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WHAT IS THE ECONOMIC COST OF CLIMATE CHANGE?*

Michael Hanemann

1. INTRODUCTION

Much of the economic analysis of climate change revolves around two big questions: What is the economic cost associated with the impacts of climate change under alternative GHG emissions scenarios? What is the economic cost of reducing GHG emissions? The economic aspect of the policy debate intensified with the publication in the UK of the Stern Review of the Economics of Climate Change (Stern, 2006). Stern concluded that, if no mitigative action is taken, "the overall costs and risks of climate change will be equivalent to losing at least 5% of global Gross Domestic Product (GDP) each year, now and forever." This conclusion has been criticized by many economists, particularly in the United States, where Professor William Nordhaus of Yale, the leading American expert on climate economics, concludes that the economically optimal policy involves only a modest rate of emission reduction in the near term, followed by larger reductions later (Nordhaus 2008).

The disagreement between Stern and Nordhaus has aroused considerable interest. Much of the existing discussion focuses on the difference in the discount rate – Stern uses a consumption rate of discount average 1.4% per annum, while Nordhaus uses one averaging 4%.[1] However, I believe that another important factor is the difference in the raw assessment of undiscounted damages from climate change. Because of limited space, that difference is the focus of this chapter.[2]

Compared to most other assessments, including those of the DICE model in Nordhaus and Boyer (2000), the Stern Review takes a more pessimistic view of the potential adverse impacts from climate change. There are several reasons. First, Stern uses an assessment model which tracks the impacts of climate change through 2200, whereas the other models run through 2100 or 2150. Temperatures continue to rise beyond 2100

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* A shortened version of this paper appears as a chapter in Stephen Schneider, Armin Rosencranz and Michael Mastrandea (eds) *Climate Change Science and Policy*, Island Press (forthcoming). A longer version is also in preparation.

[1] See the recent symposia in the *Journal of Economic Literature* Vol. 45, No. 3, September 2007, *Climatic Change*, Vol. 89, No. 3-4, 2008, and *Review of Environmental Economics and Policy* Volume 2, No. 1, Winter 2008. The impacts of climate change occur over varying periods of time, stretching, in some cases, over centuries. The costs of reducing GHG emissions occur, for the most part, in the present and near future. Therefore, mitigation involves taking action and sacrificing some consumption and wellbeing now in order to avoid a loss of wellbeing in the future. The discount rate is the rate at which one trades off wellbeing now against wellbeing in the future.

[2] A third point of difference is the treatment of uncertainty about the possibility of catastrophic impacts and the allowance for risk aversion (Weitzman in press). A fourth difference concerns the magnitude of the economic cost associated with reducing emissions; see Barker and Ekins (2004).

under many emissions scenarios, which raises the total damage when the analysis extends to 2200. Second, the economic damage and cost functions used in the other models are based largely on literature prior to 2000, while the Stern Review has better coverage of the more recent work on climate impacts; the more recent studies generally reach less optimistic conclusions than earlier ones.[3] Third, the Stern Review tends to be more global in its coverage of damages. Most of the existing damage functions were calibrated using studies of the USA which were then scaled for application to other regions of the world. The Stern Review made a greater effort to collect information about other regions, especially Africa and Asia, where the impacts are likely to be more adverse.

In this chapter, I focus specifically on the limited issue of the economic costs of climate change to the United States if there were a $2.5^{\circ}C$ increase in average global temperature.[4] This serves as something of a benchmark for the damage function in Nordhaus and Boyer's (2000) well-documented DICE model.

2. THE FRAMEWORK FOR DAMAGE ASSESSMENT

In an economic assessment the physical, biological, and social impacts of climate change – whether beneficial or adverse – are expressed in monetary terms. Given a particular future scenario, an impact assessment translates the resultant emissions first into changes in temperature, precipitation and sea level; then into a suite of physical, environmental and social impacts, e.g., changes in crop yield, water supply, disease incidence, species abundance, etc.; and, lastly, into an aggregate monetary cost.[5]

I refer to the physical, environmental and social impacts in the next-to-last step as "*damages*," and their economic valuation (the last step) as the "*economic cost*" of climate change. The impact assessment involves the use of *damage functions*, which express physical or environmental outcomes as a function of changes in climate variables; for example, there may be agricultural damage functions or health damage functions. The economic cost associated with damages is then represented through a *valuation function*, which translates the given set of damages into an economic cost. Alternatively, the impact may be expressed directly in monetary terms using a *cost function* which represents the economic cost as a function of changes in climate variables, thereby combining the two steps into one.

Each step is marked by uncertainty and some degree of scientific disagreement. Even with a given emission scenario, different climate models yield different projections of temperature and precipitation.[6] And, given a projected change in climate variables,

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[3] This is noted by Warren et al. (2006), who provide a useful review of the damage functions in the major models.

[4] The chapter by Hallegatte and Ambrosi covers similar issues, but not specifically for the US.

[5] On a national basis, the aggregate monetary impact – the change in income plus the willingness to pay equivalent of the other changes in wellbeing – is typically expressed as a percentage reduction in Gross Domestic Product (GDP), the value of the market economy.

[6] In the *Third Assessment*, where the increase in global temperature by 2100 was estimated to range from 1.4° C to 5.8° C depending on which emission scenario and climate model were used, the differences

different models use different damage and/or valuation functions and reach different conclusions regarding the economic cost.

Three points should be emphasized. First, the disagreement among damage and cost functions is significantly larger than that among climate change projections.[7] This should not be a surprise. Climate modeling has been going on for longer and at a higher level of activity than damage and cost modeling, and is therefore in a more mature state. In addition, damage estimation is inherently more complex: it involves a high level of spatial disaggregation and a wide range of biological, chemical, hydrological and physical phenomena, most of which are not yet well modeled.

Second, the paucity of the available data for many of the factors that determine the impacts of a given climate change scenario can scarcely be overstated. Because of the spotty nature of the data available, analysts inevitably have to extrapolate the results from an analysis of one location to other locations that could well be quite different. The resulting damage functions, therefore, depend very heavily on subjective judgments by the researcher. This accounts in part for the differences in conclusions regarding the economic impact of climate change.

Third, while there is some controversy both about the economic concept of value – representing the consequences of climate change through a monetary measure[8] – and also about specific approaches to the measurement of economic value, this is *not* a major factor in the controversy about the economically optimal reduction in GHG emissions. As explained below, the issues have more to do with whether the impacts are positive or negative, and how large, than with whether and how they should be monetized.

3. THE ISSUE OF AGGREGATION

Aggregation over space and time when characterizing impacts matters greatly, and accounts for some of the differences in assessed impacts. Using annually averaged temperatures masks harmful effects of high temperatures on a daily timescale and obscures crucial differences in seasonal temperatures. While warmer winter temperatures may be beneficial in some cases, including energy demand and health, warmer

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between climate models accounted for 1.9° C of the range while the differences between emissions scenarios accounted for 2.5° C (Albritton and Meira Filho, 2001).

[7] As shown below, the disagreement among damage functions is an important factor in the controversy over the Stern Review: his critics have complained that Stern's damage estimates are "10 to 20 times higher" than estimates in the existing literature (Yohe and Toll, 2007).

[8] For example, Schneider et al. (2000) recommends that five separate metrics be used to measure the impacts of climate change: Monetary loss (by which is meant market impacts); loss of life; quality of life (including conflict over resources, cultural diversity, loss of cultural heritage, and forced migration); species and biodiversity loss; and distribution/equity.

summertime temperature can have a negative impact, especially if they involve more frequent heat waves.[9]

To illustrate the potential effect of aggregation, consider the temperature implications of the B1 emission scenario. As simulated by the HadCM3 climate model, under this emission scenario there is a 2° increase in *global* average temperature by 2100, compared to the average in 1990-1999. But, the temperature increase is distributed unevenly around the globe; the increase is smaller over the ocean and in lower latitudes, and larger on land and at higher latitudes. By 2100 in California and much of the US west under this scenario, there is a 3.3^{o} C increase in *statewide* average annual temperature.

The increase is different at different times of the year. Statewide average *winter* temperature (December – February) in California rises by 2.3^{o} C, while statewide average *summer* temperature (June – August) rises by 4.6^{o} C. Moreover, there is spatial variation between the temperature increases along the coast versus inland. In the Central Valley, the main farming area in California, the increase in summer temperature reaches 5° C.[10]

Given the nonlinearity of damage function, as explained in the next section, it makes a substantial difference to the estimated impact on California agriculture whether one represents the climate change as an increase of 2° C (global average annual temperature), 3.3^{o} C (statewide average annual temperature), or 5° C (Central Valley average summer temperature). While the effect on yield of 2° C temperature increase combined with carbon fertilization may or may not be positive, the effect of a 5° C increase during the growing season is likely to be negative.

The use of spatial downscaling, such as in Hayhoe et al. (2004), has only recently become common. Many of the earlier impact studies, include many of those used by Nordhaus and Boyer (2000), focused on the change in *global* average temperature and assumed a uniform increase in monthly temperature of something like 2 or 2.5^{o} C. To the extent that there are significant seasonal and spatial differences in the rate of temperature increase, this can produce an excessively optimistic assessment of the consequences.

4. NONLINEARITY OF THE DAMAGE FUNCTION

Following Mendelsohn, Nordhaus and Shaw (1994) [henceforth, MNS], it became common in the literature to use a statistical damage function to represent the relationship between changes in temperature and precipitation and the resulting change in physical or economic outcomes (for example, farm profit, farmland value, or crop yield). Moreover,

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[9] For example, in studies of the amenity value of temperature in Italy and Germany, Rehdanz and Maddison (2004) find that, while a higher January temperature is welfare-enhancing, a higher July temperature is welfare reducing.

[10] For further details, see Hayhoe et al. (2004). For the A1Fi business-as-usual emission scenario, the corresponding figures are: a 4.1^{o} C increase in global average annual temperature; a 5.8^{o} C increase in statewide average annual temperature, broken down into a 4° C increase in statewide average winter temperature and an 8.3^{o} C increase in statewide average summer temperature; and a 10° C increase in average summer temperature in the Central Valley.

following MNS, it became common to represent the damage function using a quadratic functional form. This reflects the fact that the effects can be *mixed*: some degree of warming can be beneficial in a cold climate, while the same warming would be harmful in a hotter climate. Hence, there is a hill-shaped relationship with a unique temperature optimum; below this, increases in temperature raise yield, while above it they lower yield. The quadratic provides this general shape, but it does something more. It provides for a *symmetric* relationship such that, for two equal temperature changes spaced symmetrically around the optimum, the beneficial and harmful impacts are equal and therefore offset one another. Symmetry is a strong assumption, and it has been motivated more by considerations of mathematical convenience than the presence of corroborating empirical evidence.

The assumption was recently tested by Schlenker and Roberts (2006a,b) for major grains using a highly sophisticated non-parametric analysis which imposes no a priori restriction on the shape of the relationship between daily temperature and crop yield. They find that, as temperature rises, yield increases, but at a slow and roughly constant rate> Then there is a turning point, beyond which yield falls very sharply. The relationship is highly asymmetric and is shaped more like a mesa than a hill; the harmful effect of a temperature increase beyond the turning point greatly outweighs the beneficial effect of the same-sized increase below the turning point.

While the results are specific to the particular relationship being studied, it seems likely that a similar pattern occurs with other temperature-impact relationships, including the relationships between energy demand and human mortality and ambient temperature, namely the relationship is asymmetric and the slope becomes particularly steep for very high temperatures.

5. TAKING STOCK OF DAMAGES

Before proceeding further, it is useful to look at the breakdown of climate impact damages in the US assessed by Nordhaus and Boyer for a 2.5° C global warming, shown in Table 1. Nordhaus and Boyer represent the damages in terms of aggregate US willingness to pay to avoid the impact, expressed as billions of 1990 dollars and as a percentage of 1990 GDP. The former is shown in the second column of Table 1. The first column in the Table recasts the same impact in terms on a *per household* basis, using 2006 dollars.[11]

INSERT TABLE 1 HERE

Of the $28 billion of annual damages (in 1990$) estimated by Nordhaus and Boyer for the US, the single largest item is $25 billion as the estimate of the annual US willingness to pay to avoid the risk of catastrophic climate events such as the ending of the thermohaline circulation or the melting of the Greenland ice sheet. Setting this item aside, Nordhaus and Boyer's estimate of the net impact on the US associated with *non-*

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[11] This is my conversion of the Nordhaus and Boyer data, applying their 1990 percentages of GDP to the average US household income in 2006, taken from the Current Population Survey (CPS).

catastrophic effects of climate change amounts to about $4 billion per year. This reflects what Nordhaus and Boyer see as a large amenity benefit to the US amounting to about $17 billion per year associated with increased outdoor recreation made possible by warmer temperatures in the US. All of the non-catastrophic damages amount to only about $21 billion per year. When the amenity benefits are subtracted from these damages, the result is a net cost of about $4 billion.

As explained below, I believe the estimate for the amenity benefit from increased outdoor recreation is likely to be greatly overstated, while the estimate of the damages is greatly understated. Hence, the damages to the US from a 2.5 $^{\circ}$ C increase in global average temperature are likely to be significantly larger than Nordhaus and Boyer suggest.

6. AGRICULTURE

Agriculture is both the most heavily studied sector in the climate economics literature and also the most controversial in terms of the range of divergent impact estimates. One factor contributing to the divergence in estimates is the sheer complexity of the interactions between climate and crop growth; these involve temperature, CO_2, crop water need, pests, weeds and ozone. Moreover, different crop processes react to different aspects of temperature. Photosynthesis, by which a plant manufactures carbohydrates, occurs during daylight hours and increases with daytime temperature; respiration, which consumes plant carbohydrates, occurs during day and night, and therefore increases with nighttime temperature; if the latter increases more than the former, the net effect can be a reduction in yield. Also, for most but not all plants, photosynthesis increases when the atmospheric concentration of CO_2 rises; however, the amount of this fertilization effect is still uncertain. In short, the potential effects of climate change on agricultural production are complex, nonlinear, and multidimensional.

In most of the existing economic analysis the agricultural effects of climate change has been treated in a fairly simplified manner. The focus has generally been limited to the effects of temperature and CO_2 fertilization, and to the impact on crop yield, especially the major grain crops. The effect on product quality and the impacts of climate on water need, weeds, pests and ozone have largely been overlooked.

MNS conclude that adapting to climate change yields positive benefits to US agriculture. However, they fail to control adequately for the effects of irrigation by pooling both dry-land farming and irrigated land. They assume that local precipitation in a county is the source of water supply for the county's agriculture. While this is accurate in dry-land farming areas, it does not hold in irrigated areas, where the water supply comes from either groundwater or from surface water associated with precipitation occurring outside the region and imported into it. The richest farmland in the US is found in irrigated areas of California and parts of Arizona. These are also the driest and hottest regions of the US. If one does not control for irrigation, it looks as though being dry and very hot in the summer makes for richer farming. When Schlenker, Hanemann and Fisher (2005) control for the effects of irrigation and repeat the MNS analysis just for dry-land farming areas of

US, they find a loss in these areas of $11 billion, instead of the gain of $2.3 billion reported by MNS.

For irrigated areas, there is clear evidence that agriculture in these areas, too, will lose from climate change -- warmer temperatures will increase evapotranspiration, and thus, crop demand for water, while also reducing the effective supply of surface water. There is no comprehensive source of data on water supply for irrigated areas in the US west; the data must be assembled painstakingly for each water supply system. Schlenker, Hanemann and Fisher (2007) conduct such an analysis for water districts in California. Assuming an increase in temperature while maintaining effective water supply (which is an unduly optimistic assumption), farmland values in California towards the end of the century (2070-2099) could be reduced 24 to 52 percent, depending on the scenario assumptions regarding energy usage and technological advances.

Taken together, the revised analysis that takes into account differences in water sources between rain-fed and irrigated land indicate that climate change will entail losses to US agriculture of about $15 billion (1990$), if not more.

7. WATER

Three quarters of the freshwater used in the US comes from surface water and, therefore, depends directly on current precipitation. One might thus be inclined to assume that, with climate change, water supply will change by whatever is the change in total annual precipitation. However, this is overly simplistic because increases in temperature also affect water supply, in some regions more profoundly than precipitation.

Temperature affects both the timing and volume of runoff. In mountain areas, it affects whether precipitation falls as rain or snow, whether it runs off immediately or is stored as snow, and when the snow melts. It also affects the ground cover in a watershed, which in turn influences runoff. In forested areas, for example, the combination of higher temperature and dryer soil could cause more frequent or intense wildfires, reducing forest cover, lowering moisture retention, and accelerating runoff. Because of the water consumed by ground cover, Nash and Gleick (1993) found that, if the temperature in the Colorado River Basin increased by 4C with no change in precipitation, this would reduce the mean annual runoff there by nearly 20%.[12]

The intensity of precipitation is also important since a greater intensity means less moisture is retained in the soil. Trenberth et al. (2003) hypothesize that, with warming, precipitation will tend on average to be less frequent but more intense when it does occur. At the same time, with warming, the soil dries earlier in the year so that there can be both more winter flooding and more summer drought. Increases in summer temperature also raise crop ET, increasing the demand for agricultural and outdoor urban water use and exacerbating the effect of reduced summer supply.

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[12] The effect is likely to be nonlinear. A recent estimate for river basins in Australia by Young (personal communication) suggests that 1% reduction in precipitation there will lead to a 3% reduction in reservoir inflows, but a 10% reduction in precipitation could lead to a 50% reduction in inflow.

In areas that rely on the snow pack for natural storage like California, the Pacific Northwest and the Colorado River Basin, winter warming reduces the portion of winter precipitation that is still retained in the snow at the beginning of spring. Without additional costly manmade storage to capture the extra winter time runoff, this reduces the water supply available for use in the summer. In California, the Sierra snow pack accounts for about one third of the state's total surface water supply storage and, by 2070-2099, it is projected to decline by 70-90% under the A1Fi scenario (Hayhoe et al., 2004).

Hanemann et al. (2006) analyze some of the costs associated with this supply reduction in California. The main economic impact for both agricultural and urban water users occurs not in average years but in drought years, which happen with greater frequency under the climate change scenarios. For example, for urban water users in Southern California in 2070-2099, under the A2 scenario shortages that require rationing occur twice as frequently (1/3 instead of 1/6 of years) as with no climate change, and are more intense (1/3 greater loss of consumer's surplus). The net impact of climate change to urban water users in Southern California is a loss of about $4 billion per drought year.

Nordhaus and Boyer assume that a 2.5° C increase in global average annual temperature will have no net economic impact on water supply in the US. A more plausible estimate for the US might be a loss of something like $10 billion per year.

8. SEA LEVEL RISE

Nordhaus and Boyer observe that the damage from major tropical storms in the US over the period 1987-1995 averaged about $5.5 billion per year and – as a rough guess – they assume that climate change might cause storm damage to double in real terms by 2100. Based on this, they estimate that the WTP to prevent sea-level rise in the US associated with a 2.5 C warming might be about $6 billion per year (in 1990$). This estimate seems overoptimistic.

 For one thing, the damage estimates used by Nordhaus and Boyer account only for property damage and government expenditures.[13] They do not account for costs associated with business disruption and economic dislocation;[14] the misery and loss of wellbeing associated with being flooded, even if one is uninjured; and injury or loss of

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[13] Although they include some allowance for uninsured losses, they are skewed towards insured losses and are influenced by the limits on coverage for loss of personal property..

[14] Even if the business itself is not flooded and its workers are not forced to evacuate, it may have to shut down because of a lack of electricity or other services, disruptions in the flow of materials, or the loss of customers. In the aftermath of Katrina, costs of interrupted economic activity exceeded $100 million per day. In addition, constraints on production capacity in the economy may raise the cost of repair and replacement; after Katrina, the prices of some building products rose by 5-10%. The result can be an "economic amplification" as production losses magnify the direct damage impact (Hallegatte, Hourcade and Dumas, *Ecological Economics*, 2007, 330-340).

life.[15] The magnitude of these additional costs varies nonlinearly with the size of the flood; while they may be minor for small floods, they grow disproportionately larger for severe floods.[16] Hurricane Katrina provides an example of how the costs multiply. While the US Department of Commerce places the damage from Katrina at $125 billion, this does not include uninsured and non-property losses. Unofficial but more comprehensive estimates place the damage, including the costs of economic dislocation, in the range of $250-350 billion.

Also, Nordhaus and Boyer's damage estimate covers only impacts on the Atlantic and Gulf coasts. It omits flood damages along the west coast. West coast floods are associated with wet winter storms rather than tropical hurricanes, but they can still cause billions of damages in damages.

Not only do Nordhaus and Boyer understate the existing damages from coastal flooding in the US, but they also understate the likely future *increase* in damages as climate changes during the course of the century. Even if, in the future, there were no increase in the frequency or intensity of hurricanes with warming temperatures – which now seems unlikely – there are two factors which would intensify the magnitude of coastal flood damages beyond the mere doubling assumed by Nordhaus and Boyer. One factor is the trend for an increasing proportion of the US population to live near the coast. This implies that, even if nothing else changes, the damages from coastal flooding in the US are likely to rise faster than GNP and, therefore, to become a larger fraction of GNP. The second factor is the rising sea level. A rise in sea level causes an exponential increase in the probability of coastal flooding (Cayan et al. 2006).

For these reasons, Nordhaus and Boyer's estimate that sea level rise associated with a 2.5° C warming would cause damages in the US amounting to $6 billion per year (in 1990$) seems too low by a factor of 5 or 10. For the purposes of analysis below, I will raise this to $35 billion (in 1990$).

9. ENERGY

Nordhaus and Boyer assume there would be no net economic impact on the US energy sector from a 2.5° C increase in global average annual temperature. They justify this by pointing out that the higher temperature lowers wintertime demand for energy for space heating, even as it raises summertime demand for energy for space cooling. However, there is little reason to believe that the one effect offsets the other with such large temperature changes.[17] A nonparametric analysis shows the relationship is asymmetric:

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[15] Over the period 1987-1995, an average of 27 lives were lost annually due to tropical storms and hurricanes in the US; over the period 1995-2004, the figure was 44 lives annually. In Katrina, there were 1833 confirmed deaths with several hundred more people unaccounted for.

[16] For example, it was recently estimated that, if London were flooded due to sea level rise, it might take 10 years to fully recover from the damage (BBC News 7/12/07). It seems likely that something similar applies for New York City or Miami.

[17] As noted above, a 2.5° C increase in global average annual temperature translates into a 4.6 ° C increase in summertime temperature in California. In California, the metric for identifying occurrences of peak

the increase in demand at high temperatures is much steeper than the decrease at low temperatures (Engle, et al., 1986).Moreover, residential winter space heating occurs most at night and involves baseload energy while residential space cooling typically occurs in the late afternoon and involves peak power. From an economic perspective, the latter is considerably more costly than the former.

In addition to the effect on demand, climate change can also affect the *supply* of energy when extreme weather events occur. During the 2003 heat wave in Europe, energy production in France's nuclear power stations fell because the river water was too hot for adequate cooling. In the US, power plants discharging cooling water often face restrictions of the temperature of the discharge water and sometimes have to limit operations when the ambient air and water temperature become too high, notably along the Gulf of Mexico. Extreme heat also lowers the carrying capacity of electricity transmission lines. Hurricanes, storms and extreme weather conditions can sometimes disrupt the production and distribution of energy; Hurricanes Katrina and Rita in 2005 damaged 558 pipelines and destroyed more than 100 offshore oil platforms.

Consequently, it seems likely that there will be a negative net impact on the US energy sector with a 2.5^{o} C increase in global average annual temperature. A crude estimate is that this could run to $5 billion per year or more (in 1990$).

10 HEALTH

Nordhaus and Boyer estimate the human health impacts in the US associated with a 2.5^{o} C increase in global average annual temperature at about $2 billion in 1990$. This is based on the assumption that there will be no direct health effects from extreme heat, only an increase in mortality from increased ozone and vector-borne disease.

With regard to the direct effects of heat, they assume that any increased mortality in the summer is completely offset by reduced mortality from winter warming. This is likely to be over-optimistic. The precise shape of the relation between temperature and mortality varies by location. The estimated impact depends on some key measurement issues, including whether one uses monthly or daily average temperature, whether one distinguishes between different levels of extreme temperature (e.g., treating all temperatures above 90°F as being in the same category), whether one uses absolute or relative temperature maxima (e.g. days over 90°F, versus days over the 99th percentile for that location), and whether one allows for interactions between the temperature one day and that on previous days (e.g., 3 or more consecutive days over 90°F) or between temperature and other factors such as humidity and air quality (e.g., ozone). In general,

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power demand is the so-called T90 temperature – the historical 1961-1990 maximum temperature exceedance threshold for the 10% warmest days in June - September. Daily maximum temperatures above the T90 occurred an average of 12 times a year during 1961-1990. By 2100, they are projected to occur three or four times more frequently under the B1 scenario (Miller et al., 2007).

the more refined the measure of temperature extremes, the more likely is the study to find that the increase in summer mortality outweighs the reduction in winter mortality.

There are several important limitations to Nordhaus and Boyer's analysis. They estimate the mortality associated with increased ozone and vector-borne disease using a crude and simplified regression analysis of aggregate mortality in different regions of the world as a function of regional average annual temperature. Compared to other estimates in the literature based more on epidemiological studies, their mortality estimate seems too high but the economic value they place on the mortality is too low. They value life years lost in terms of annual income; when their value is converted to the equivalent of the value of a statistical life (VSL), it amounts to the equivalent of $988,450 in 2002$. By contrast, the US EPA uses a VSL value of $6.2 million in 2002$. In addition, they do not allow for other forms of mortality, for example from increased cancer deaths associated with warmer temperatures (Jacobson, 2008). If the USEPA VSL is applied to Jacobson's combined estimate of ozone and cancer mortality in the US associated with a 2.5° C warming, it amounts to an annual loss of about $15.5 billion.[18]

11. AMENITY BENEFITS

It is certainly likely that some regions of the country will experience an amenity benefit from warming temperatures, even as other areas experience a loss. However, the net effect is unclear. As noted earlier, Nordhaus and Boyer estimate an amenity net benefit amounting to $17 billion (in 1990$). This is an estimate of the net economic value of increased outdoor recreation in the US associated with a 2.5° C increase in global average temperature. The estimate is based on a very simple regression of hours of outdoor recreation in US states as a function of average temperature. From this, they calculate that the increase in temperature triggers an increase in outdoor recreation. They make no allowance for the negative effect of high daily or afternoon temperatures during the summer. Moreover, they value the putative increase in outdoor recreation using the daily wage rate, and make no allowance for substitution from other leisure activities towards outdoor recreation. These assumptions are questionable. As a guess, a more plausible figure for the amenity benefit might be on the order of $5 billion (1990$).

12. ECOSYSTEMS

Nordhaus and Boyer have a category for impacts on ecosystems and human settlements. This includes impacts on natural ecosystems, especially irreversible effects and immobile ecosystems, and also impacts that arise because "immobile population, cities, or cultural treasures cannot emigrate with climate change." Examples the give are Venice, Bangladesh, and the Netherlands. For small countries, they observe. "the need to adapt or migrate will impose significant costs on the population."

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[18] This does not account for additional *morbidity* associated with increased temperatures in the US. Nor does it account for increased mortality or morbidity from other climate-related changes such as flooding or wildfire, including water-borne disease associated with flooding and air pollution associated with wildfires.

Nordhaus and Boyer estimate the willingness to pay to avoid impacts on human settlements and ecosystems by assuming that (1) the capital value of climate-sensitive human settlements and natural ecosystems is some fraction of national output (in the US, 10%, and (2) annual willingness to pay to avoid the disruption associated with a 2.5° C increase in global average temperature amounts to 1% of this capital value or, in the US, about $67 per household in 2006$.They admit that their estimate is speculative. It may also be low given that, as noted before, a 2.5° C global warming translates into considerably higher temperature increases in the US and, also, that climate change occurs on top of considerable population growth and land use development which, by 2100, will have greatly reduced available habitat. Instead, I will use a value corresponding to $120 in 2006$.

13. SUMMING UP

The last column of Table 1 presents an accounting of the impacts on the US of a 2.5° C increase in global average annual temperature if one accepts my suggested revisions of the Nordhaus and Boyer estimates. These revisions are necessarily speculative, but are intended to provide a more realistic accounting of what climate change might mean for the United States.

Two main factors account for the difference between my estimates and those of Nordhaus and Boyer: (1) A change in global average annual temperature, on which they tend to focus, translates into significantly larger changes in *seasonal* temperatures *in the US*. (2) Much of the impact is driven by extreme weather conditions occurring on the time scale of a few hours or a few days, not by the conditions that occur most of the time. Damage functions are asymmetric, and the most severe damages are triggered when thresholds are crossed. This is lost in Nordhaus and Boyer's broad brush assessment.

Like other estimates in the literature, including Nordhaus and Boyer, the estimates presented here do not allow adequately for adaptation. Undoubtedly some adaptations will occur that reduce damages below what we anticipate now. But, adaptations are themselves costly, and their cost would need to be factored into any accounting. Moreover, adaptation does not occur instantaneously and, when it does occur, it may not perfectly offset all adverse climate impacts. Depending on the timing and efficacy of adaptation there will still be some interim and permanent losses. Adaptation has the potential to reduce losses compared to those shown in Table 1 to a degree that is not yet known.

On the other hand, the estimates in the table are by no means comprehensive; it is likely that other sectors of the market economy not considered here will also sometimes be adversely impacted by climate change. For example, a recent report on transportation in the US concludes that this will be affected by extreme climate events and, while the effects vary by mode and region, they will be widespread and costly (Transportation Research Board, 2008). This is not accounted for here. Moreover, while in their estimate for catastrophic events Nordhaus and Boyer allow for risk aversion as a factor that boosts the willingness to pay to avoid these damages, they do not allow for risk aversion in any

of the other impacts. The other impacts – e.g., crop damage from extreme heat events, drought emergencies because of a decline in stream flow -- occur on a less global scale but it is likely that some of the people who are vulnerable to them would themselves be risk averse and would be willing to pay a risk premium to avoid this risk. This, too, would raise the damages beyond what is shown in Table 1.

TABLE 1: ESTIMATES OF THE ECONOMIC IMPACT OF 2.5' C WARMING: ANNUAL DAMAGES IN THE US

	NORDHAUS & BOYER (2002)		MY REVISED ESTIMATE
	PER HOUSEHOLD $ 2006	US TOTAL $ 1990 billions	US TOTAL $ 1990 billions
MARKET IMPACTS			
Agriculture	$46	4	15
Energy	$0	0	5
Water	$0	0	10
Sea Level	$69	6	35
MARKET SUBTOTAL*	$126	11	60
NONMARKET IMPACTS			
Health, water quality, human life	$11	2	10
Human amenity, recreation, nonmarket time	-$195	-17	-5
Human settlements, ecosystems	$67	6	11
Extreme and catastrophic events	$287	25	25
NONMARKET SUBTOTAL*	$195	17	41
MARKET + NONMARKET TOTAL*	$321	28	113

* Totals do not add due to rounding.

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