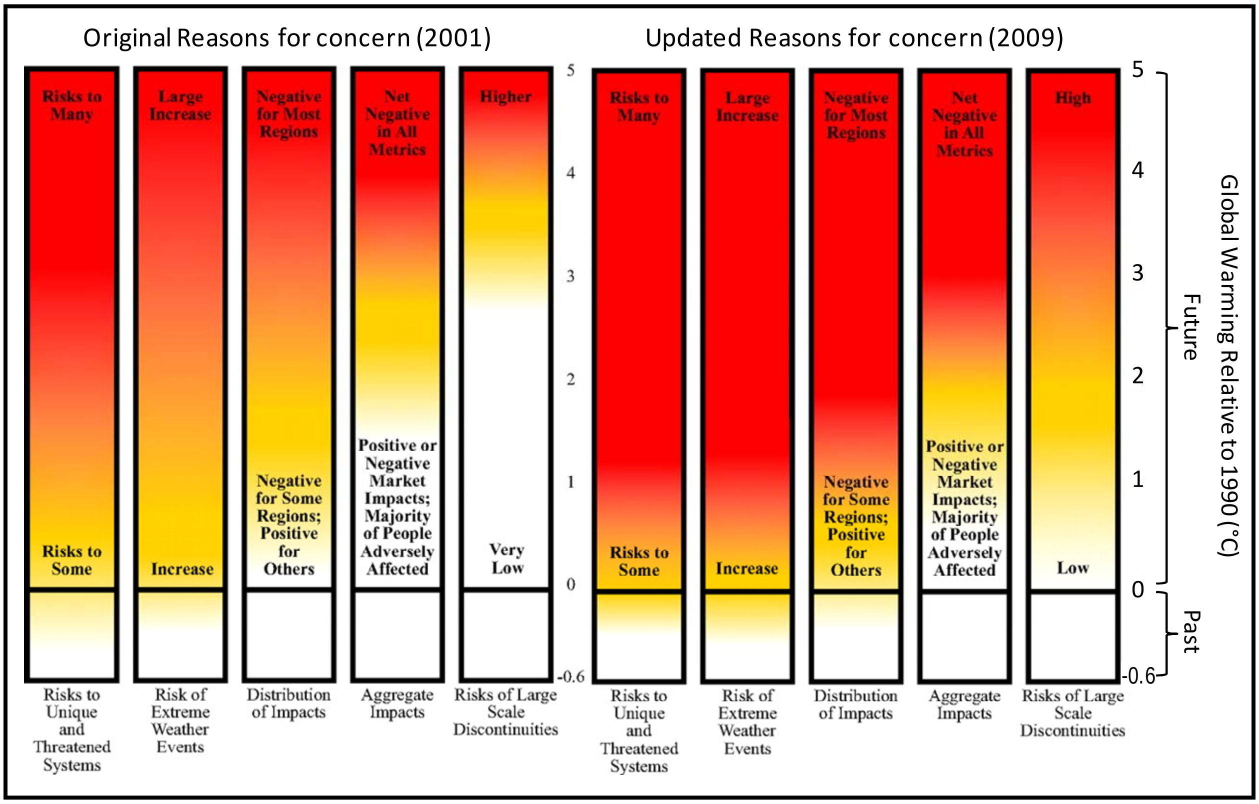
contributed to observed increases in heat waves, intense precipitation events, and intensity of tropical cyclones.

- Distribution of impacts and vulnerabilities concerns disparities of impacts, i.e. whether the poor are more vulnerable than the wealthy. Some regions, countries, and populations face greater harm from climate change while other regions, countries, or populations would be much less harmed and some may benefit. New research finds, for example, that there is increased evidence that low-latitude and less-developed areas in, for example, dry areas and mega-deltas generally face greater risk than higher latitude and more developed countries. Also, there will likely be disparate impacts even for different groups within developed countries.
- *Aggregate damages* cover comprehensive measures of impacts from climate change. Impacts distributed across the globe can be aggregated into a single metric such as monetary damages, lives affected, or lives lost. New evidence supports the conclusion that it is likely there will be higher damages for a given level of increase in average global temperature than previously thought, and climate change over the next century will likely adversely impact hundreds of millions of people.
- *Risk of large-scale discontinuities* represents the likelihood that certain phenomena (sometimes called singularities or tipping points) would occur, any of which may be accompanied by very large impacts, such as the melting of major ice sheets. For example, there is now better understanding that the risk of additional contributions to sea level rise from melting of both the Greenland and Antarctic ice sheets may be larger than projected by ice sheet models assessed in the IPCC (2007a, 2007b) and that several meters of additional sea level rise could occur on century time scales.

Figure 5 displays the differences in the "burning embers" thresholds for these Reasons for Concern between the 2001 version published in the Third Assessment Report (IPCC, 2001a, 2001b) and a more recent interpretation by many of the same authors (Smith et al., 2009). In general, the authors judge that significant risks, depicted by red coloring in the figure, occur at lower temperatures than previously assumed. These authors have revised their perceptions of risk based on the past decade of observations showing that both developing and developed countries alike are more vulnerable to extreme weather impacts than previously realized and also from observations that the climate system may react more strongly and abruptly to warming.

The critical insights to be derived from this discussion is that the notion of risk (as the product of probability and consequence) has been firmly ensconced in the discussions of impacts and benefits of climate policy and that investigations of how to respond to climate change have begun to recognize the diversity of potential vulnerabilities beyond the narrow economic spectrum of aggregate and regional impacts that can be calibrated in currency.

Figure 5. Risks from climate change, by Reason for Concern – 2001 compared with 2007. Climate change consequences are plotted against increases in global mean temperature (°C) after 1990. Each column corresponds to a specific Reason for Concern (RFC). The left panel displays the RFCs from the IPCC Third Assessment (IPCC, 2001a, 2001b). The right panel presents updated RFCs as described in Smith et al. (2009) and represents additional information about outcomes or damages associated with increasing global mean temperature. The color scheme depicts progressively increasing levels of risk, and should not be interpreted as representing "dangerous anthropogenic interference," which is a value judgment. The historical period 1900 to 1990 warmed by about 0.6°C and led to some impacts. This figure addresses only how risks change as global mean temperature increases, not how risks might change at different rates of warming. Furthermore, it does not address when impacts might be realized, nor does it account for the effects of different development pathways on vulnerability.



4.3. Another Reason for Concern from Martin Weitzman

At first blush, Weitzman (2009) adds even more complexity to the valuation problem by showing that profound uncertainty about fundamental parameters like climate sensitivity can overwhelm any economic estimate of climate damages. In practice, his result follows directly from our inability to observe the extreme ranges of climate impact distributions with enough frequency to learn anything useful about their relative likelihoods. He concludes that uncertainty will dominate any calculation of expected climate damage because even systematic learning over time about the critical variables is never strong enough to keep expected marginal damages finite; and so his result argument clearly casts doubt on results derived from economic calibrations of damages avoided by mitigation. On the positive side, his result indicates that the value of some types of information is far greater (and perhaps infinitely greater) than the value of other information. It can therefore offer some guidance on where to devote scarce research resources in climate and policy science. Moreover, offers sound theoretic footing for a generalized risk-based approach designed explicitly to examine and clarify the definition of tolerable climate change.

To explore the implications of his result a little more fully, it is appropriate to put it more squarely into the context of what we know about climate change. Tol (2003), for example, worked within a benefit-cost framework that recognized multiple regions with and without equity weighting. His simulations across a wide range of possible futures noted the small but non-zero probability that utility consequences of marginal impacts could grow infinitely large in one or more regions where some "not-implausible" climate futures could drive economic activity to subsistence levels. As long as these regions were given non-zero weight in the expected welfare calculation, their plight would dominate the policy calculus because expected marginal damages would approach infinity

Yohe (2003) suggested that the problem highlighted in Tol (2003) could be overcome by implementing a second policy instrument designed to maintain economic activity above subsistence levels everywhere – a foreign aid program designed simply to prevent economic collapse anywhere in real time, even if collapse happens to be the result of an extreme climate impact someplace in the world. Tol and Yohe (2007) examined this suggestion within the original modeling framework and found that, with sufficient aid, the issue of infinite marginal damage could be avoided. While this work did not envision globally distributed extremes as reflected in Weitzman's characterization of uncertainty surrounding climate sensitivity, it nonetheless suggested that timely social or economic interventions that effectively "lop off the thick tails" of regional climate impacts could undercut the power of his result. If, however, the catastrophe were felt globally, then virtually any insurance or compensation scheme based on transfers from well-off to less well-off regions would break down because non-diversifiable risk would be unbounded. It is here, therefore, that a generalized precautionary principle – the logical implication of Weitzman's insight – is an appropriate frame from which to derive a potential response. Yohe (2009) goes so far as to suggest that it is here that the analogy to hedging against deflation in the conduct of monetary policy carries the most weight. Indeed, Weitzman has recently used this analogy to argue for spending up to 3 percent of GDP per year for hedging insurance (The Economist, 2009).

Yohe and Tol (2009) nonetheless suggest that the policy community should instead ask the research community to develop greater understandings of the fundamental processes in areas other than climate sensitivity – processes that produce catastrophic *impacts* from whatever climate change happens to materialize, for example. Even if they cannot rely on the scientific community to reduce the range of possible scenarios in the temperature domain, they could ask it to (1) explore the triggers of more regional catastrophe, (2) identify the parameters of fundamental change that define those triggers, (3) contribute to the design of monitoring mechanisms that can track the pace of change relative to these triggers, and (4) conduct small- and large-scale experiments in models, laboratories and perhaps the real world to learn more about the relevant processes.

Risk profiles of the sort displayed above can also provide some critical insights in into the practical applicability of Weitzman's warning about thick tails in the climate system. One can easily see in Figure 1, for example, that any decision-maker concerned with protecting New York City from the risks associated with increases in the frequency of the current 100-year flooding anomaly would become acutely concerned within the next decade or two. One can, as well, see that this concern does not necessarily depend on a thorough understanding of the distribution of climate sensitivity. Put another way, Weitzman's insight could be less relevant in cases where climate futures driven by the middle of the sensitivity distribution produce intolerable impacts a little bit further into the future than the Weitzman-esque extremes of the same distribution. Why worry about the low-probability extremes when even high-probability outcomes could be intolerable a few years later?

To be clear, the point of focusing on the links between physical climate processes and potentially catastrophic impacts at a regional level is not to dismiss the need for hedging through mitigation against catastrophic globally-distributed futures that might be housed in the extremes in distributions of variables like climate sensitivity. It is, instead, to inform investments in adaptation that complement global hedging on the mitigation side of the policy equation.

5. "Sustainability, Equity and Attitudes toward Risk"

Sustainability, equity and attitudes toward risk are cross-cutting themes that permeate throughout everything noted above. The ability of the research community to accommodate their implications into analytical techniques is not well developed, but it is not difficult to demonstrate that they matter and should therefore be considered in risk management and policy making.

With regard to sustainability, for example, there are synergies across the determinants of adaptive and mitigative capacities and the precursors of sustainable development. Because they match to a large degree, initiatives designed to promote progress with respect to the Millennium Development Goals can support climate policy. The news is not all good, though, because the potential for conflicting objectives is real and diversity confounds general insights. With regard to the later, whether or not the links between an economic intervention (or an adaptation) and its desired outcomes are strong, weak, or actually run counter to expected benefits is essentially an empirical question in nearly every instance. And while it is widely known that unabated climate change can impede progress toward achieving the Millennium Development Goals, for example, there is such a thing as dangerous climate policy – adaptive or mitigative programs that retard economic growth and thereby undercut the ability to develop sustainably (e.g., Tol and Yohe, 2006).

The relative importance of equity and attitudes toward risk can, perhaps, best be displayed formally by exploring the dual roles that they play in determining the proper discount rate to be applied to monetized damages. In this regard, it is essential to remember that climate change is a long-term problem even if the appropriate approach to designing policy is to work iteratively. Greenhouse gas emission reductions over the near-term would mitigate future damages, but they would do little to alter the present climate and/or the present rate of change in climate impacts. Moreover, mitigation must continue well into the future if long-term objectives are to be achieved and long-term progress is to be sustained. In a cost-benefit framework, therefore, the discounted costs of emission abatement must be justified by the discounted benefits of avoided impacts in the future. In a risk-management framework, the discounted costs of abatement must be minimized subject to the constraint of achieving the desired reductions in climate risk. It follows from either approach, therefore, that any statement about the desirability of climate policy necessarily contains a value judgement about the importance of future gains relative to present and future sacrifices.

To understand why, it is sufficient to realize that people discount future consumption for two reasons. First, they expect to become richer in the future, and so they expect an additional dollar to buy less happiness then than an additional dollar would buy today. In economics, the amount of happiness (or utility) an additional dollar can buy is called the marginal utility of consumption. The interest rate at which a dollar would need to grow to entice its owner to invest it rather than spending it today is called *elasticity of marginal utility of consumption*. Second, people are impatient, preferring to consume now rather than later, regardless of future circumstances. The interest rate at which an invested dollar would need to grow to entice its owner to invest in the future rather than spending impatiently is called the *rate of pure time preference*.

Together, these two motives for discounting the future drive the so-called Ramsey discount rate (denoted by r below) that was designed to sustain optimal saving over time (Ramsey, 1928). The Ramsey equation therefore consists of three components:

$$r = \rho + \eta g$$

where ρ is the rate of pure time preference, g is the growth rate of per capita consumption, and η is the elasticity of marginal utility of consumption.

The rate of pure time preference calibrates inter-temporal trading so that individuals who anticipate constant levels of consumption from one period to the next would be willing to sacrifice one dollar of present consumption if he or she would be compensated with $\$(1 + \rho)$ of *extra consumption* in the next period. Higher values of ρ reflect higher degrees of impatience because greater compensation would be required to compensate for the loss of \$1 in current consumption.

Consumption levels need not be constant over time, of course, and the second term in the Ramsey equation works the implication of this fact into this trading calculus. While g measures the growth rate of material consumption, ηg reflects the growth rate of happiness measured in terms of underlying personal utility. If consumption were to climb by $g \cdot 100$ percent from one period to the next, then each future dollar would be worth $g \cdot \eta \cdot 100$ percent less (assuming no impatience so $\rho \equiv 0$). It follows that our individual would consider sacrificing one dollar in current consumption only if he or she could be compensated by an amount equal to $\$(1 + g\eta)$ in the future.

In contemplating welfare-based equivalence of consumption over time, it is now clear that this trading-based accommodation of growing consumption works in exactly the same way as the pure rate of time preference in defining the rate at which the future needs to be discounted. Put another way, if one considered empirical estimates for both ρ and η, then both parameters should play equally important roles in determining the appropriate discount rate. Perhaps because “impatience” is intuitively clear while the role of the “elasticity of marginal utility of consumption” is not, the debate over how to discount the future has focused undue attention on ρ almost to the exclusion of η.

Climate change is not only a long-term problem; it is also a very uncertain problem with the potential of reducing future consumption (risk), and a problem that differentially affects people with widely different incomes (inequity). The rate of pure time preference ρ speaks only to the first characteristic of the climate policy problem – the intergenerational time scale. The elasticity of marginal utility of consumption, the parameter η, speaks to all three characteristics (intergenerational equity, the risk of uncertain but negative outcomes, and differential impacts on people with different incomes). First, it indicates precisely the degree to which an additional dollar brings less joy as income increases for one individual. Second, it can be interpreted as a measure of the utility of an extra dollar for a rich person relative to the utility of an extra dollar for a poor person. This is why η is occasionally referred to as the parameter of inequity aversion. Third, it can be interpreted as a measure of how increases in consumption improve welfare more slowly than reductions in consumption diminish welfare. This is why η is also referred to as the parameter of risk aversion; and it is in this role that it helps explain why risk-averse people buy insurance.

As suggested in the opening paragraph of this final section, the purpose of this brief discussion is not to explain exactly how sustainability, equity, and attitudes toward risk can be incorporated into deliberations about climate policy; that is still a work in progress. It is, instead, to confirm that the first principles of risk-management approaches support the importance that negotiators place on each concept as they contemplate how to respond to nations’ obligations under Articles 2 and 4 of the United Nations Framework Convention on Climate Change – i.e., to frame actions that will help us avoid “dangerous anthropogenic interference with the climate system" while helping the most vulnerable among us to cope with the impacts of residual climate change.

6. Concluding Remarks

IPCC (2007c) tells us that insights derived from a risk-based perspective should now be inserted into public arguments over what to do about climate change – arguments that have heretofore too often been stuck in a false dichotomy between strained claims of certainty ("The verdict is in, now is the time for significant action regardless of cost, it won't cost much anyway, etc…"), and impassioned invocations that generic uncertainty justifies inaction ("Climate change is uncertain, we lack proof, mitigation is too expensive, R&D alone will solve the problem, etc…"). Sensible decisions and prudent management of risks require that we work in the "murky arena" between these two extremes by acknowledging that coping with uncertainty will play important roles in both the identification of policy objectives and the design of specific policy initiatives. People do not ignore uncertainty when making investments and purchasing insurance, nor should analysts and policy makers ignore uncertainty when assessing climate change policies.

The various sections of this paper can perhaps offer some preliminary guidance into how to find our way through the "murk". Section 2 tells us not to be too ambitious – to acknowledge that "mid-course corrections" will be required; and so it follows that greater attention has to be paid to exactly how to design a process by which these corrections can be accomplished. Section 3 tells us that the lens of risk-management can be productive in this regard; some macro-scale policies have already been framed in terms of hedging against particularly troubling possibilities, but there are no guarantees. Section 4 tells us not to expect that all outcomes can or should be quantified in units of currency; benefit-cost analyses may be the traditional standard for decision-analysis, but they must be complemented by risk-based approaches that can, when uncertainty dominates, carry the day as policies are designed. Section 5 adds the ambiguity of imbedding climate choices into discussions of sustainability that recognize attitudes toward inequality and risk. Every participant in the policy discussions must understand that his or her attitudes about both inequality (across time and space) and uncertainty are value-laden perspectives that have far-reaching consequences. Difficulties in creating and interpreting aggregate and disaggregated indices of risk surely persist, but adopting a risk perspective will bring new clarity to our understanding of the diversity and complexity of the climate problem. The strength of collections of direct or even qualitative profiles of risk lies in their ability to accommodate alternative metrics of vulnerability and/or reasons for concern in ways that allow comparisons across context.

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Appendix

Further discussion of existing damage estimates for climate change impacts in Figure 3, *areas II – V*.

Some investigators, notably West and Dowlatabadi (1999), Yohe et al. (1999), and Strzepek et al. (2001), have tried to capture the market-based implications of extreme events whose intensities and frequencies have or will be altered by a changing climate, but their efforts to add content to *area II* have been most successful when framed in the limiting context of impact thresholds beyond which climate variability produces severe damage.

Nordhaus and Boyer (2000) were essentially alone in their initial attempt to incorporate abrupt climate change into climate damage estimates; of course, Stern et al. (2006, 2007) as well as Nordhaus (2008) contributed to this small literature in attempts to expand our understanding of *area III.* It is important to note, however, that none of their approaches are anchored on robust analyses of economic damages that might be produced along abrupt climate change scenarios. They are, instead generally inferred from risk-premium calculations based on underlying utility structures and rather arbitrary assumptions. Nordhaus and Boyer (2000), for example, assigned low probabilities to large economic costs (on the order of 10 percent of global economic activity) for the middle of this century. These assumptions allowed them to report estimates of the willingness to pay to avoid such risk – estimates that are equivalent to the maximum amount that an individual would be willing to pay for "perfect insurance" that would eliminate (at a cost) all climate-related uncertainty about the future. Since no such insurance is available, though, these estimates should be viewed as indices of the economic cost of catastrophic climate change.

A few studies, authored for example by Nordhaus and Boyer (2000), Tol (2002a, 2002b), Stern et al. (2006, 2007), and Nordhaus (2006) among others, have tried to include some (but certainly not all) non-market impacts driven by trends in climate change (*area IV*). Their representations are not, however, particularly comprehensive since data are limited and estimation methods are sometimes extremely controversial.

The same authors tried to bring assessments of non-market impacts of extreme weather events into their integrated assessments of climate change; that is, they tried to work constructively in *area V.* Their efforts have, however, also been severely limited by a paucity of robust economic estimates of impacts. Link and Tol (2004) made some progress in this regard, but Stern et al. (2006) was the first attempt at comprehensive (though much criticized) inclusion to attract much attention. Finally, the Millennium Ecosystem Assessment (MEA, 2005) also contributed to *area IV* and *area V*, but that work stopped well short of trying to assign economic values to ecosystem services. Moreover, while various working groups within the MEA process developed scenarios within which those services produced utility, few of them paid much attention to climate change as a driver of risk.

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