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ASSESSING CLIMATE CHANGE RISKS: VALUATION OF EFFECTS

by

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Anthony C. Fisher and W. Michael Hanemann*

1. Introduction

Other papers presented at this workshop have discussed and documented the many and varied impacts of projected global warming—and the uncertainties about the importance of the impacts. We do not propose—we are not qualified—to contribute anything of substance to this discussion. Instead, it will be the purpose of this paper to speculate about some of the implications for economic valuation. Our emphasis will be on ways of thinking about and dealing with major impacts, even, or perhaps especially, where there remains disagreement about magnitude and timing. In doing so, we are not necessarily coming down on the side of those who foresee the gravest impacts. Rather, the question we wish to address is, what if they are right? What are the implications for valuation? For that matter, what if there is a reasonable chance they are right? How does this affect valuation?

The next section of the paper briefly reviews what is probably the best known treatment by an economist of the damages to the United States from global warming—namely, the recent Economic Journal article by William Nordhaus (1991). The estimated damages, in fact, come from an EPA Report; Nordhaus' chief contributions are estimation of the costs of slowing warming and (1989) development of a model balancing these costs against the damages. Section 3 examines the appropriateness of the valuation exercise conducted by the EPA with regard to both which impacts were included and how these were analyzed. It seems fair to say that the EPA/Nordhaus view of the risks associated with global climate change is relatively sanguine, whereas others see higher probabilities of more drastic and even catastrophic impacts. Section 4 is about implications for valuation and policy choice if at least some elements of the less optimistic view are credible. Here we shall give particular attention to uncertainties, irreversibilities, and nonlinearities. Recommendations concerning the direction of future research are offered in Section 5.

2. Damages from Global Warming: No Cause for Alarm

The EPA estimates of damages from global warming associated with a doubling of carbon dioxide (CO_2), for the U.S., are given in Table 1 (taken from Nordhaus 1991). The salient feature of these estimates is that they are very modest: just $6 billion, or 1/4% of GNP in 1981 dollars. We shall discuss the individual categories in just a bit. But we first observe that it appears to be conventional, in the literature on climate change, to focus on the warming—variously estimated as between 1.5° and 4.5°C—and related impacts associated with a doubling of CO_2. This may be due to the standard climate model projection of a doubling over the next several decades, and the understandable reluctance of climate modelers—or economists—to make projections beyond a horizon of several decades. Or, it may be due to model projections of an equilibrium at that level. We shall return to this issue, which may be the crucial one for our discussion—and, for that matter, for the wider policy debate—in the next section. In the table, two sectors, agriculture and forestry, are shown to have the potential to be severely impacted. No quantitative estimate of damages is given for the latter, only an indication that the value of the impact could be positive or negative—and is small in either case. With regard to agriculture, impacts could range (in round figures) from plus to minus $10 billion; the harmful effects of higher temperatures could be offset by the beneficial effects of higher CO_2 levels on plant and tree growth. Judging from Nordhaus' central estimate of the total damages, the net damage assigned to agriculture is about $0.45 billion (all figures in 1981 $).

Several sectors—construction, water transport, energy, and real estate—are classified by Nordhaus as having (in his opinion) the potential to be moderately impacted. Quantitative estimates are provided only for the latter two, though it is indicated that the impact on construction will be positive. For energy, an increase in the need for space cooling is largely offset by a decrease in the need for space heating, so that the net cost is $0.49 billion. This leaves real estate, with a net cost of $5.29 billion, by far the largest component of the damages. These costs consist of the estimated value of land—about 4,000 square miles—lost due to flooding and the estimated costs of protecting high value property and open coastal areas.

Both the EPA and Nordhaus acknowledge that these estimates are incomplete, since they do not take into account impacts on ecosystems not immediately tied to the market economy or, for that matter, on nonmarketed goods and services in general. Nordhaus cites one study as suggesting that global warming will provide major amenity benefits in everyday life (National Research Council, 1978); he concludes that "climate change is likely to produce a combination of gains and losses with no strong presumption of substantial net economic damages" (p. 933).

3. Damages from Warming: A Critical Analysis

Placing an economic value on the consequences of global climate change is an enormous challenge. It involves impacts not only on the supply of commodities that are traded in markets, but also on non-market goods. As noted above, these impacts could be quite profound, and they are likely to be widely spread over time and space. Quantifying these impacts in monetary terms surely pushes the existing techniques of economic valuation to their limits. Here, we want to review the types of analysis that were performed by the EPA's economists and its consultants in their report on the potential effects of global climate change on the United States and examine how successful they were in meeting this challenge.

Let us start by considering just what was valued. What impacts would you expect to find included in a study of global climate change? An answer is provided in the opening lines of the Executive Summary of the EPA report:

> "Scientific theory suggests that the addition of greenhouse gases to the atmosphere will alter global climate, increasing temperatures and changing rainfall and other weather patterns . . . . Such climate change could have significant implications for mankind and the environment: it could raise sea level, alter patterns of water availability, and affect agriculture and global ecosystems" [US EPA (1989) xxv].

Thus, four types of impact are to be expected: a rise in the sea level, a change in the patterns of water availability, impacts on agriculture (including forestry), and impacts on global ecosystems. In addition, there are the impacts on air quality and human health, noted above. However, what was actually quantified in the EPA report was a somewhat narrower set of impacts. This process of winnowing is described in these additional excerpts from the Executive Summary:

> "After consulting with scientific experts, EPA developed scenarios for use in effects analysis. Regional data from atmospheric models known as General Circulation Models (GCMs) were used as a basis for climate change scenarios . . . . The GCMs generally agree concerning global and latitudinal increases in temperature, but they disagree and are less reliable concerning other areas, such as regional changes in rainfall and soil moisture . . .
>
> Because the regional estimates of climate change by the GCMs vary considerably, the scenarios provide a range of possible changes in climate for use in identifying the relative sensitivities of systems to higher temperatures and sea level rise . . ." [ibid, xxvii].

Thus, the EPA's quantitative analysis actually focused on the economic impact of the rise in sea levels on real estate, the economic impact of higher temperatures on agriculture, and the demand for electricity. Left out are the economic impacts associated with a change in the pattern of water availability for agricultural, municipal and industrial uses, impacts on economic infrastructure in general, impacts on ecosystems, and impacts on human health.

The Executive Summary notes some other limitations on the analysis. For example, it notes that the scenarios assume no change in "the frequency of events, such as, heat waves, storms, hurricanes, and droughts in various regions, which would have affected the results presented in this report" [ibid xxix]. The scenarios also assume that climate variability does not change from recent decades; this is because, when the results of the GCMs were examined, "we found that no firm conclusions can be drawn about how global warming would affect variability" [ibid xxix]. Another limitation noted is the failure to consider human adaptation to the effects of climate change through changes in population and technology.

All of this raises two set of questions: (1) What are the reasons for these limitations? Why did the EPA researchers exclude certain potential impacts, and what explains the impacts that were included? (2) Do these exclusions matter—and, do they matter enough that the researchers should have done something to avoid them? With regard to the first question, obviously, part of the answer is that there were problems with the GCMs, including divergences with regard to their predictions of regional changes in precipitation, and limits on their ability to track inter-temporal variability in climatic conditions on both a small temporal scale (say, within-year, seasonal variation) and a larger scale (say, year-to-year or decade-to-decade variation). But, we do not believe that this was the only reason. We presume that another reason was the availability of economic models suitable for examining some impacts but not others. For example, we presume that this explains why the impacts of global climate change on agriculture and electricity demand were studied, while the impacts on the demand and supply of water for irrigation or municipal and industrial uses were not.

A few years ago there was a popular song with these lines: "If you're not with the one you love, then love the one you're with." For researchers, the equivalent of this advice to the lovelorn might be something like: "If you can't measure what's important, then play up the importance of what you can measure." There are at least some grounds for concern that this is happening here. Before considering them further, however, we want to examine how the EPA researchers treated the impacts that they did quantify; because, we have reservations about some aspects of the methodologies that were employed.

The Cost of Sea Level Rise

We will start with the impact of sea level rise on real estate. As noted earlier, part of the economic impact is measured by the costs of protecting open coasts and certain sheltered areas from flooding, while the other part is measured by the value of land that is not saved from flooding. Here, we focus on the latter. The methodology is illustrated in Figure 1, which is taken directly from Yohe (1989). This shows a hypothetical property value gradient for land as a function of its proximity to the shore. For concreteness, suppose that there are seven tracts of land running from tract A, which is immediately adjacent to the shore, to tract G, which is furthest inland. The property values of these tracts decline with distance from the shore: they are highest ($100,000 per lot) for seafront land in tract A, next highest (at $90,000 per lot) in tract B, and eventually they stabilize at $50,000 per lot at lot E and other, inland, lots (F, G).[1] Now, suppose that tract A is flooded because of the rise in sea levels. There are two components to the resulting estimate of damages: the value of the lost structures that had formerly stood on tract A, and the value of the land that is now lost to human uses. Yohe's analysis of the latter runs as follows:

> "Were the sea to rise so that the first lot were lost, then the second lot would become a shoreline lot and assume the $100,000 value originally attributable to the first. The value of the third lot would climb to $90,000, and so on. The community would, in effect, lose the economic value of an interior lot located initially more than 500 feet from the shoreline. The true economic loss would be the equivalent of a $50,000 lot instead of the shoreline $100,000 lot; there would be a distributional effect, to be sure, but the net social loss would be $50,000" [ibid, 4-4].[2]

For small marginal losses of shoreline land, this is clearly a valid approach—with the caveat that it depends on the use to which the new shoreline will be put. A sandy beach, for example, could take centuries to form. With larger non-marginal changes, two additional problems could arise. First, the analysis assumes that there is no shortage of land on which the owners of the flooded tracts can relocate—in effect, there is an infinitely elastic supply of inland tracts like E, F, and G. This is a reasonable assumption on a featureless plain like, say, Kansas. It is more problematic if there are natural barriers—mountains, lakes, or rivers—which limit the space available for human occupation, as might happen along the coast of California, for example.[3] In that case, when some land is inundated, the remaining land becomes more scarce, its value increases—even for inland tracts like E, F, and G—and the damage is understated if one prices the lost land at the pre-flood value of interior tracts.

Second, a non-marginal loss of coastal land presumably involves the destruction of a significant amount of public infrastructure—roads, bridges, seawalls, etc.—which then has to be rebuilt along the new shoreline. It is not clear that the costs of replacing this infrastructure have been captured in the EPA/Nordhaus estimate of lost land values. Two separate questions are being raised here: (1) To what extent do the market values of private property incorporate the value of adjacent public infrastructure that is a complement to the private property? (2) To what extent do property values reflect the replacement cost of infrastructure capital? With regard to the first of these questions, the answer would seem to depend on the nature of the public infrastructure. Access to a road might be expected to increase the value of nearby private land; therefore, the value of the road should be captured, at least partly, in the value of the private land. However, moving costs or other impediments to free mobility might prevent the complete capitalization of the value of public infrastructure in private property values. Moreover, the road might be perceived as a bad—due to noise, say, or air pollution—and, therefore, it might reduce the value of adjacent private land. Similarly, with a sewage treatment plant. The point is, what is capitalized is the value of the public infrastructure to residents, not necessarily its cost.[4] With regard to the second question, there is some evidence that the replacement cost of public infrastructure has risen over time relative to other types of capital and relative to the prices of other goods and services, because it involves relatively labor-intensive construction activity and because it has not experienced the same rate of technical progress as the supply of other goods and services. Therefore, the gap between historic and replacement cost may be especially large.

There is a larger question here about how a community might adjust to the loss of physical capital when sea levels rise. The analysis described above implicitly assumes a smooth and efficient adjustment process that minimizes the damage: after tract A in Figure 1 is flooded, tract B becomes shoreline, and everybody dutifully moves over one tract to the right. Regrettably, this does not describe the world as we know it. For example, the failure of state and local governments in the United States to regulate floodplain development is notorious. Another example is somewhat closer to home: there have been about a half dozen wildland fires in the Berkeley-Oakland hills since 1930, culminating in last October's tragic fire. Each time, residents rebuilt after the fire in the same location, and few lasting efforts were undertaken to eliminate the future threat of a fire or to mitigate its potential impact. In one prosperous community south of San Francisco, a ban on shakes and other flammable roofing materials was imposed after a serious fire in 1981, only to be repealed three years later due to public pressure. Such bungled responses raise the costs of natural disasters. The inability to respond effectively is a cost of doing business that has to be included in any estimate of the economic impacts of global climate change.[5] We are not suggesting that the government ought to prohibit all risky activities—though there may be a case for prohibition, or other control, where externalities (wood shake roofs cause a fire to spread) are present. Rather, the point is that where many people are involved in a decision, such as reconstruction in a region following a natural disaster, the transaction costs are likely to be large, and need to be taken into account in assessments of the damages. For all of these reasons, we feel that there are grounds for questioning the EPA/Nordhaus estimates of the impact of sea level rise on real estate. We turn next to their estimate of the impact of a doubling of CO_2 on agriculture.

The Costs to Agriculture

The EPA report actually presents four estimates of these economic impacts, which are reproduced in Table 2. Two of the estimates incorporate the impacts on crop yields not only of higher temperatures but also of higher CO_2 levels, the latter involving beneficial effects associated with increased photosynthesis and improved water-use efficiency. These estimates, which Nordhaus employs for his own analysis, are either a net loss of consumer's surplus plus producer's surplus amounting, on an annual basis, to $9.7 billion (in 1982 dollars), or a net gain amounting to $10.6 billion.[6] When the effects of higher CO_2 levels are omitted and one focuses on the consequences of higher temperatures alone, the EPA estimates a net loss ranging from $5.9 billion to $33.6 billion.

The other factor that accounts for the different estimates in Table 2 is a divergence between the predictions of two GCMs that EPA used regarding regional climate changes; in each case, the higher damage estimate is associated with the temperature scenario generated by the Geophysical Fluid Dynamics Laboratory GCM, while the lower damage estimate comes from the temperature scenario of the Goddard Institute for Space Studies GCM. These models differ with regard to what they predict about the reduction in rainfall in the Southeast (which lowers crop yields, especially for non-irrigated crops) and the increase in temperature in the very northern areas such as Minnesota (which extends the frost-free growing season).

The differences between the two GCMs are actually greater thân the differences between the with-CO_2 and without-CO_2 scenarios. Obviously, we have no competence to discuss the former. With regard to the latter, we do wonder about the magnitude of the beneficial effects attributed to higher CO_2 levels. Indeed, the EPA report itself warns that they may be exaggerated:

> "The direct effects of CO_2 in the crop modeling results may be overestimated for two reasons. First, experimental results from controlled environments may show more positive effects of CO_2 than would actually occur in variable, windy, and pest-infested (weeds, insects, and diseases) field conditions. Second, since the study assumed higher CO_2 levels (660 ppm) in 2060 than will occur if current emission trends continue (555 ppm), the simulated beneficial effects of CO_2 may be greater than what will actually occur" [ibid, 100].

Suppose the increase in CO_2 does lead to increased yields. What factors might counter this beneficial effect? One possibility is that the same effect will be seen for weeds and pests (Daily and coauthors, 1991). Further, the related warming will widen the range of pest species, in particular by increasing overwintering survival (Gleick, 1991). A dramatic illustration of the potential for this effect was given just last year by the sudden invasion of California's Imperial Valley, a prime agricultural area in the southern part of the state along the Mexican border, by the apparently omnivorous silverleaf whitefly. A halt to the tiny pest's devastating march through the Valley was achieved only after some cooling in surface temperatures. And it is only the modestly cooler temperatures now prevailing in California's great Central Valley that offer protection to the $19 billion agriculture industry there. Warming would also widen the range of crop and livestock disease organisms—in particular, very debilitating ones now limited to tropical regions (Gleick, 1991; EPA 1989, p. 94).

So far, we have considered crop yield considerations that could make the damage estimate of $9.7 billion significantly too low. What about the rest of the economic analysis performed by EPA's consultants for the agricultural sector: are there any other factors that could influence the damage estimates one way or the other? Three such factors come to mind. The first concerns the specification of the substitute uses of land that enter into the calculation of damages from climate change. It is inevitable that the damage estimates are sensitive to what substitute uses are included in these calculations. Errors can be caused both by excluding substitutions that should be included and by including substitutes that should properly be excluded. As Mendelsohn, Nordhaus, and Shaw (1992) have observed, to the extent that the EPA's analysis focused on measuring the reduction in yields for specific crops, such as wheat or corn—that is, ignored the possibility that farmers might switch to other crops, or to other uses of land, that are not as greatly affected by climate change, its analysis will overestimate the damages from climate change. Conversely, however, if one includes in the analysis alternative crops or alternative uses of land that are not, in fact, part of economic agents' choice sets, the result would be to underestimate the damages. This is a problem, for example, with programming models of agricultural production in California and some of the other western states which tend to include an extremely large array of crops in the choice set—larger than is likely to apply to any individual farmer or groups of farmers. The point is that ensuring the correctness of the specification of the choice set requires effort and is something that researchers frequently tend to overlook, but if it is not done it can impart a significant bias to damage estimates.

Another factor is the time dimension of the analysis. Clearly, this presents an enormous challenge: the EPA's researchers were using models calibrated to 1980-83 conditions to predict economic impacts in agricultural markets in 2030-2060, some fifty to eighty years later. These are static models, with no change on the supply side or the demand side. The EPA report notes that some of the changes that might be anticipated on the supply side could mitigate the economic effects of global climate change. It points out that changes such as higher yielding crop varieties, chemicals, fertilizers, and mechanical power have historically enabled the agricultural sector to boost yields and it estimates that, if the same rate of yield increase experienced from 1955 to 1987 were to continue into the future, most of the adverse impacts of climate change could be offset. On the other hand, it points out that changes on the demand side—increasing food demand from higher United States and world populations—could aggravate the economic loss from climate change. These are certainly valid points, and we have nothing to add to them.

However, there is another feature of the model used for the agricultural impact analysis that we believe could affect the cost estimate, but has received relatively little attention. In effect, the model assumes malleable capital that can be shifted costlessly in response to perfectly anticipated economic changes. It is a static, spatial-equilibrium model;

as the EPA report notes, "it simulates an equilibrium response to climate change, rather than a path of future changes" [ibid, 103]. Thus, it doesn't say how long the economy takes to move from one equilibrium to another, nor what the economic costs are during the out-of-equilibrium phase. It is our understanding that the model does not include adjustment costs, nor indeed capital costs generally—just the variable costs of production. There is an implicit assumption that the unmeasured disequilibrium costs are small in magnitude relative to the measured costs of switching from one long-run equilibrium to another.

Indeed, this assumption underlies most of the EPA/Nordhaus treatment of the impacts of climate change: their analysis focuses on changes in the annual flow of goods and services, rather than on changes in the stocks of economically significant capital—physical, human or natural. We believe that this is an important omission. It is our hunch that some of the most important impacts of climate change arise because of the effect on capital stocks which, if not destroyed, are rendered prematurely obsolete. The costs of these effects depends critically on their timing relative to the normal replacement cycle of the affected capital. If the capital was going to be replaced anyway and the effects of climate change are well anticipated, an adjustment to climate change can be incorporated with minimum cost and disruption. If the capital was not due for replacement—or is difficult or costly to replace—then the costs are much greater. In this regard, it is quite possible that the costs of obsolescence prematurely imposed on human or natural capital could be significantly larger than for physical capital. Take, for example, the effects of rising temperature and related declines in soil moisture in areas currently well suited to grow grains and other crops, such as the American Midwest and Central Europe (Cline, 1991; Daily and coauthors, 1991). These impacts could require a drastic and slow adjustment given the existing investment in physical infrastructure, extension and credit institutions, etc. Moreover, it is unlikely that the natural capital stock—the soil that has evolved a set of characteristics suited to these crops—could be similarly "adjusted" in any time frame of interest to human beings. Productivity characteristic of the American grain belt may not be transferable to the thin acidic soils of the Canadian shield (Brown and Young, 1990).

We emphasize the distinction between this "capital-oriented" view of the impacts of climate change and the conventional "flow-oriented" view because we believe that the social value of a dollar of added investment cost may exceed the social cost of a dollar of reduced flow of goods and services, for at least two reasons. First, there is the potential for a "crowding out" of conventional and productive investment in order to make way for the replacement investment induced by climate change. If there are constraints on the supply of savings, this could have a long run cost in terms of reduced economic growth. Second, to the extent that climate change requires a collective response—for example, a collective decision to relocate in upland areas—there is some likelihood that imperfect coordination will inflate the costs of adjustment, as in examples of floodplain zoning and rebuilding after the Bay Area fires cited above.

This distinction becomes even more significant when one considers the possibility, discussed below, that the change in climate will not stop at a doubling of CO_2 but could involve even larger increases. The greater the disruption of physical and natural systems, the greater the economic impact in terms of premature obsolescence of valuable physical, human or natural capital, and the greater the potential downward bias from employing a flow-oriented approach to measuring damages.

Unmeasured Impacts

We have spent some time discussing how the EPA researchers measured some of the costs of climate change that they did quantify. What about the costs that were not quantified, and how do these relate to the capital-oriented approach to damage measurement that we have advocated? Of the various impacts that are listed but not quantified in the EPA report, two stand out as especially relevant here—the impacts on water availability and urban infrastructure. We want to emphasize the importance of the former from the perspective of the Western United States. To someone living on the East Coast, changes in the timing or regional incidence of precipitation may seem of secondary importance. In the arid West, however, they are critical. In California, for example, on a statewide and annual basis there is more than adequate rainfall at least for the current population. However, two-thirds of the precipitation falls north of Sacramento, while two-thirds or more of the population have always lived south of Sacramento; similarly with the timing of precipitation, which occurs almost entirely in the winter, while peak demands for agricultural, in-stream, and even some urban uses occur in the late spring and summer. Preliminary studies suggest that these imbalances will be exacerbated by climate change, which is expected to result in an increase in winter rainfall and a reduction in the snowpack, leading to less runoff in the late spring when irrigation needs are highest. The solution to the imbalances has always been to store water in aquifers or in above-ground reservoirs for carry-over to the summer months and for transport to the areas of use. But this traditional approach to water resource management is now under severe challenge from several sources, including fiscal and legal. Ever since the Carter administration, there has been a marked decline in the willingness or ability of the federal government to subsidize the construction of new water projects while, at the same time, their costs have escalated dramatically. Legally, there has been a substantial shift, starting with the Mono Lake decision in 1983 upholding the use of the Public Trust doctrine to disrupt otherwise established water rights to divert water for off-stream uses. This was reaffirmed and expanded in the 1986 decision in *US v. SWRCB* which set aside the State Water Resource Control Board's 1978 decision on water diversions from San Francisco Bay/Delta on the grounds that it gave insufficient attention to in-stream needs and was not based on a *balancing* of *all* needs within the basin, in-stream as well as off-stream. Accordingly, while we do not regard the problems posed by climate change for water supply in the West as insuperable, we do anticipate that the costs of overcoming them could be very substantial.

Other impacts that were left unquantified in the EPA study, such as the destruction of natural ecosystems, are obviously likely to have a substantial cost. Wetlands and coral reefs are particularly at risk. Coastal wetlands, blocked by dikes, roads, and other impediments, may be unable to migrate inland to escape rising sea levels, and coral reefs are exceptionally sensitive to changes in water temperature. Losses to either or both of these ecosystems would adversely affect productivity of ocean fisheries, which depend on them for nursery grounds and food supplies (Daily and coauthors, 1991). Terrestrial ecosystems would also be affected.

From just a doubling of CO_2, the southern boundary of forest ranges could move northward by 700 km. Since the known historic rate of migration is just 50 km per century, very substantial loss of forest is indicated, with an associated increase in species extinctions (EPA, cited by Cline, 1991). Ecologists are in general agreement that these and other warming-related changes would accelerate an already worrisome loss of the biodiversity that plays a crucial roll in sustaining agricultural productivity (through continuing infusion of wild strains), the pharmaceutical industry, and, most importantly, a wide range of life support systems ranging from cycling of nutrients to disposal of wastes (Harte, 1991; Ehrlich and Ehrlich, 1981).

Perhaps less grand, but more obvious, are potential impacts on human health and well-being. Noteworthy here are an increase in the frequency and intensity of heat waves experienced in temperate regions such as most of the United States, and the spread of diseases now confined to the tropics (Harte, 1991; Daily and coauthors, 1991). Very small increases in yearly mean temperatures could permit the extension of tropical parasitic diseases into Europe and North America (Haines, 1990). Moreover, the EPA study indicates that there could be adverse impacts on human health due to hotter temperatures, greater variability in temperature, and increased air pollution resulting from climate change.[7]

There is a further point about the unquantified impacts on air quality and human health. As Ayres and Walter have observed, the human actions that give rise to global warming—most importantly, the combustion of fossil fuels—also have significant negative impacts on air quality and human health. While those impacts are not part of the costs of climate change, the benefits from reducing those impacts certainly are joint products of actions taken to avert or mitigate climate change. Looked at this way, the damages to air quality and human health resulting from the combustion of fossil fuels are relevant information in any assessment of policies for averting or mitigating global climate change. Ayres and Walter have suggested that, on a per ton of CO_2-equivalent basis, they could be an order of magnitude larger than the costs quantified in the EPA/Nordhaus analysis.[8]

We could continue with these examples of impacts from global warming associated with a doubling of CO_2. But just from what has already been presented, it seems plausible (at least) that damages may be more widespread, and more severe, than indicated in the EPA estimates. More importantly, the really crucial issue, as Cline (1991) has emphasized, is whether it is appropriate to limit our focus to the impacts associated with a doubling of CO_2, as opposed to some larger increase.

Beyond a Doubling

Is there reason for believing that a doubling would represent an equilibrium? Not that we can discover. Perhaps the most authoritative recent report, that of the Intergovernmental Panel on Climate Change (IPCC, 1990), projects a doubling by the year 2025, with an associated warming of 2.5°C, assuming "business as usual." In most accounts, the story stops there. But, the IPCC goes on to project a warming commitment of 5.7°C by the year 2100. The scientific literature on what happens after that is relatively sparse, though not nonexistent. Cline projects carbon emissions out to the year 2275, on the basis of assumptions of low growth rates (claimed, though not presented) for population and economic activity, and known availability of fossil fuel resources at reasonable recovery costs. The projected carbon emissions imply an increase in atmospheric concentration of CO_2 to almost eight times pre-industrial levels. These emissions are augmented on the basis of IPCC estimates of the relationship between carbon and other greenhouse gas emissions. The result (Cline, p. 914):

> "Over a horizon of 250-300 years the stakes of global warming are closer to a central estimate of 10°C rather than the 2.5°C associated with the benchmark doubling of CO_2 which has so far dominated both scientific and policy discussions."

One may, in fact, wonder if even this is a sufficiently distant horizon; has an equilibrium been reached, or is the process explosive? Cline suggests, citing a study by Sundquist (1990), that on time scales of 250-300 years mixing into the deep ocean becomes important, opening a much greater sink. Of course, this is not certain; the process may be explosive. Or the indicated concentrations of CO_2 and other greenhouse gases may not be reached; the ocean sink may open sooner, enhancement of cloud albedo by sulfur dioxide air fpollution may interfere (Booth, 1990), and so on. In our judgment, a scenario for a much greater level of warming (than that associated with a doubling of CO_2) has been constructed that has at least some credibility, though on a time scale beyond that with which economists (and perhaps climate modelers) are usually comfortable.

The usual objection would be that projections beyond a few years, and certainly beyond a few decades, are unneeded and unwarranted, given discounting and given the uncertainties involved (see for example Beckerman [1991], who also argues that the nearterm effects are not likely to be significant). We do not share this view. The impacts associated with a 10°C warming are likely to be very much greater even than those discussed earlier in this section. If they are, discounting will not make them go away. Alternatively, some might argue that discounting catastrophic impacts on future generations is simply immoral. Either way, it seems to us that discounting cannot be relied on to free us from the obligation to estimate, as best we can, impacts beyond the usual time horizons of economic models. With respect to uncertainties, the implication for valuation is not that we should throw out damage estimates to which they are attached. Instead, as we shall suggest in the next section, the estimates may, more appropriately, be augmented by option values and risk premia.

We stated just above that the impacts associated with a 10°C warming are likely to be very much greater than those associated with a 2.5°C warming. What, specifically, might happen? Here we are on very thin ice, since most of the literature focuses on impacts of the lesser warming. Cline (1991) sketches some possibilities. Looking first at agriculture, CO_2 fertilization effects are less than linear and contribute little beyond the first doubling (USDA, 1989). Moreover, yields collapse at temperatures in the range of 35°C (fine grains) to 45°C (coarse grains), temperatures which would be routinely reached in the American grain belt. (Recall that even a seemingly modest increase in global mean temperature implies an increase in the frequency and severity of local or regional heat waves.) Thus—shifting the focus from agriculture—Cline calculates that the number of major U.S. cities experiencing average daily maximum temperatures in July of 100°F or more would rise from 2 to 44. We have already noted that the more modest warming associated with a doubling of CO_2 could have a serious impact on human health. Presumably, the impact would be multiplied by a 10°C warming with its frequent and prolonged episodes of extreme high temperatures.

The increase in sea level associated with just a doubling of CO_2 is generally estimated in the range of 30-60 cm (Nordhaus, 1991; Daily and coauthors, 1991). EPA's real estate damage estimates (their only substantial damages; see Table 1) are based on a 50 cm rise. The IPCC projects a rise of from 31 to 110 cm, with a central estimate of 66 cm, by the year 2100, but this assumes that the Antarctic is a sink for water, rather than a source (melting ice around the edges is more than compensated by increased snowfall in the interior). Cline suggests that at the temperatures expected to prevail, the Antarctic, with 90% of the world's ice, will instead become a major source. By the year 2100 it could contribute 220 cm to a total sea level rise of 367 cm (Hoffman and coauthors, 1986). The Hoffman and coauthors estimates are for the high end of a range, and their range lies above the IPCC's own, but the question is not so much who is right about the medium term, but what happens in the longer term. Climate models suggest that relatively greater warming takes place at the higher latitudes; for an average warming of 10°C, regions around the poles could be expected to experience a warming of 15°-20°C. At these temperatures, it is at least possible that enough ice would melt to establish the Antarctic as a net source, and probably a major one, as in the Hoffman and coauthors projections. Cline concludes that an increase in global mean temperature of 10°C would result in a sea level rise of at least 400 cm, or 4 meters. A rise of 1 meter would eliminate 3% of the earth's land area, and a larger percentage of its cropland (Rosenberg and coauthors, 1988), including over 30% of the most productive cropland (Wilson, 1989). To our knowledge, there are no similar estimates of the impact of a

4 meter rise, but it seems safe to say that it would be catastrophic. It is worth noting that this is a compelling example of a nonlinearity in the underlying physical process that has implications for economic analysis, as we shall spell out in the next section.

There is one other aspect of the predicted impacts, whether associated with a doubling of CO_2 or an 8-fold increase, or something in between, that deserves mention before the discussion of economic implications. The impacts are essentially irreversible, on a time scale of interest to human beings. Perhaps this is too strong. Concentrations of CO_2 and other greenhouse gases have a residence time in the atmosphere that is measured in decades, even centuries. Making the extreme and unrealistic assumption that emissions are totally eliminated, concentrations would approach pre-industrial levels only after several decades at the earliest. And even if climate change were reversible in the short term, important impacts of the elevated concentrations, such as accelerated loss of species or inundation of coastal improvements (roads, rails, buildings, power plants, etc.) would be irreversible.

4. Theoretical Implications for Valuation and Policy

There are three considerations that seem relevant to the valuation of climate change risks that follow from our discussion to this point. One we have just noted is that certain kinds of decisions or actions are, for all practical purposes, irreversible. Another is that some of the potential impacts are catastrophic. The two may be related—the prospect that a loss or cost will be endured in perpetuity may tip an otherwise modest impact into catastrophe. What sort of actions are irreversible? We have just seen that emissions of CO_2 (and CFCs) qualify, by virtue of their very long residence times in the atmosphere. Burning a ton of coal today contributes to an irreversible warming commitment for the future. Similarly, cutting and burning an acre of rainforest (without replanting) contributes to the warming commitment. Investment in certain kinds of fixed facilities also contributes, in a somewhat different way. Siting a road or a power plant along a coast subject to flooding in the event of sea level rise is "storing up" future damages, with some nonzero probability.

A third important characteristic of the value of damages that would follow from actions that lead to warming commitments, or even the siting of potentially affected facilities, is that it is uncertain. We may know that a doubling of CO_2 implies a warming commitment of 2.5°C and even that this in turn will result in certain kinds of damage, as for example, to agricultural productivity in a region. But how much? And even if we are certain about the physical impacts - even if we know, for example, that the production of wheat will be reduced by 25%, what is this worth? An answer to this question clearly involves knowledge of demand, or preferences, for future goods. Information relevant to an answer presumably improves as the "future" gets closer.

Elsewhere, we have shown that when an action or decision has the characteristics that it is irreversible, that future costs and benefits are uncertain, and that information about the costs and benefits improves with the passage of time, there is a value ("option value") to refraining from the action during the current period. Alternatively, there is a cost, in the shape of a reduction in the ability of the decision maker to realize the value of information, attached to going ahead with the action in the current period (Fisher and Hanemann, 1986a, 1986b, 1987). In one of these studies (1986a), we tried to calculate the option value of preserving a site that was later found to contain a potentially useful plant species, a wild relative of corn that is also a perennial. The calculation was done on the basis of some empirical information (about demand and supply functions for corn) coupled with several assumptions (about probabilities of successful hybridization, and of realized values of alternative uses of the site), and so does not qualify as a true empirical application. Moreover, even if it did, it is about the benefits of preserving just one species, in just one site. With these caveats, we think it is worth noting that the calculated option value turned out to be substantial in relation to the conventionally estimated expected benefits in the example: around one third of the expected benefits of preserving the site, and from one tenth to two thirds of the hypothetical expected benefits of developing, depending on what was assumed about these benefits. Clearly, we are a long way from knowing how to attach costs representing the foregone value of information to all of the actions leading to global warming commitments. But we should at least be aware that we may be leaving out a substantial part of the cost of such actions.

Now, let us consider the implications of catastrophic impacts. Here, we would like to propose a very simple framework that is best explained with the aid of a couple of diagrams. Figure 2 shows total damages from global warming, on the vertical axis, plotted against a measure of warming on the horizontal axis. (The horizontal axis could alternatively represent emissions, or concentrations, of greenhouse gases). Of course, all of this is hypothetical, as we have not done any measuring or estimating. Nevertheless, we probably know enough about the phenomenon of environmental disruption generally to specify some properties of the functional relationship in this case. Thus the curve slopes up and to the right, indicating that damages increase with warming. Further, the curve is convex from the origin to point A, and again beyond A. Ignoring for the moment what happens at A, the convex functional relationship between warming and damages indicates that damages not only increase with warming, but do so at an increasing rate. Convexity of the damage function is a fairly standard assumption in environmental economics, presumably based on some evidence, as well as intuition. Yet the curve in Figure 2 taken as a whole, that is, including the sharp increase or jump at A, is nonconvex. What is different here is clearly the existence of a jump in the damage function—this is the way we represent a catastrophic impact. There may well be more than one such jump in reality, though one is sufficient to illustrate the argument here.

Figure 3 translates total damages to marginal. Marginal damages increase to A, fall at A, and then begin to increase again. The significance of the resulting break in the marginal damage function is clear when it is displayed along with the assumed marginal benefit function on the figure. The benefit function slopes down and to the right, indicating that the benefit of increasing the level of activities that lead to warming is diminishing. Another way of understanding the behavior of this curve is to read it from right to left, in which case, it represents the (rising) cost of controlling emissions, reducing concentrations, or mitigating impacts. Notice that the curves intersect three times around A, at the points labeled E and F, and again at point G. More generally, whenever the damage function becomes highly nonlinear or discontinuous, as at A, the benefit function may intersect it more than once, as here. The intersection at F has no welfare significance, since net benefit can be increased by moving to either E or G. Strictly, a choice between these points would require a benefit/cost analysis to determine whether the losses represented by area I in the figure exceed the gains represented by area II. If area I is larger, and perhaps also in the likely case that sufficiently precise determination is not possible, the implication for policy is that emissions of greenhouse gases should be controlled to some point before A, to avoid a catastrophic warming commitment with a margin of safety. This point is strengthened by recognition of the uncertainty surrounding estimates of damages from warming, in particular of the uncertainty about where the damage function becomes highly nonlinear or discontinuous, and the prospect that better information will make possible better estimates with the passage of time. An option value then attaches to refraining from actions that increase the warming commitment to a point near A.

In this context, we want to express our concern over the disconnect that is apparent in much recent discussion between the valuation exercise and the consideration of specific policies for mitigating climate change. The implicit assumption is that the damage estimation and the policy analysis can be conducted on two separate tracks: i.e., damages can be assessed without knowing what control policies or, indeed, what levels of control will be selected after the damage figures have been developed. If economic analysis were a free good and if one could readily obtain a perfect and comprehensive analysis of every impact, this would be a harmless approach. But this isn't so, and it becomes necessary to focus the damage assessment and quantification on the control actions and control levels that are relevant for the policy debate. The discussion tends to focus implicitly on a particular policy tool—viz., the imposition of a uniform carbon tax on CO_2-emitting activities. For the purpose of that policy, all one needs to know is the marginal damage of an additional unit of CO_2-equivalent. A carbon tax may well be desirable, but it is not necessarily the only policy action that needs to be taken to deal with climate change, or even the best one. The literature on the relative merits of standards and taxes, or marketable permits and taxes, is relevant here. In particular, where damage functions exhibit the kinds of sharp nonlinearities and discontinuities sketched above, we know, following the work of Weitzman (1974) and others, that (other things equal) quantity controls will tend to be preferable to charges. Thus a system of standards and marketable permits will be superior to a tax. Of course much more work needs to be done to determine the optimal choice or mix of policy instruments to slow global warming. Our point is simply that there is a link between valuation and decision, and that these exercises ought not be conducted entirely on separate tracks.

5. Conclusions: Directions for Further Research

We do not put ourselves forward as natural scientists, qualified to pronounce on the questions of the physical impacts of global climate change. We have presented some observations and conjectures, taken from the scientific literature, that in our judgment credibly suggest the possibility of much larger impacts than those with which most economists are likely to be familiar. These impacts, in turn, can be expected to result in "badly behaved" damage functions: nonconvexities in total damages, severe nonlinearities or discontinuities in marginal damages. We have suggested several reasons why the marginal damages may not be constant, independent of the level of climate change. First, the physical and biological damages—for example, the damages to wetlands or aquatic ecosystems—may well be a nonlinear function of carbon emissions or the rise in sea levels. Second, the economic costs of adjustment are likely to be a nonlinear function of the magnitude of the adjustment, although here the nonlinearity could perhaps go in either direction. On the one hand, it might be argued that the greater the physical change the greater the likelihood that people will recognize it and factor it into their future planning. On the other hand, the greater the change the greater the need for collective action to deal with it, and the greater the difficulties and costs of coordinating this response. Moreover, the greater the change the greater the potential crowding out effects associated with the requisite infrastructure investment.

We conclude with two observations. First, since knowledge of the damage functions—in particular of the regions where they are badly behaved—is crucial for policy regarding emissions of greenhouse gases, we would urge support for research that focuses on what happens beyond the doubling usually assumed for concentrations of CO_2. Second, we would urge that more of the economic research be focused on the potentially very large costs of adjustment affecting stocks of physical, human, and natural capital. Most economic analysis—and virtually all of the economic research on that has been performed so far on the subject of climate change—is comparative statics in nature. It deals with economic equilibrium, and the shift in equilibrium conditions that can be expected as a result of climate change. By contrast, the issues lying at the heart of climate change concern disequilibrium—how long will it take for people to perceive changes in climate and respond to them? Will they refuse to acknowledge such changes when they occur, or will they quickly anticipate them? Will they adapt readily or with difficulty? Are there steps that can be taken to foster the recognition of change when it has occurred and accelerate adaption to it—for example, by encouraging greater flexibility and reducing costs of adjustment? What is the scope for induced technical change that might lower the costs of both abating emissions and adjusting capital stocks? Answering such questions should receive a high priority in future research.

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Notes

*We are grateful to Peter Gleick and John Harte for conversations that have helped us to better understand climate change and climate modeling.

1. This property value gradient is something that one could quantify using information from tax assessors' records, which is the method that Yohe employed.

2. The application of this methodology on a national scale to produce an overall estimate of the value of 4,000 square miles in the U.S. lost through flooding caused by an 0.5 meter rise in sea levels is presented not in the EPA report but in Nordhaus' article. According to Ayres and Walter (1991), Nordhaus valued the flooded land at $2,023/acre ($5,000/ha). However, there appears to be some confusion here: if one divides the $1.55 billion in Table 1 by 4,000 square miles and assumes a capitalization factor of 10%, which Nordhaus appears to use for the other real estate calculations in Table 1, the result is an imputed land value of approximately $6000/acre. The figure of 4,000 square miles is from Nordhaus; the EPA report gives a range of 2,180 - 6,147 square miles for a sea level rise of 50 centimeters [ibid, 140].

3. Or other parts of the world. For example, Ayres and Walter point out that arable cropland is worth about $30,000/ha in the Netherlands. Since the U.S. is relatively abundant in land compared to many other countries, this makes it difficult to perform a simple extrapolation of damage estimates for global climate change from the U.S. to the rest of the world.

4. There can be a gap between marginal value and marginal cost because public infrastructure involves lumpy investment.

Tables

Table 1. Estimated Impacts of Doubling of CO_2, U.S.

Sectors	Billions (1991 $)
Severely impacted sectors	
Farms	
Impact of greenhouse warming of CO_2 fertilization	-10.6 to +9.7
Forestry, fisheries, other	Small + or -
Moderately impacted sectors	
Construction	+
Water transportation	?
Energy and utilities	
Energy (electric, gas, oil)	
Electricity demand	-1.65
Non-electric space heating	1.16
Water and sanitary	-?
Real estate	
Land-rent component	
Estimate of damage from sea level rise	
Loss of land	-1.55
Protection of sheltered areas	-0.90
Protection of open coasts	-2.84
Hotels, lodging, recreation	
Total	
Central estimate	
Billions, 1981 level of national income	-6.23
Percentage of national income	-0.26

Note: A positive number indicates a gain; a negative number indicates a loss.

Source: Nordhaus (1991, Table 6)

Table 2. Aggregate Economic Impacts on Agriculture ($ billion/yr in 1982 dollars)

	No CO_2 effect	With CO_2 effect
Goddard Institute GCM	-5.9	+10.6
Geophysical Fluid Dynamics Lab GCM	-33.6	-.97

Note: General Circulation Model (GCM)

Source: EPA (1989) Table 6-4, p.104

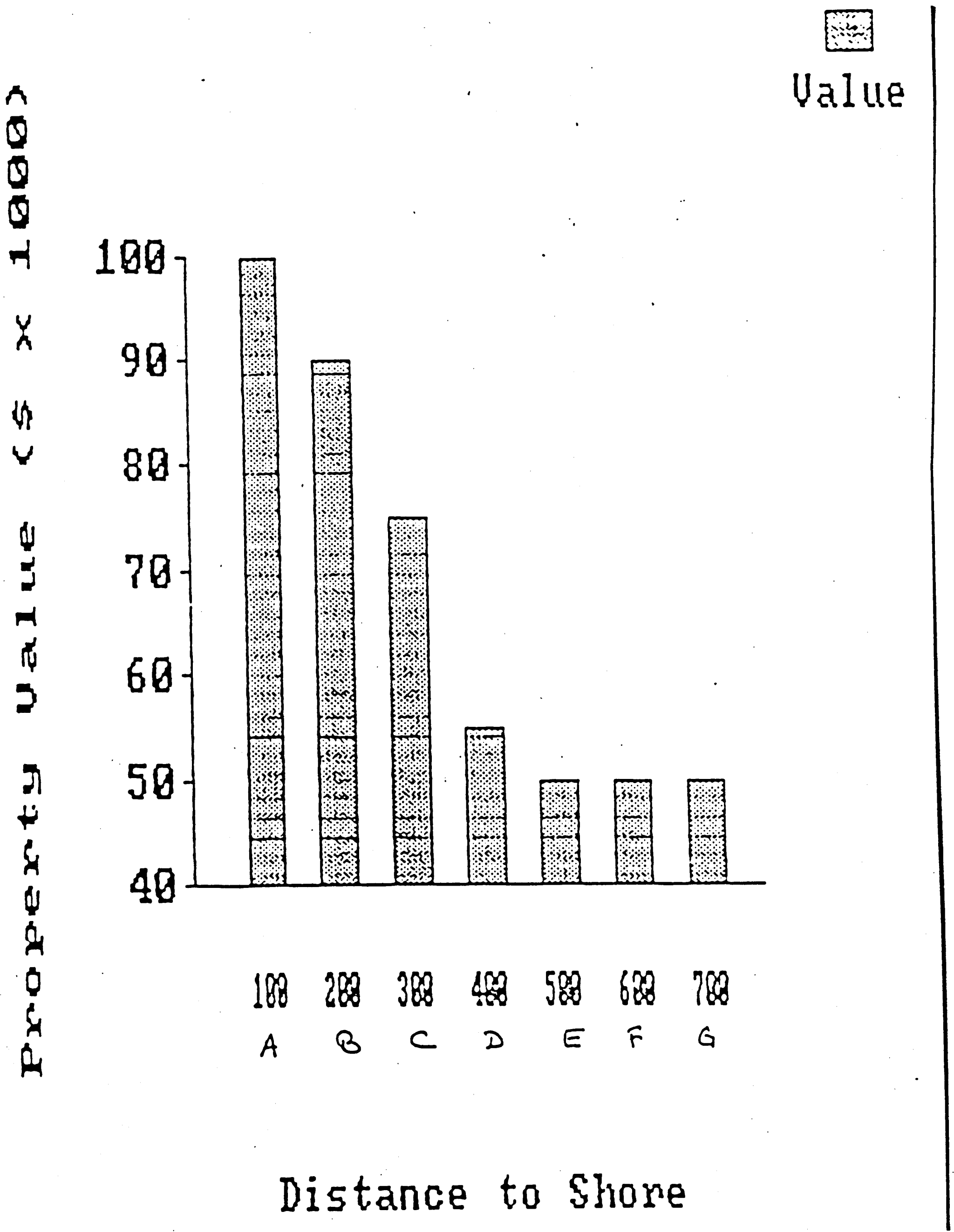

FIGURE 1: THE PROPERTY VALUE GRADIENT

FOR LAND ADJACENT TO THE SHORELINE

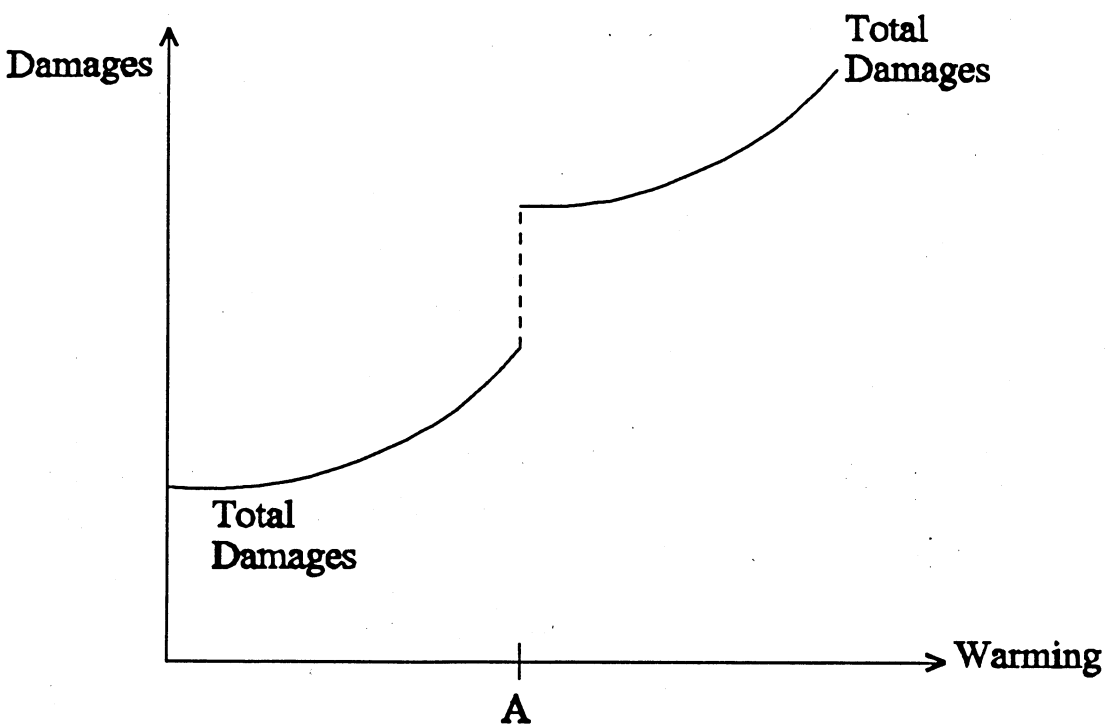

FIGURE 2: THE BEHAVIOR OF DAMAGES FROM GLOBAL WARMING.

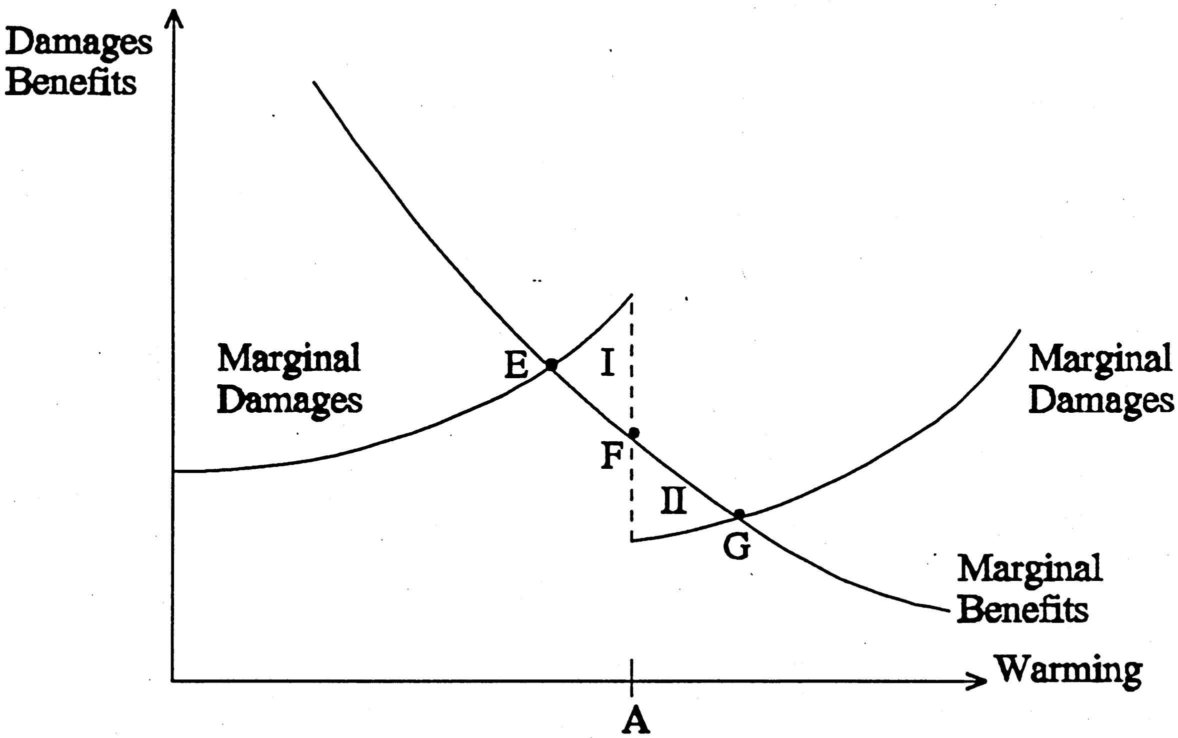

FIGURE 3: THE BEHAVIOR OF MARGINAL DAMAGES AND BENEFITS FROM GLOBAL WARMING.