WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

Challenges to Providing Quantitative Estimates of the Environmental and Societal Impacts of Global Climate Change

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Abstract

As the impacts of climate change become more apparent and the prospects grow for more severe impacts in the future, policy makers are intensifying their efforts to craft an international agreement to "prevent dangerous anthropogenic interference with the climate system."[1] Equally daunting, however, is developing and implementing the domestic policies needed to achieve the goals set forth in such an agreement. In formulating environmental regulations in the United States, the most commonly used analytic approach is to weigh the costs of control measures against the benefits (or reduced costs) resulting from reducing environmental and societal damage. Within this cost-benefit framework, it is argued that no more should be spent to reduce pollution than the resulting economic benefits would yield.

However, complexities of the climate system and its linkages with society complicate the development of accurate estimates of the costs and benefits of a given policy to address climate change. This paper presents, from the viewpoint of a climate scientist, an overview of the key challenges to understanding and incorporating in policy analyses the impacts of climate change for specific regions and on shorter time scales. While not attempting a comprehensive evaluation, this paper emphasizes those aspects of the Earth system and its connection with human society that introduce challenges for economic analyses of climate change impacts. It also suggests a minimum set of impacts that might be useful to consider in quantitative policy analyses; beyond these, there are many potential impacts, some catastrophic, that would be better considered using a risk-based approach rather than a cost-benefit analysis.

[1] Article 2, United Nations Framework Convention on Climate Change, 1992.

1. Introduction

Over the past 150 years, human activities have increased the atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4) by over 35 percent and 150 percent, respectively. The concentrations of other greenhouse (heat-trapping) gases have also increased (Forster and Ramaswamy, 2007). The climate of the world has started to respond:

- Global average temperature has risen about 0.8 °C (1.4 °F) since 1850 (Trenberth and Jones, 2007; Hegerl and Zwiers, 2007);
- Minimum summer sea ice extent in the Arctic has decreased about 21 percent since 1979 (Serreze et al., 2007);
- Mountain glaciers and the Greenland and Antarctic ice sheets have started to lose mass (Dyurgerov and Meier, 1997; Chen et al., 2006; Cook et al., 2005; Alley et al., 2008; Rignot, 2008; Rignot et al., 2008);
- Sea level has risen by about 0.2 m (0.7 ft), and the rate of rise in the early 21st century is about double the average rate for the 20th century (Bindoff and Willebrand, 2007);
- Both the broad mid-latitudinal bands of precipitation and the dry subtropical bands have started shifting poleward (Zhang et al., 2007; Milly et al., 2008).

When viewed as global averages, these changes and others seem to occur slowly, leaving the impression that climate change in general is likely to proceed in a slow, steady fashion. This impression leads to the common presumption that there will be ample time to prepare for climate change and its associated impacts. Such a delay in facing impacts would, it is argued, allow time for the economy to adjust gradually, with slow emissions reductions and gradual planning and implementation of adaptation measures. But is this assumption about slow, steady climate change really true?

Because scientists typically average climate variables (e.g., temperature or precipitation) over long time periods (~30 years) and over large regions, reported climatic conditions are likely to continue to appear to change slowly. On the other hand, the actual impacts are likely to be more sudden and more concentrated in particular locations. For example, storms, which often have dramatic local impacts, are likely to become more intense (Meehl and Stocker, 2007). Around the world, observations indicate that a larger fraction of rain is coming in downpours[2] (Trenberth and Jones, 2007; Aumann et al., 2008) and that an increasing fraction of tropical storms (i.e. hurricanes, cyclones, and typhoons) are

[2] With more of the precipitation occurring in downpours, the fraction of precipitation that runs off tends to increase, more rapidly filling streams and rivers. When falling on snowpack, heavy downpours increase the melting rate. Such episodes increase the likelihood of flooding (Groisman et al., 2004).

intensifying toward the most powerful categories[3] (Elsner et al., 2008). Conversely, longer intervals between significant rains are leading to prolonged periods with increased evaporation and therefore more periods with dry soils and drought (Meehl and Stocker, 2007). In addition to agricultural losses and disrupted water supplies, one consequence of prolonged dryness is an increase in the frequency and intensity of wildfire, which is already occurring in western North America (Westerling et al. 2006; Bachelet et al., 2007).

High and low daily temperature extremes also shift in both magnitude and frequency as the climate changes (Chritensen and Hewitson, 2007). Greenhouse-gas-induced warming tends to shift daily temperatures to a higher average value,[4] which leads to a disproportionately larger increase in the likelihood that, for example, the high or the low temperature of a particular day or a sequence of days is above a particular threshold value, such as the local temperature above which heat is considered extreme. Consequently, the frequency of heat waves and heat-induced deaths can greatly increase, especially in urban areas and regions where air-conditioning is not widespread and the population has not had time to acclimate to heat extremes (Ebi and Meehl, 2007).

The most important near-term impacts are likely to result from changes in local weather extremes rather than the slow changes in global or regional long-term averages (e.g., IPCC, 2007b). For example, particularly significant consequences can result from local increases in maximum and minimum temperature, storm surge height with resulting inundation and coastal erosion, transition into repeated or persistent drought with a resulting increase in the frequency of wildfire, intense rainfall that results in flooding and landslides, higher minimum temperatures that lead to pest survival and tree death, and reduced snowpack that leads to changes in the timing of snowmelt and runoff. These sporadic changes in extreme weather will lead to significant impacts to the environment and to societal infrastructure and well-being.

In the context of analyzing mitigation policies, evaluating the potential impacts of climate change requires special attention to short time scales and intermittent—even rare—extreme events. As an example, the most intense rains fall in regions of complex topography, creating flooding along particular river systems, while drought and hot weather combine to create fires in certain regions, and hurricanes strike in other locations. So that society can be safe and function effectively, design and building standards have been crafted to greatly limit the damage below chosen thresholds of weather extremes

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[3] Because tropical cyclones are becoming more powerful, they are expected to lead to higher and stronger storm surges with greater damage and more frequent inundation; furthermore, sea level rise means that less intense storms can also lead to inundation.

[4] Day-to-day variations in the weather about the long-term average are generally distributed in the shape of the familiar bell curve. For example, daily high temperatures for a given month tend to be distributed in this way, with the average representing the average daily high temperature for that month and the width of the bell curve representing the degree of variation. Daily low temperatures form a similar curve. As the climate changes, both curves tend to shift toward higher values, increasing both high and low extremes.

(e.g., many structures are designed to withstand a one-in-a-hundred-year flood—based on the historical record).

As gradual climate change shifts the statistical envelope that bounds the intensity, range, scale, and duration of weather extremes, intense events that can cause significant damage are projected to become much more likely. The result is that large areas are likely to be more frequently exposed to conditions that exceed existing tolerance thresholds (e.g., ecological, precipitation, temperatures, and sea level) to which the environment and society have become accustomed over long periods of time. *The nonlinearity of the results can greatly complicate estimation of the likely impacts of climate change and the benefits of taking particular policy actions.*

With increasing attention on the relative merits of various policies for cutting greenhouse gas emissions, decision makers are likely to expect more and more detailed results from cost-benefit analyses (CBA) and integrated assessment models (IAM).[5] As climate change intensifies and generates a greater variety of impacts, and as the degree of change further exceeds historical norms, preparing such analyses in a convincing way will become more and more difficult. Several chapters in IPCC (2007b) and earlier IPCC assessments address the strengths and weaknesses of cost-benefit and other approaches for evaluating the implications of climate change on global to regional scales. In general, the results of these evaluations suggest that risk-management approaches are superior to CBA for dealing with the complexity of the Earth system and the inherent uncertainties arising from trying to project ahead a century and more.

The next section describes how the most important complications create systemic problems for moving from global to regional and local scale damage functions to represent the costs of future consequences. In that U.S. attention is likely to focus on U.S. impacts, the third section describes the challenge of estimating costs and benefits (i.e. of developing a quantitatively rigorous damage function) for just the United States. The fourth section suggests an alternative approach to such analyses, laying out a minimum set of climate change impacts that should be considered in estimating the significance of climate change for society. Policies costing less than the benefits gained by avoiding these impacts would seem to be favored. In addition to these baseline impacts, however, many additional risks have the potential to introduce additional complexities into the decision process and will need to be considered through the lens of risk management.[6] The concluding section offers thoughts on moving forward and on the importance of the decisions being made as governments move to develop implementation policies.

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[5] See the papers by Ackerman et al. and Mastrandrea in this volume for detailed background on cost-benefit analysis and integrated assessment models.

[6] See the paper by Yohe in this volume for detailed discussion of risk management.

2. Systemic Problems with Estimating the Economic Costs of the Future Consequences of Global Climate Change

Many public policy decision processes involve the weighing of the costs and benefits of particular actions. For decisions that involve well-defined steps and consequences, typically focused on the near-term and on limited spatial domains, the technical basis and art of conducting such studies have developed over recent decades.[7] While criticisms and problems remain, such efforts have often been illuminating in deciding among various courses of action, particularly for marginal improvements.

The choice of a discount rate illustrates one important problem with cost-benefit analyses as applied to climate change policies. Use of a discount rate is the traditional approach to deriving the net present value (or expected ultimate economic cost) of an investment, including the environmental and societal consequences projected to occur in the future (e.g., over the operational and depreciable lifetime of a major energy facility). In such analyses, the higher the discount rate, the greater the weight given the present and near future as opposed to the long term. Because many climate change impacts develop over time and lead to consequences far in the future, the long-term costs (and uncertainties in their determination) tend to become obscured when even a modest discount rate is used. This has the effect of deemphasizing the accumulating long-term significance of climate change and the increasingly significant consequences that will face future generations due to greenhouse gases emitted today. While the differences in viewpoint and results in the analyses of Stern (2007) and Nordhaus (2007) are in large part due to the differences in their economic assumptions, other differences also arise because long-term changes in the atmospheric, oceanic, terrestrial, and biospheric components of the Earth system (and their uncertainties) play an especially significant role when the discount rate is low.

This section describes some of the inherent problems with evaluating climate change impacts and their global implications. (Additional problems with estimating the impacts of climate change for the United States or a smaller geographic region are considered in the next section). Many of the problems described here appear to be inherent to the complexity of the Earth system; uncertainties from these problems are therefore likely to persist in spite of future advances in understanding. The challenges are grouped below into two broad categories: (1) challenges arising from characteristics of the atmospheric, oceanic, cryospheric, and biospheric components of the climate system, including limits in scientific understanding of how to project the future climate; and (2) challenges arising from the interactions of society with the climate system. Although many of the specific examples refer to the United States, such examples can be found all around the world, and all nations will need to deal with these limitations as efforts intensify to limit emissions and adapt to unavoidable changes.

[7] See the paper by Ackerman et al. in this volume for background on cost-benefit analysis.

2.1. Characteristics of the climate system

In many discussions, the limitations in understanding climate change are often lumped with statements about uncertainties in the climate sensitivity, which is defined as the equilibrium warming that would result from a doubling of the CO_2 concentration in the atmosphere. The IPCC Fourth Assessment (IPCC, 2007a), for example, found that "the climate sensitivity is likely[8] to be in the range 2 °C to 4.5 °C, with a best estimate value of about 3 °C," and that it is "very unlikely[9] to be less than 1.5 °C." The implication is that global average temperature can be projected to within about 50 percent (i.e., the sensitivity is essentially 3 ± 1.5 °C). Using the climate sensitivity as the single measure of the uncertainty in scientific understanding of climate change, however, is misleading. First, the observational record does not allow the upper bound of the climate sensitivity to be as well established as the lower bound—in fact, some approaches to estimating the climate sensitivity suggest that it could be higher than 4.5 °C. Also, the historical and paleoclimatic records provide insights into the climate system that allow a deeper appreciation of the levels of uncertainty and confidence in various findings than can be gained from consideration of the climate sensitivity alone.

Most serious of all, however, is that the climate sensitivity is not particularly helpful in making quantitative estimates of the impacts of climate change and of their significance and uncertainty. Evaluating impacts requires information on the rate, magnitude, and location of changes in the broad set of factors that define the climate. Unfortunately, developing such estimates reveals many complexities in the climate system that greatly increase the uncertainty of cost-benefit analyses. Among the most important are the following:

1. **Both climate change and the resulting impacts typically have a strong local component, making generalization difficult.** Geographic features, resources, and development can combine to create significant local and regional differences in the effects of climate change, especially because resilience and vulnerability tend to vary by location and adaptive capacity. Cost-benefit analyses largely fail to capture impacts on local ecosystems, communities, and facilities, and local decisions regarding land use and development can play an important role in the severity of impacts.[10]
2. **Greenhouse gas emissions cause impacts in both the near and long term, but different greenhouse gases persist in the atmosphere for different time periods.** For long-lived gases like CO_2, impacts could persist for centuries or longer (Solomon et al., 2009; Charbit et al., 2008). Failing to include in the analyses the long-term implications of near-term actions would yield a very incomplete and misleading portrayal of their significance.

[8] The IPCC defines "likely" as better than 2:3 odds.
[9] The IPCC defines "very unlikely" as less than 1:10 odds.
[10] See the paper by Ebi in this volume.

3. **Response of the climate system lags behind actual emissions, and response time differs among systems.** This means not only that an impact analysis would be starting from conditions that do not reflect the full consequences of past emissions, but also that the impacts of future emissions (including reductions from policy actions) will extend far into the future and will be very hard to distinguish from the continually developing responses to past emissions.

4. **Impacts result from natural climate variability in addition to human-induced climate change.** Distinguishing the fraction of damages to associate with the influence of human activities will not be sufficient, because the human influence is on top of the natural component and relationships are nonlinearly coupled and dependent on each other. With the human contribution to climate change increasing over time, with ongoing natural variability (the variability of which may be altered by human activities), with sea level rising due to human activities, and with the couplings and processes being nonlinear, distinguishing the consequences of human-induced climate impacts from effects that would have occurred naturally without climate change is very likely to involve significant uncertainties, especially when there are synergetic interactions between natural and human-induced climate phenomena.

5. **A number of impacts of climate change are projected to be irreversible or virtually irreversible** (IPCC, 2007a; 2007b). For example, warmer temperatures may persist for at least 1000 years without returning to preindustrial levels (Solomon et al. 2009). Polar and high-altitude species are likely to be pushed to extinction as their habitats disappear.

6. **The climate system is nonlinear, and thresholds are likely to be exceeded beyond which damages increase dramatically.** Examples include increased heavy downpours, the duration and severity of droughts and heat waves,[11] the melting of permafrost and sea ice, the loss of mass from the Greenland and Antarctic ice sheets, the likelihood and intensity of flooding,[12] and the spread of pests and loss of forests (ACIA, 2004; IPCC, 2007b). Detailed projections of the impacts need to consider the chaotic behavior of both physical and social systems, something particularly difficult to handle in cost-benefit analyses.

7. **The complex and nonlinear nature of the climate system increases the likelihood of surprises.** Because of the potential for surprises and extremes, the probability of which cannot be objectively estimated, there is a strong likelihood that

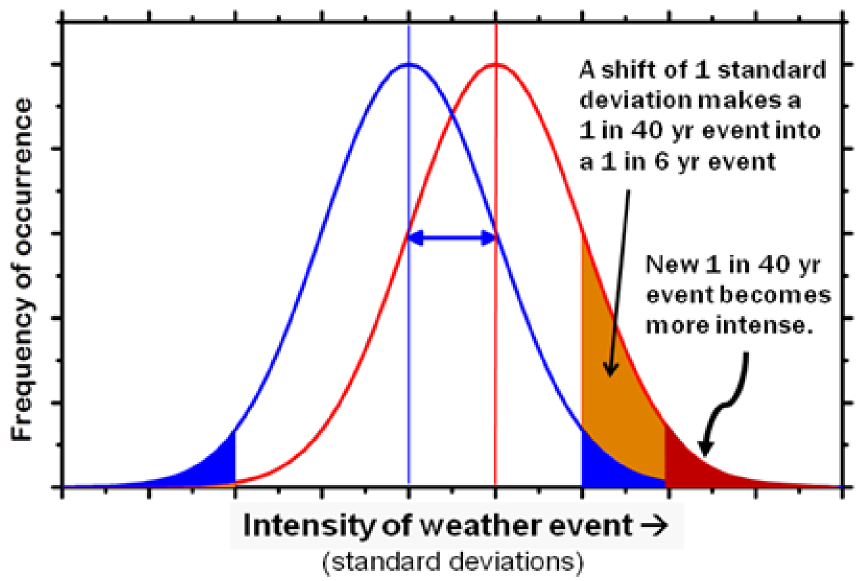
[11] For some species (e.g., some crops), warming can have no or even positive effects until a temperature threshold is exceeded, and then very significant negative consequences can result. In cities, when weather conditions exceed the design criteria for healthy conditions in buildings, there can be a sharp increase in cases of heat stress.

[12] In southern Florida, for example, the underlying geology is such that levees would eventually fail, leading to inundation (Miami-Dade County Climate Change Task Force, 2007). In the Northwest, a slight lengthening of the warm season and increase in minimum winter temperatures has led to near total loss of major forest areas to greatly amplified infestations of the pine bark beetle.

actual impacts and their importance will be underestimated in cost-benefit analyses (Weitzman 2009).

8. **Weather, not climate, is what is actually experienced at a given location and time; historical extremes, and worse, will become more commonplace as the climate changes**. Shifts in the bell-shaped distribution of weather conditions will alter the frequency of extreme events, often sharply (Fig. 1; Christensen and Hewitson, 2007). A shift in the average leads to a much greater likelihood of exceeding certain temperature and precipitation thresholds (Battisti and Naylor, 2009).[13] Given that extremes result in most of the damage, uncertainties in estimating the likelihood and thus costs of extremes are likely to be particularly large and important.

Figure 1. Simplified depiction of the changes in temperature and precipitation in a warming world. *(Adapted from CCSP, 2008*



9. **Climatic regimes are shifting, causing extreme weather events in unlikely places and rendering the historical record useless in predicting future climate in some places.** Estimating the timing and severity of impacts (particularly at the moving edges of climate regimes) is problematic,[14] and averaging over these effects would

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[13] For example, the Canadian Climate Model suggests that in 100 years, today's 1 in a 100-year flood will likely be occurring every 30 years, and today's 1 in every 300-year flood will likely be occurring once every 100 years (Zwiers and Kharin, 1998). Most infrastructure has been designed based on the frequency of extremes in the past, and it will not be easy to upgrade many facilities without replacing them (e.g., bridges built to withstand a 1 in a 100-year flood).

[14] For example, will a hurricane causing a storm surge that floods Miami or New York occur within a few years or not occur for a few decades? Here the choice of the discount rate will make a striking difference in the net present value of the impact.

seem likely to grossly underestimate the significance of low probability, high consequence events in particular places (Weitzman 2009).

10. **The ocean is becoming more acidic as a consequence of absorbing excess atmospheric CO_2, with potentially severe consequences for marine life and associated effects for society** (Orr et al., 2005; Monaco Declaration, 2009; Raven, 2005). While some attempts have been made to quantify the economic value of coral reefs (Brander 2009) in particular, these analyses largely neglect some important impacts that are not easily monetized. The non-market impacts on ecological services provided by marine life, such as coastal protection by coral reefs, subsistence fishing in island and developing nations, and ecosystem diversity and resilience, would not seem to be representable using the traditional cost-benefit analysis.[15]

2.2. Characteristics of society and its linkages to the climate system

In addition to the complexities of the climate system itself, a useful estimation of long-term impacts must allow for the ongoing development of society over time, including its responses to climate change impacts. Developing realistic estimates of the costs and impacts of climate change and mitigation policies is challenging due to the long lifetime of greenhouse gases and investments in infrastructure, along with complex linkages between society and the environment. Among the most important are the following:

1. **Global environmental and social systems are both very complex and interdependent, and ecological services are often assumed to be substitutable by technology.** However, the value of many such ecological services, such as cleansing of air and water, regeneration of oxygen, and sustaining biodiversity, which have been estimated to be roughly comparable in value to the beneficial services of the global economy (Costanza et al., 1997), are not replaceable by technology on anything but a very small scale. Due to limits in understanding of the environment and of societal dependencies, only the simplest representations of the linkages and their economic significance have the potential to be included in cost-benefit analyses.
2. **Increasing atmospheric concentrations of greenhouse gases and the resulting changes in climate and ocean acidification are not the only human influences on the environment.**[16] Assigning consequences among the various stresses would need to vary by location, the intensity of the individual stresses, the time history of the influences, characteristics of the local situation, etc. In many cases, climate change is increasing vulnerability to other stresses. Determining how best to separate out the

[15] See the papers by Ackerman, Mastrandrea, Rose, and Yohe in this volume for background on non-market impacts.

[16] Coral reefs, for example, face threats due to contaminants, coastal development, fish harvesting, and recreational use, along with the impacts of warming, sea level rise, and ocean acidification. Terrestrial systems face stresses created by land cover change, invasive species, human-produced chemicals, and so on.

contributions of climate change, and then of climate change policies, is likely to create significant uncertainty as well as disagreement among different attempts to construct such estimates.

3. **The impacts from climate change will be complicated by human decision making.** Projection of societal development is predicated on a set of emissions and behavioral scenarios. In the case of disasters such as hurricanes and wildfires, preparedness by citizens and responsiveness by governments will affect the severity of impacts. All levels of decision making, from individual to local and national governments, both near-term and long-term, have the potential to influence the severity of impacts.

4. **The effects of climate change raise serious equity issues—geographically, socio-economically, and generationally.[17]** In attempting to deal with the problems of equity that arise across incomes, communities, nations, and generations, uncertainties created both by climate change and societal development complicate both projections of climate change and the weighting and aggregation of impacts.

5. **The potential for adaptation must be considered in estimating impacts.** Adaptive measures to reduce impacts, such as the construction of sea walls to protect against rising sea levels, can reduce impacts from climate change (Tol, 2007). However, climate change is likely to overwhelm some adaptation strategies, eventually forcing retreat (Yohe et al., 2007). A critical issue is going to be whether retreat is going to take place before or after disaster.

6. **The impacts of climate change also depend on rates of societal change and technological improvement.** Since the ability to make accurate societal (i.e., demographic parameters such as location, age, profession, wealth, size, vulnerability) and technological (i.e., capabilities, cost, efficiency, availability) projections is at least as limited over the long-term as for climate, uncertainties in social development will likely be more reliably addressed in a probabilistic sense than in a deterministic framework.[18]

7. **Geoengineering has the potential to limit impacts, but very little is known about the potential for adverse side effects.[19]** Evaluation would be needed not only of the impacts that geoengineering might be able to moderate (Caldiera and Wood, 2008), but also of the potential unintended consequences as well as the likely persistence

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[17] Those suffering the largest impacts, some of which may well be irreversible, tend to be the poor, whereas those experiencing benefits are richer, both individually and on a national basis. A similar situation exists in time—those living today are likely to suffer relatively modest consequences, whereas those living in the future, who have no voice in decisions made today, are likely to experience larger consequences. (See, for example, the statement of the U.S. Conference of Catholic Bishops, at http://www.usccb.org/sdwp/international/globalclimate.shtml.)

[18] See the papers by Mastrandrea and Rose in this volume for discussion of deterministic vs. probabilistic analyses.

[19] In addition to the potential for adverse side effects, no geoengineering approach (or set of them) appears to be capable of counter-balancing all negative impacts.

and effectiveness of the required governance structure extending far into the future. With the pace of climate change accelerating and projections indicating that "dangerous anthropogenic interference with the climate system" may be imminent, calculation of the global benefits and impacts in detail is likely to be especially difficult and uncertain.

Together with the problems relating to economic formulation in cost-benefit analyses (not considered here), the complexities of the climate system and its coupling to society should prompt exploration of alternative approaches for evaluating policy options.

3. Special Complications for Estimating Consequences for the United States

In addition to the global-scale and systemic challenges identified above, a number of additional issues arise in identifying uncertainties resulting from impacts affecting the United States or regions within the US. This section provides an overview of these special challenges:

1. **The United States is part of a global community—neither the natural world nor the global economy can be readily separated at the U.S. border.** The nations of the world are interconnected through trade (including climate-dependent products and services, such as food crops and water-intensive products); environmental resources (e.g., fisheries, migrating species, and freshwater in lakes and rivers); human health (e.g., through various disease vectors, such as West Nile virus, flu epidemics, etc.); familial and ethical connections (e.g., as a result of previous immigration, remaining family connections, historical linkages, work experience, etc.); and national security (since environmental disruption can cause regional dislocations and act as a threat multiplier). Quantifying climate change impacts for the United States thus requires quantifying impacts around the world.
2. **The United States is more than the 50 states—it includes Indigenous Peoples, Native Americans, Caribbean Islands, and Pacific Islands.** The complexities of the United States—its multilevel and distributed government structure and its natural and developed environments—are likely to make it difficult to generalize the national impacts of climate change. For example, Native Peoples face more impacts than the general population because their activities and lifestyles are more directly connected to the environment (NAST, 2000; ACIA, 2004).
3. **Democratic systems generally tend to be more reactive than proactive in responding to environmental problems and threats** (Healy and Malhorta 2009). Economic estimates should account for delays in addressing impacts, including the acceleration of environmental damage during the period of delay, and the presence of thresholds over which the impacts are likely to develop before being addressed.

4. **The complexities of land ownership and responsibility pose unique obstacles to policy implementation.** Because of the large fraction of private land and financial ownership,[20] the distributed nature of government, and the limited ability of government to affect behavior, it is likely to take longer to adapt to climate impacts than the perfectly rational response that cost-benefit analyses typically assume.[21] For example, along many rivers and coasts, the response to flooding and inundation has been to rebuild instead of retreat, although retreat may ultimately be necessary in many areas.
5. **The potential exists for the United States to allow or bar entry of environmental refugees into the country from other parts of the world facing climate disasters.** With most growth in U.S. emissions resulting from the increase in population (which in turn results in the need for additional homes, infrastructure, and services) projecting actual immigration will be important but problematic for quantifying impacts, partly because it can be affected by migrations from disasters abroad (e.g., Hurricane Mitch in 1998) and in the United States (e.g., Hurricane Katrina in 2005 and southern Mississippi River flooding in 1927).
6. **The United States has a tremendous investment in its existing infrastructure (e.g., roadways, railroads, sewage treatment plants, and entire cities) that are exposed to a range of potential impacts from changes in climate and extreme weather.** Much of this infrastructure is located on low-lying coasts where protection from rising sea level and storm surges is ultimately likely to be more expensive than relocation. The unique situations of each location will make estimation of overall impacts quite difficult, especially when considering issues and costs of relocation and rebuilding. In addition to the physical costs, there are also many complex social costs and implications that merit inclusion (e.g., GAO, 2004).
7. **Because human-induced climate change is a result of the collective actions of the nations of the world, integrated over time, the result of any individual domestic policy action is very likely to look quite modest.** While domestic actions may seem small compared to the scope of the problem, the collective *in*action of all nations will ultimately destroy the value of the commons for virtually every nation (Hardin 1968). To avoid getting tied up in evaluation of the value of a multitude of limited domestic actions, effective analyses must evaluate the adequacy of the overall national policy on climate change in the context of the responses by other nations. Subdividing the evaluation into analyses of the costs and benefits to the United States

[20] In the UK, where all land is held under a dispensation of the monarch, a national policy not to build right on coastal lowlands quickly had an important effect around the nation; were such a regulation issued by the U.S. government, political and legal reactions would delay its effect.
[21] See the paper by Ackerman et al. in this volume for a discussion of the "rational actor" assumption.

without including the response of the global community is not likely to be particularly helpful for deciding among specific policy options.[22]

8. **The scope of the action required is enormous.** There really is no other option than all nations doing all that they can to reduce emissions as promptly and aggressively as they reasonably can (MacCracken 2008). Carrying out detailed impact analyses of the marginal cost-benefit of imposing specific policies is likely to require significant effort for very limited insight. Instead, a better approach would be to evaluate only the comparative costs of implementing alternative policies seeking to achieve some specific outcome without trying to make detailed comparisons of the full cost implications of impacts due to climate change.[23]

The scientific basis for conducting cost-benefit analyses remains tenuous, but consideration of climate policies in the near future would traditionally require such analyses. Neither the National Assessment completed in 2000 (NAST, 2000), the Arctic Climate Impacts Assessment completed in 2004 (ACIA, 2004), nor the recently released assessment of the U.S. Global Change Research Program (Karl et. al., 2009) have attempted an economic analysis of the impacts within the United States. In lieu of a full analysis, leading economic models have generally either used a parametric curve to represent impacts or attempted to calculate the impacts of public policies using only very large-scale approaches to representing the largest impacts (Mastrandrea, 2010). Neither of these choices would seem to be satisfactory for a serious rule-making analysis

Given the complications outlined above and the limited research support available, the problems with traditional cost-benefit analyses seem likely to persist in the near future. The next section suggests an alternative approach.

4. Formulating a Minimum Set of Risks for the United States

Although it cannot provide a bottom-line estimate of the significance or costs of the impacts (or at least those that would be alleviated by a particular policy action), a list of the most serious consequences can provide an indication of the range and significance of the risks of global climate change. As a starting point, the value to society of ecological services and natural capital has been estimated to be roughly equivalent to the services provided by the world economy (Costanza et al., 1997), and the most important and direct impacts of climate change have been estimated to amount to several percent of that amount (Stern, 2007).

Drawing from four extensively reviewed scientific impacts assessments [the U.S. National Assessment (NAST, 2000), Arctic Climate Impacts Assessment (ACIA, 2004),

[22] See the paper by Rose in this volume.
[23] See the paper by Ackerman et al. in this volume for discussion of the appropriate role of economic analyses in climate policy.

Intergovernmental Panel on Climate Change (IPCC, 2007b), and the Unified Assessment of the Climate Change Science Program (Karl et. al., 2009)], this section provides an overview of the most important consequences likely to affect the United States.[24] The selected impacts provide a minimum set for consideration in evaluating the relative merits and effects of various policy actions—any policies with costs less than the damage resulting from these minimum impacts would easily be deemed cost effective. Benefits of action beyond those listed here would justify additional costs (Lester and Smith, 2010).

The consequences that are likely to be most disruptive and economically costly for the United States (including its states, tribal lands, territories, and trusts) include the following:

1. **An increase in extreme weather.** Observations show, for example, an increase in the frequency of heavy downpours (Trenberth and Jones, 2007) and in the strength and overall destructive power of hurricanes (Emanuel, 2005; Elsner et al. 2008). The increasing intensity of rain and shifting precipitation bands will likely increase the frequency and extent of flooding, which, combined with increasing populations and infrastructure in vulnerable regions, will greatly amplify damage. Because of experience in estimating damage from past storms, damage from a greater frequency of intense storms could, for example, likely be projected using regionally resolved models to simulate the details of likely changes in the character of extreme weather. Such models are only beginning development and do not inform current economic analyses.
2. **Increased inundation in coastal regions.** Several recent studies project that the total rise in global sea level[25] during the 21st century could be as much as 3 to 6.5 feet (Rahmstorf et al., 2007; Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009). Exposure is high.[26] Although some protection is possible (e.g., storm surge barriers to protect Manhattan and interior New York City), there is no practical way to protect some populated coastal areas and barrier islands (e.g., Brooklyn, Long Island, and the Florida and Texas coasts). Ultimately, retreat will be necessary, which is feasible for individuals but costly for structures and communities (GAO, 2004). The economic, psychological, social, and dislocation costs are likely to be much larger when retreat is in response to a disaster.
3. **Increased stress on water resources, storm runoff, and sewage systems.** Impacts on water resources were the primary concern of virtually all of the regions

[24] To avoid cluttering the text, specific referencing of these assessments is not included throughout this section.

[25] The consequences of sea level rise tend to become most evident during especially high tides or storm surges caused by tropical storms, and in regions where coastal margins are sinking. Although little damage will result from a small rise in sea level, much more extensive damage can be expected once natural and human barriers (e.g., dunes, mangrove swamps, rock barriers, and sea walls) are overcome.

[26] While Hurricane Katrina showed the vulnerability of New Orleans, there are many other exposed regions, including the Chesapeake and San Francisco bays, the Sacramento-San Joaquin Delta in California, and New York City and Boston harbors.

participating in the U.S. National Assessment (NAST, 2000). Climate change affects water resources by shifting tracks, intensity, and timing of storms (thus altering precipitation patterns) and by reducing the snowpack that feeds reservoirs. Increased storm intensity could more frequently exceed the capacity of storm sewer and runoff systems, and higher sea level can require the modification or relocation of water and sewage treatment facilities. In some regions increased drought will render current water storage and planning approaches inadequate.

4. **Accelerating changes in land cover.** Land cover provides society with a wide variety of ecological services and economic benefits[27] and is affected by climate change.[28] Changes in land cover are affecting or will affect many regions in the United States, such as the Pacific Northwest (pine beetle infestation), southern California (faster growth of plant species[29] that provide more fuel for wildfires), the Southeast and Southwest (drought stress, which increases vulnerability to wildfires), and the Northeast (shifting of species like the sugar maple into Canada). Because the shift from one ecosystem to another takes decades, the transition brings risks and costs.[30] The most direct costs (e.g., fire-fighting, loss of lumber, etc.) can generally be readily estimated but the indirect losses involving social disruption and regional character changes are more difficult to assess.

5. **Increasing stress on wildlife and biodiversity.** Wildlife has evolved in conjunction with the climate and landscape and faces shifting or loss of habitat as a result of climate change and societal development.[31] Projections suggest a substantial decrease in biodiversity as species are pushed past their limits to shift and adapt (Thomas et al., 2004).[32] Experience has been, for example, that removing single species has actually led to quite significant changes in habitats (e.g., removing the wolf in the western United States allowed grazing animals to multiply, leading to changes in land cover), and introduction of new species (especially if invasive) can also dramatically change

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[27] These include, for example, wood and fiber products, soil and coastline stabilization, water purification, air cleansing, aesthetics, recreation, and jobs.

[28] Land cover is dependent on prevailing climate through the character of vegetation and soil.

[29] The increasing CO_2 concentration is likely leading to faster growth of the chaparral that covers the hills and mountains of the region (NAST, 2000), thereby more rapidly building up the mass of dry brush that becomes the fuel for intense wildfires.

[30] The loss of a prevailing ecosystem is likely to be much more rapid than the growth of a new ecosystem. With the pace of climate change accelerating, the time and climatic stability that allow new relationships to develop is lost.

[31] Climate change is leading to poleward and upward shifts in the ranges of species on land (e.g., butterflies, birds, etc.), in rivers (fish, etc.), and in the oceans (e.g., fisheries, anadromous fish, whales). Shifts in the timing of migrations and life cycles are also occurring (Fischlin and Midgley, 2007). In the Arctic, the retreat of the sea ice is disrupting the habitats of major species such as the polar bear and other marine mammals (ACIA, 2004).

[32] Shifts in the range of species are actually causing the numerical biodiversity in some regions to increase (e.g., there are more different species now in the Arctic) in the short term, but this trend is expected to reverse as the climate continues to warm.

landscapes and ecosystems.[33] These effects can also have significant economic impacts, such as reduced storm surge protection from coastal wetlands and loss of valuable natural products used in foods and drugs. Thus, with the pace of climate change accelerating, the potential for significant disruption of wildlife and loss of biodiversity is quite possible and the impacts should be accounted for in risk analyses.

6. **Ocean acidification.** The response of marine species to changes in ocean chemistry[34] is unclear but fundamental.[35] If the CO_2 concentration continues to rise as projected, some calcifying marine organisms may not be able to adapt, making disruption and even extinction more probable (Monaco Declaration, 2009; Raven et. al., 2005). Projections are that surface waters will become corrosive to most coral by mid-century (Silverman et al., 2009). The need to understand the full consequences for the marine food chain urgently merits further research, but consequences could be significant as calcifying marine organisms provide many critical ecological services, including augmenting terrestrial food resources, coastal protection by coral reefs, cultural amenities, and others.

7. **Increasing health risks.** Both weather and climate influence the location and frequency of health impacts, both directly (extreme weather events) and indirectly[36] (alterations to ecosystems and disease transmission). The severity of future health impacts will be determined by changes in climate combined with adaptation measures and socioeconomic factors (e.g., wealth, distribution of income, status of the public health infrastructure, provision of medical care, and access to adequate nutrition, safe water, and sanitation). Climate change could exacerbate a variety of health-related issues, including heat-related mortality (Kosatsky, 2005), diarrheal diseases, and diseases affected by high concentrations of ozone[37] and by allergens (Ebi et al., 2008). Demographic trends (i.e., a larger and older U.S. population) will increase overall vulnerability and socioeconomic factors will influence vulnerability at the local level.

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[33] There is relatively limited understanding of the roles of the many species that make up particular ecosystems (plants, animals, soil organisms, etc.) and especially whether there are particular sets of species that might be considered critical to the ecosystem.

[34] The increased uptake of CO_2 by the oceans is reducing the pH of seawater, making it more acidic.

[35] Acidification is reducing the amount of available calcium carbonate, which is the construction material for skeletons and protective shells of many marine organisms. Early research indicates that there is a wide range of sensitivities to acidification, suggesting that the initial consequences will involve changes in the relative populations of different species in marine ecosystems.

[36] Indirect effects can influence the incidence and prevalence of water-, food-, and vector-borne diseases, malnutrition, and diseases associated with poor air and water quality.

[37] There is a growing body of evidence that ozone concentrations would be more likely to increase than decrease in the United States as a result of climate change, assuming that precursor emissions are held constant (U.S. EPA, 2009). An increase in ozone could cause or exacerbate heart and lung diseases and increase mortality (Patz et. al., 2005).

8. **Impacts on Indigenous Peoples and cultures.** Much more than most, Indigenous Peoples draw resources from and depend upon the outdoor environment. Faced with changes in the natural environment, they have traditionally relied on two responses, both of which are largely unavailable to them in modern times: relocation to follow the sources of traditional plant and animal species (which is often not possible due to restriction to tribal lands and barriers to resource migration) and sharing of resources (loss of traditional culture[38] could change these relationships). For these peoples, whether on islands, in high latitudes, or elsewhere, the threats of climate change and sea level rise are viewed as terribly disruptive—making an irreversible switch to a market culture with a very nebulous and incomplete safety net is viewed as cultural destruction. Such losses are difficult or even impossible to value monetarily.
9. **Risks to the economy and to national security.** Due to the strong interconnectedness of the global economy, the consequences of significant regional disruptions[39] are now felt around the world, particularly affecting the nations that are most vulnerable (whether due to economics, changing climate, or environmental stress). The United States typically experiences a price change in response to a disruption, but elsewhere the impacts can be much more significant, endangering local, regional, and even international security.

These represent the minimum likely impacts from past and future emissions, assuming unconstrained or weakly constrained emissions in the future. In general, these impacts are a direct response to the changes in climate and the rise in the CO_2 concentration. With sufficient research, it should be possible to develop estimates of the associated minimum economic costs. Refining the estimates, however, will remain problematic because of inherent limits in scientific knowledge concerning the climate system and of how society will develop (e.g., the pace of technological improvement and choices society will make in deriving its energy) and adapt to changes in the climate.

While these impacts might represent a minimum set, there are at least two key problems in using this information for the type of cost-benefit study done in the past. First, because of the inertia of the climate system, these impacts will only be avoided by very large policy actions, and the benefits of the policy will only be seen well in the future; therefore, even moderate discounting can make the level of policy required appear not to be cost effective,

[38] Sharing all that was harvested or hunted became the social safety net of Indigenous society and culture. To the extent that climate change forces Indigenous Peoples away from their traditional food and clothing resources, the whole basis of cultural interrelationships changes and the long-lived lessons of how to co-exist within nature (i.e., the Indigenous knowledge that is the basis of so many of their customs) are lost or become irrelevant.

[39] Food and fiber production, generation of hydroelectric and other renewable energy, water resources, personal safety (in the face of extreme weather conditions), tourism and recreation, etc. are critically dependent on the climate and prevailing environmental conditions.

even if the likely impacts include socially unacceptable outcomes.[40] Second, being only a minimal set of impacts, there is significant potential for the actual impacts to be well above this minimum, especially because of the very real possibility that thresholds, tipping points, and surprises lie ahead. As Weitzman (2009) makes clear, even very low probabilities of very large impacts can significantly affect the conclusions that emerge from comparative analyses of costs and benefits. It is for this reason that an alternative approach such as risk management is likely to be much more appropriate for use in climate policy analyses, limiting the role of integrated assessment models to comparative evaluation of the suitability of alternative policy approaches aimed at meeting particular reduction goal.[41]

5. Conclusions

As the climate changes faster, as impacts become more evident, and as global emissions continue to grow, the global community is rapidly approaching a critical fork in the road. On one path lies ongoing accelerating warming, shifting precipitation bands, intensifying droughts, and sea level rise of a meter or more per century, to name only a few likely impacts. This path even poses significant risks of catastrophic events or surprises, as poorly known thresholds are crossed. Failure to reduce and ultimately stop emissions of greenhouse gases in a timely fashion leads down this path. While the costs of energy may only modestly increase, the losses due to the impacts on the environment and on many societies will bring significant costs. The costs could include relocation of cities and infrastructure along many low-lying coastlines, even in the United States, and could be significantly greater than the costs calculated by the current generation of cost-benefit analyses.

Along the second path, the rate of warming is reduced, leading to less significant shifts and intensification of storms, an eventual slowing of the rate and final extent of sea level rise, a reduction in the projected pace and ultimate number of species extinctions, and, if emissions controls are aggressive, a greatly reduced likelihood of catastrophic outcomes. This is the projected path if the world aggressively limits cumulative greenhouse emissions during the 21st century to essentially no more than the emissions that occurred over the 20th century (IPCC, 2007a).

Although there are uncertainties, the present state of knowledge, as exemplified in the recent IPCC assessment (IPCC, 2007a, 2007b), clearly distinguishes the two paths. Essentially, as Australian scientist Barrie Pittock (2007) has said; "Uncertainties are inevitable; risk is certain." The science clearly demonstrates that global cooperation and participation starting in the near future will be required to avoid putting the world at risk of very severe climate disruption. Although some attempts at a cost-benefit analysis of this decision have been attempted (e.g., Stern, 2007) and may be insightful, they are, and will

[40] See the paper by Ackerman et al. in this volume.
[41] See the paper by Yohe in this volume.

continue to be, fraught with uncertainties and value judgments that may be impossible to resolve. Indeed, if a government's decision is based on resolving such uncertainties [as the Climate Change Science Program of the United States seemed formulated to attempt (CCSP, 2003)], the decision to constrain emissions can never be taken.

To overcome the limitations of cost-benefit analyses, especially given the range of uncertainties and possible nonlinearities and surprises described in Sections 2 and 3, a risk-based approach seems more viable. Section 4 provides a starting baseline of impacts with the potential to underpin such risk-based analyses—the listed impacts are largely unavoidable, although adaptation may moderate their harshness. With the unprecedented speed of the changes in atmospheric composition caused by the burning of fossil fuels, the consequences could quite plausibly overwhelm the biosphere and human society. Therefore, it seems essential that implementation of policies to limit emissions not be delayed by requests for the impossible—namely, for precise and detailed cost-benefit analyses.

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