Toward Economic Evaluation of Climate Change Impacts: A Review and Evaluation of Studies of the Impact of Climate Change

by

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MIT-CEEPR 93-009WP June 1993

TOWARD ECONOMIC EVALUATION OF CLIMATE CHANGE IMPACTS: A REVIEW AND EVALUATION OF STUDIES OF THE IMPACT OF CLIMATE CHANGE

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June 29, 1993

This research was supported by NOAA Grant No. N26GP0460-01 and by the MIT Joint Program on the Science and Policy of Global Change, a shared activity of the Center for Energy and Environmental Policy Research and the Center for Global Change Science.

ABSTRACT

Efforts to assess climate change have generally been unsuccessful in describing the economic damages (or benefits) associated with climate change or the functional relationship of damage (or benefits) to climate. Existing integrated economic studies have developed an aggregate damage estimate for the United States associated with equilibrium doubled trace gas climate that is unlikely to occur for 100 years or more. These estimates are used to extrapolate damages to other regions and over time. There is little or no basis for such extrapolation. It is possible to introduce climate explicitly into standard economic models but such models have generally not been estimated. Potentially affected sectors include 1) forestry and ecosystems 2) agriculture 3) coast 4) fisheries 5) water resources and 6) communities and households. An impact classification system is developed that considers short and long run flexibility to adapt to climate change, the existing knowledge or capacity to adapt, and the degree to which climate matters after adaptation (i.e the degree to which damages can be avoided).

1. INTRODUCTION

Advance in human societies has been to a large extent a history of adaptation to climate that has allowed human populations to expand their geographic range and/or shield themselves from climates that include daily, seasonal, and inter-annual variation. Shelter, lighting, clothing, space conditioning, agriculture, crop and food storage, and water systems are all responses to climate to some degree. To review all that is known about climatic interaction with human systems thus is well beyond this review. The immediate focus here is on societal effects of climate change.

Further, we choose to limit our consideration to effects of climate change on the economy, and more broadly on systems that humans value. There is an element of redundancy in this statement; if the effect is to change systems that humans value then it is an economic effect. The danger of not including the redundancy is that treating the economic effect as the effect on the economy is sometimes read to exclude so-called non-market effects of climate change. Recognizing that the methods for valuing non-market effects are controversial and imprecise is separate from the issue of whether such changes occur.

As broad as the inclusion of non-market effects can be, the review is narrow in its focus on systems that human's value. What matters here is whether the change affects the sense of well-being of humans. The stronger views of environmental preservation ask about the rights of human population to make decisions that endanger other species. Here, again, much of the difference among views is semantics rather than substance. A human-valued perspective asks the question; what is the value of preservation whereas a preservation-as-rights perspective asks what actions must society take to ensure the right. The latter perspective may face a decision of whether to compromise the right if the required actions are very costly. The particular quandary of global change from a preservation-as-rights based perspective is that the recognition of the widespread links between any human system and the environment means that a climate change solution may reduce one threat to natural systems while increasing the threat from other sources (coal versus nuclear, petroleum versus biomass). Different risks will also affect natural systems differently. Thus, the choice of which risks to accept implies valuing some systems over others.

The organization of the paper is as follows: Section 2.0 reviews broad efforts to assess potential climate change including ongoing efforts. Section 3.0 reviews the few existing attempts to model climate change as an integrated cost benefit problem. The particular focus of Section 3.0 is on the representation of the damage function in integrated economic analyses. Section 4.0 describes standard economic production and consumption models, identifying how, in general, climate considerations could be introduced. Section 5.0 reviews current approaches and estimates of impacts by affected sector, specifically focusing on how biological and physical impacts have been translated into economic efforts. Finally, Section 6.0 develops an impact classification system based on underlying basic considerations of adaptation potential.

2. BROAD ASSESSMENT EFFORTS

2.1 Past Studies

The principal guide for climate impact analysis remains Kates, Ausubel, and Berberian, *Climate Impact Assessment (1985).* The volume covers biophysical impacts of climate in agriculture, fisheries, pastoralism, water resources, and energy resources. Social and economic considerations include health, nutrition, and human development; microeconomic analysis; social analysis; human perception of change; analysis of extreme events; and adjustment. A final section covers integrated assessment, including global economic and systems models, biosphere models, scenario analysis, historical climate impact assessment, and a review of several efforts to broadly assess climate. The aim of the volume is to provide a guide to conducting assessments rather than to conduct an assessment. In a similar vein, Schelling (1983) provides a framework for thinking about climate change effects and for reviewing possible damages.

Other major efforts to broadly assess potential future changes in the climate/atmosphere and the effects of such changes include the Department of Transportation Climatic Impact Assessment Program (CIAP), (Baur, 1974; Caldwell, 1974; Daly, 1974; Hidalgo, 1974a, b; Oliver 1974; and DOT, 1975,); National Academy of Sciences (NAS) studies of CFCs and Ozone Depletion (NAS, 1976); the National Defense University Study (NDU, 1978, 1980); the NAS in *Changing Climate* (NAS, 1983) and in *Policy Implications of Greenhouse Warming* (NAS, 1992), the US Department of Energy (USDOE) (McCracken and Luther, 1985a; McCracken and Luther 1985b; Trabalka, 1985; Strain and Cure), the US Environmental Protection Agency (EPA) (Smith, et.al. 1990), and the Intergovernmental Panel on Climate Change (IPCC)(Tegart, et. al, 1990, 1992). None of these successfully arrives at an aggregate value of prospective climate changes nor do they develop approaches for linking a change in climate forcing to avoided damage. Most effects are described only in terms of the direction of impact and frequently only by a few case studies. How one might use such case studies to extrapolate to other cases is left unspecified.

CIAP considered the possible effects on the stratosphere from fleets of supersonic transport (SSTs). The attempted effort to consider economic and social effects was generally regarded as unsuccessful. A principal problem in the economic and social component of the study was that it began later than the physical science components and key results from other components of the study were unavailable until it was nearly completed. The NDU study was based on expert judgment and concluded that the magnitude of climate change in the time horizon considered (to the year 2000) was unlikely to be significant. With that judgment, economic analysis was unnecessary. For the agricultural sector, crop yield changes developed through expert judgment were analyzed in an economic model of agricultural markets. NAS (1983) and USDOE (1985) were largely physical scientific assessments of the state of knowledge and were particularly limited in regard to the potential effects. NAS (1992) reviewed policy options without focusing much on either the effects of climate change or on responses that would aid in adaptation to climate change.

US EPA and IPCC provide the most comprehensive assessment of impacts. Neither attempted to arrive at an aggregate estimate of the value of potential changes. As with the NDU study, both the US EPA and IPCC proceed furthest in assessing agricultural impacts, providing assessments of effects on US prices and welfare (US EPA) and international price sensitivity to yield changes (IPCC). Damages associated with potential sea level rise were evaluated in terms of costs of building sea walls or of taking other actions to avoid damage. Other impacts were evaluated in physical terms or narrower case studies were reviewed.

Even agriculture and sea level rise studies have significant limitations. Most notably, the estimated impacts are those associated with equilibrium climate associated with a doubling of trace gases. This is probably more of a limitation for agriculture than for sea level rise for two reasons:

1) the transitory climates for regions may not show a smooth or even monotonic change in relevant climate variables such as temperature or precipitation.

2) even with smoothly changing climate/atmosphere variables, agricultural yield changes may not be monotonic--i.e. they may increase over some ranges of the climate variables and decrease over others.

In comparison, there is no evidence that sea level increase could be beneficial, hence, the error in interpolating from $0 damages at present (beyond the damages normally expected from storms) to the future estimated level under the new climate is clearly bounded from below. The major limitation in analysis based on equilibrium changes in sea level is that the timing of damages (or expenditures to limit damages) is unspecified. Costs are typically reported as total capital costs of constructing sea walls, beach nourishment, or lost land and structures for a given sea level rise. To properly sum such damages over time they should be discounted to a common year and to do so requires knowledge of the date of the damage or expenditure. Because damage from sea level rise typically occurs with storm surges, and sea walls are lumpy investments, efforts to limit damage must occur far in advance of any expected sea level rise. Whether to protect, and what type of protection to use depends on the expected future path of sea-level rise (Yohe, 1992b).

A further limitation in both the IPCC and US EPA impact studies is that the level of change considered, as measured by temperature or sea level rise, is now expected to occur far in the future given the new results of transient climate models. For example, many impact studies based on doubled trace gas climates might place these impacts between 2030 to 2070, at roughly the same time when trace gases are expected to double. Equilibrium General Circulation Model (GCM) runs at 2x CO_2 give 4° to 5° C increase in global mean temperature, but the IPCC Scientific Assessment (which assumed equilibrium temperatures in this range) estimated that mean global temperature would increase on the order of only 3° C above present by 2090. Similarly, the most recent estimates of sea level rise over the next century range from 35 to 55 cm, whereas most estimates of damages from sea level rise are based on 1 meter increases (Wigley and Raper, 1992).

2.3 Continuing Efforts

The IPCC has continued with an update (IPCC, 1992) and a work plan for a third report in 1995. The US EPA is nearing completion of an international study of climate change impacts which essentially takes the methodologies used in the United States and applies it to other countries. With the exception of agriculture, the US EPA effort involves case studies of countries or areas within countries rather than a comprehensive assessment. The emphasis in selecting case study areas has been include areas where analysis has to date been more limited.

2.4 Study Coverage

The broad studies that have been conducted to date tend to consider the negative consequences of climate change and generally do not consider changes that might be beneficial. An exception is that carbon dioxide fertilization of crops is now generally included. Some efforts to consider reductions in fuel for heating are made. A recent US study suggests that expenditures on heating could fall more than increased expenditures on air conditioning (Rosenthal, personal communication). Other examples of possible, but often overlooked, benefits include reduction in the cost of snow clearing, reduced road maintenance and accidental loss due to less severe winters, or the potential to extend summer, spring, and fall recreation activities further into the winter. However, there are also recognized biases that may lead to underestimates of damages. Examples include increased pests in agriculture and the spread of infectious diseases, e.g. malaria or onchocerciasis, borne by insects whose range could expand if temperature increased.

Adaptation has proved to be a particularly difficult issue to address, and few studies appear to address it effectively. Important considerations include (1) whether adaptation occurs autonomously or requires specific recognition of climate change and action for adaptation, (2) whether adjustment requires substantial time, and (3) whether the knowledge or capacity to adapt currently exists. In studies of agricultural response, adaptations are either not considered, or where considered, the goal of adaptation is to find measures that offset the initial yield loss. If an area is projected to experience a yield gain, then adaptation is generally ignored. Similarly, if a set of adaptations is assumed to compensate for yield loss then further actions are not considered (e.g., Rosenzweig et al., 1993 and Rosenzweig, personal communication). Some approaches base evaluations on cross section evidence, which can be interpreted as implicitly incorporating full adjustment. Examples include for agriculture Hansen (1990) and Mendelsohn and Shaw (1992) and for health effects via increased mortality EPA (in press). The error in such efforts is that the adjustment itself may be costly. For example, health and mortality-related effects measured cross-sectionally may show relatively small climate sensitivity but if areas have adapted (more air conditioning or the addition of specific public health services) then the added cost of such services (or benefit if the need for a service is reduced) should be considered as an effect of climate change. The reliability of such statistical cross-section estimation depends critically on controlling for other factors that may be correlated with climate and also affect, in the above cases, agriculture or mortality. Omitted variables can lead to either under- or over-estimation of climate effects. Other studies do not include any adaptation and therefore may overestimate the damage or underestimate benefits of climate change. Efforts that do explicitly attempt to account for adaptation, however, sometimes take the view that as long as technical solutions exist to compensate (more or less) for physical losses then damage has been avoided (i.e., irrigation in agriculture, see Easterling et al., 1992, Rosenzweig, et al., 1993). These adjustments may, however, entail significant costs.

2.2 Studies of Areas Outside the United States

Many developed countries have now prepared assessments of potential impacts including, for example, the U.K. (Parry et al., 1991), Australia (Henderson-Sellers and Blong, 1989), The Netherlands (GWAO, 1990), US (Smith and Tirpak, eds. 1989) and Germany (Enquette Commission, 1992). Studies of developing countries are forthcoming including discussions of Costa Rica, Nicaragua, Zimbabwe, South Africa, and Vietnam (Secrett et al., 1993) and for various coastlines and river basins in developing countries (EPA, 1993). Regional effects have been discussed for Africa (Ominde and Juma, 1991), South East-Asia (Parry et al., 1992) and the Southern Hemisphere (Climate Change, 1991). The International Institute for Applied Systems Analysis (IIASA) has projects on a number of aspects of climate change focused on global modeling (e.g. Leemans, 1990; Kaczmarek, 1990; Kaczmarek and Krasuski, 1991; Zavaratelli, 1988).

3.0 INTEGRATED ECONOMIC ANALYSES

Nordhaus (1991b, 1993), Cline (1992a, 1992b), Peck and Teisberg (1992a, 1992b), and Falk and Mendolsohn (1992), have considered the costs and benefits of actions to limit climate change which necessarily requires both a schedule relating the cost of control to different levels of emissions and a schedule relating damage to a measure of climate change. All of these efforts seek to evaluate the optimal level of emissions by considering costs and benefits. All are highly aggregated, modeling a single (world) region and representing damages as a single aggregate function. As such, estimates of the damage function depend completely on more detailed research efforts. Nordhaus evaluated the US EPA study and derived estimates of damages for the United States. His analysis involved numerous assumptions about the timing of damages and defensive expenditures (e.g., seawalls). Nordhaus assumes that GNP/GDP can be used to scale damages to other countries and over time. In recognition of the fact that climate-sensitive sectors may be a larger proportion of the economy in developing countries and impacts for which he had no values were omitted, he allows that damage may be a larger proportion of GNP than his calculations project. He arrives at damages at .25 percent of GNP for explicitly valued damages in the United States, but estimates that damages may be 1 percent of GNP for the world (with an upper estimate of 2 percent).

Peck and Teisberg (1992a, 1992b) and Falk and Mendolsohn (1992) rely completely on Nordhaus's damage assessment as a starting point. The models they have developed provide somewhat more flexibility in representing damages as non-linearly related to a single climate change indicator and they explore the implications of damages that are linear, quadratic, and cubic in the climate variable. Peck and Teisberg also examine the case where damages are related to the rate of change rather than the level of climate change. If damages are related to the rate of climate change, the economically optimal level of control is less. This is the expected result because if only the rate of change matters, the damage from, for example, the first .3°C change only causes damage when the change occurs. If climate stops changing at any level, no more damages occur. In contrast, if the level of change matters, then the flow of damages accruing during each period continues to accumulate even if climate change is halted. To stop the flow of damages, climate change must actually be reversed. Viewing damages as related to the rate of change is consistent with a view that damages are due largely to adjustment, where slow climate change may have negligible effects even if the rate persists over many years. In considering these different possibilities, Peck and Teisberg do not provide evidence for any particular damage function relationship. Their work only illustrates the importance of further research to clarify how damages can best be represented.

Cline (1992) attempts to develop damage estimates independent from those produced by Nordhaus but relies on many of the same sectoral impact studies. Cline's estimates for impacts associated with a trace gas doubling are very similar to the estimates of Nordhaus (i.e., 1 to 2 percent of GNP). Clines's principal addition is to extend damage estimates to the very distant future (to 2175) when, if emissions of trace gases are uncontrolled, trace gas concentrations could reach 3 or 4 times pre-industrial levels. Under such situations, he considers the possibility that damages could range from 6 to 24 percent of GNP. Reilly and Richards (in press) investigate the current value of control, based on world agriculture from a study conducted by Kane, et al., (1992) They assume that damages in other climate sensitive sectors are similar to those in agriculture. This approach leads to estimates surprisingly similar to those derived by Nordhaus assuming that Nordhaus's base estimate of damage ($52 billion) grows with GNP.

Reilly and Richards (in press) show that for a wide range of discount rates (3 to 10 percent), Cline's relatively high damage estimates for the very distant future have very little impact on current values of control. At discount rates of 4 percent and above, the earlier years weigh far more heavily than the later years when a quadratic relationship implies very high losses. That is, Cline's high estimates for damages in the very long term mean that far tighter controls may be desirable in the future, but that little effort is worthwhile over the next 10-15 years.

More importantly, this result highlights how dependent forecasts are on assumptions made from interpolating current (when no climate change related damages are presumed to occur) to the arbitrarily chosen doubling of trace gases. The damage estimates of Nordhaus are based on damages associated with equilibrium climates associated with a doubling. The major climate models(Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), United Kingdom Meteorological Office (UKMO)) on which these impact studies are based predict climate changes on the order of 4° to 5.2°C. s cited earlier, changes from present temperatures are unlikely to be observed for over 100 years based on current views on the transient climate response (IPCC, 1990, 1992). Thus, the damages likely over the next 50 years, which have the greatest impact on estimates of how much emissions should be limited today, are dependent on interpolation between assumed damages of 0 at present and an estimate for a point more than 100 years in the future.

The other type of integration that has been attempted involves consideration of a small region and explicit analysis of multiple effects of climate change, and sometimes the possibility of carbon emission limits as well. Dudek as part of the US EPA (Smith and Tirpak, 1989) integrates water supply changes, urban demand for water, and agricultural yield changes including changing water demand for irrigation. Easterling, et al., (1992) consider forestry, agriculture, water (as it affected river transport), and energy effects on the four state area, Missouri, Iowa, Nebraska, and Kansas. They do not explicitly deal with competing demand for resources (such as water) brought on by changing climate but considered the economic effects together using a regional input output model. Godden and Adams (1992), use a general equilibrium model of Australia to consider how both agricultural and fossil fuel limits to control climate change (via impacts on the Australian coal industry) might affect the Australian economy. As part of the ongoing international effort of the US EPA, an integrated study of Egypt is being conducted (EPA, 1993). These efforts have generally considered production sector impacts to the exclusion of amenity and ecosystem change and how such changes may affect the regions' livability or tourism and recreation industries.

By far the biggest limitation of integrated regional studies is that they must make largely arbitrary assumptions about changes in the region relative to changes in the rest of the world. Changes outside the study region would affect net demand for the regions exports or supply of imports of products from climate sensitive sectors (e.g. agriculture, forest products, and energy from hydropower). Tobey et al., (1992) demonstrate for agricultural effects that the sign of the impact can be reversed if changes in world prices are considered, particularly for areas that are significant exporters. Water resources are particularly troublesome in regional studies because the watersheds that feed major rivers in the study area may originate well beyond the region of study. At a minimum, climate impacts on the entire watershed are needed. Upriver users of water may also change their demand as a result of climate change (e.g., for the Nile in a study of Egypt (EPA, 1993) or the Missouri River in the study by Easterling, et al., (1992)). For California, water is itself imported into the state via larger water projects, and these supplies may be reduced if use increases in areas that are the source of these supplies.

Finally, if the effect on a region is particularly severe, one might expect out-migration of population but such out-migration would likely depend on how the region faired relative to other areas, at least those nearby. Alternatively, in-migration could occur if other areas are more severely affected. In creating different scenarios of potential societal impacts of climate, some authors have used the term "environmental refugees" in considering the possibilities that populations would be forced to move due to deteriorating climatic and resource conditions (IPCC, 1990). The likelihood of such scenarios are uncertain but there is agreement that there is greater potential in developing countries than in developed countries where the economic base for most areas is relatively diversified. The general lack of integrated regional analyses to address migration is a significant shortcoming.

From an economic perspective, a strong argument can be made to consider any of the regions as appropriately modeled as small countries (i.e. prices are given from the world market) but usually these studies use models where prices are determined endogenously within the region as a function of the climate-induced changes in supply with net world demand unchanged. The price changes that result from such exercises have little if any relationship to the world price changes that might occur with climate change.

4.0 ECONOMIC PARADIGMS AND MEASUREMENT OF THE EFFECTS OF GLOBAL CLIMATE CHANGE

In the general sense, existing economic theory and economic paradigms are well-equipped to address issues of the economic effects and the cost of adjustment to climatic change. The basic problem of evaluation of the economic effects is in terms of empirical measurement and in creating a structured accounting so that different effects can be aggregated in such a way as to determine the combined impact of the many different aspects of climate change on the relevant economic actor. The relevant economic actor or decision maker may be individual households, producers, public agencies, nations, or international conventions aimed at global environmental management. For example, the individual may see higher food prices if agricultural prices rise, higher prices for water or restrictions on its use, lower heating bills, higher air conditioning bills, changed job opportunities, changes in real estate markets as a result of in or out migration induced by climate change, changes in property insurance resulting from changed storms or sea level changes. A nation may see farm income increasing if world commodity prices rise while food consumers suffer from the same change. Assessment must strive to model these integrative (competing) forces. In this section, we review current economic concepts and general approaches relevent to climate changes.

4.1 The Static Production Paradigm

The basic economic model of production posits producers who respond to changing input and output prices within the boundaries of technical constraints (see, e.g. Lovell and Smith, 1985 for an earlier discussion). Optimizing behavior is assumed. Thus, for output QS_k with price P_k, a profit maximizing firm is assumed to

$$\max\left\{P_k \bullet QS_k - \sum_{i=1}^{n} p_i X_i : QS_k \le f(X_1,\ldots,X_n,C_1,\ldots,C_l)\right\} \qquad 1$$

where X are production inputs, n is the number of production inputs, p are input prices, C are climatic and atmospheric inputs, and l is the number of climatic inputs such as precipitation, temperature, and storm intensity and f describes the production function (technical relationships) among both climate and other inputs. Following conventional analysis, profits, input demands and output supply can be derived as functions of measured market inputs and climate variables even though the relevant climate resources are not traded. I.e. maximum profits are given by

$$\pi^* = \pi^*(p_1,\ldots,p_n,C_1,\ldots C_l) \qquad 2$$

the supply of output k associated with maximum profits is given by

$$QS_k^* = QS_{ki}^*(P_k,p_1,\ldots,p_n,C_1,\ldots,C_l), i = 1,\ldots,n \qquad 3$$

and input demand associated with maximum profits is given by

$$X_{ki}^*(P_k,p_1,\ldots,p_n,C_1,\ldots,C_l), i = 1,\ldots,n \qquad 4$$

Econometric analysis is frequently used to estimate equations like 2, 3, and 4 independently or as a system, however, climate variables are usually not included. With specific inclusion of climatic variables, the relationship between changes in climate and output are obtained. Because relative prices matter within this framework, the climate itself does not have to vary if other input prices vary over the sample. Efforts to specify such a system with climate variables has, however, not proved particularly successful even for the relatively straightforward case of agriculture.

Given these problems, studies of impacts of climate change in practice implicitly partition the production relationship in equation 1. Typically estimates of, for example, yield changes are made, and these are introduced into economic models as measures of supply shifts. The implied partition of inputs and the assumed production structure is then

$$\max\left\{P_k \bullet QS_k - \sum_{i=1}^{n} p_i X_i : QS_k \le f_1(X_1,\ldots,X_n) * f_2(C_1,\ldots,C_l)\right\} \qquad 5$$

This partitioning allows fairly complex technical relationships among market inputs as described by econometrically related production relationships and among climate inputs as described by crop response models. It then allows

$$\hat{Q}S_k^* = P\left[\hat{Q}S_{1k}^*(p_1,\dots,p_n) * \hat{Q}S_{1k}^*(C_1,\dots,C_l)\right] \qquad 6$$

where $\hat{Q}S^*$ is the new optimal supply based on the specific production relationships f_1 and and f_2. This interpretation means that the direct effects of climate change are represented essentially as a simple, Hicks neutral technical change. The second part of equation 6, once estimated, is simply a horizontal shift in supply. Because there are many possible ways to substitute other inputs for climate--in the agriculture example, irrigation, drainage, crop drying, planting and tillage techniques, can be changed--this assumption will bias analyses toward larger supply shifts. Notably, this bias will operate whether climate resources are improving or degrading. If one considers many different regions, some with improving and some with degrading climatic resources, this implies that predicted biases will be larger yield losses for areas with degrading climatic resources and larger yield gains for areas with improving climatic resources. Thus, there may be some tendency for these biases to balance out in the aggregate but the change in regional comparative advantage would be overestimated.

4.2 Climate Change and Impacts on Consumers

Virtually all economic analyses of the potential impacts of climate change focus on production sector impacts. Yet, the ultimate purpose of economic activity is to provide enjoyment (in economic terms, utility or welfare) to members of society (consumers).

The basic consumer problem recognizing the dependence of welfare and consumption on climate is:

$$\max\left\{U(QD_1,\dots,QD_m,C_1,\dots C_l):\overline{Y} \geq \sum_{j=1}^{m} P_j \bullet QD_j\right\} \qquad 7$$

where m is the number of consumer products. This problem gives corresponding consumer demands:

$$QD_k^* = QD_k^*\left(\overline{Y},P_1,\dots,P_m,C_1,\dots,C_l\right) \qquad 8$$

Thus, similar to production, climate variables can be included in demand estimation to infer the value of climate as long as there is some relationship between the activities which lead to amenity or disamenity of climate and marketed goods. Even where there is very little connection to marketed goods, if the utility of the climate service is derived from spending leisure time enjoying it, then the value can be derived by considering the relationship to the valued leisure time which is a complementary good. This basic recognition is the foundation of valuing nonmarket goods using travel cost or hedonic estimation. Consumers purchase travel services and spend leisure time traveling to enjoy a park. Consumers pay more for property with desirable environmental features (e.g. with trees, near parks, with views of the ocean) and less for property with undesirable features (e.g. near industrial parks, landfills).

Semantics, misunderstanding, and the particular focus of economic research on impacts that have proved more easily quantifiable in economic terms has contributed to a significant gap in communication between economists and other scientists working on global change. The difficulty stems from the tenuous connection between economic welfare and economic activity as measured by an aggregate like GNP. The inappropriateness of using GNP as a measure of welfare is well-recognized in economics yet in much applied work, particularly where economists have not been involved, economic impacts of environmental change are confused with macroeconomic issues of employment and job creation or with gross measures of effect such as changes in revenue. The frustration of non-economists with economic reasoning in this regard appears to stem from the non-economists' perspective that the pleasures and enjoyment derived from environmental attributes (at risk due to climate change) is an alternative to a consumption-driven economy rather than a part of it. Economic valuation of environmental attributes, in fact, makes explicit use of the non-economists observation. The willingness to give up market goods with observable values and costs of production provides the ability to measure the value of non-market goods as described in equations 7-8.

Braden and Kolstad (1991) contains chapters reviewing both the theorectical and empirical issues in estimating the demand for environmental quality. The focus of most work in this area has not been on climate change but rather on local pollutants such as air quality or soil erosion. While such valuation is possible in principle for climate change it has not been done and there are many difficulties in actually doing so. Data availability is limited. How to measure climate in relevant terms is an open question; the value temperature or precipitation may interact with other geographic variables such as the existence of mountains or beaches. Variability through the season or variability within a geographic range may be important. The value of climate may depend on economic variables such as income, prices (e.g. of fuels, water, transportation). Thus, the value of more or less precipitation or warmer temperatures is likely to vary widely in magnitude and sign across geographic areas and cultural/technological/economic conditions. The more difficult issue to overcome, however, is that the values estimated in this manner are applicable to small changes and assume that other options are unchanged or are irrelevant to the valuation problem. Thus, estimation of property value impacts of climate variables in one area assumes that climate does not change in other areas that may serve as alternative locations. The long-term nature of climate change with decades to adjust, to anticipate change, and for technology and income to change separate from climate amplifies these problems.

Some aspects of effects of climate change on households can be usefully thought of in terms of the household theory of production. The household can be viewed as producing higher order goods such as transportation services, outdoor summer recreation, outdoor winter recreation, outdoor living, prepared meals, conditioned living space, health, and other services from purchased inputs such as fuel, vehicles, food, medical services, and housing. As related to climate, it is useful to consider what types of desirable services households are producing and whether a specific change in climate (e.g. warmer, wetter) is a beneficial change or a detrimental change. For example, households desire living space conditioned to 75°F. To achieve this in a given climate, they purchase housing with a defined set of space conditioning requirements and energy for heating and air conditioning. In producing transportation services, climate related factors such as snow, road salt, ice, and rain may imply purchases of snow tires, chains, towing services, car body repair, and greater numbers of vehicles because of shortened vehicle life. From the perspective of a household theory of production, the consuming household can be represented as:

$$\max\left\{U\left(g_1\left(Qd_{11},\dots,Qd_{ml},C_1,\dots C_l\right),\dots,g_s\left(Qd_{1s},\dots,Qd_{ms},C_1,\dots C_l\right)\right):\overline{Y}\geq\sum_{j=1}^{m}P_j\cdot QD_j\right\} \qquad 9$$

where $QD_j=\sum_{t=1}^{s}Qd_{jt}$, s is the number of higher level services produced by the household, g_k is the household production function describing the technical relationships for producing service k, and Qd_{jk} is quantity demanded of good j to produce service k. As represented, climate characteristics are indivisible and thus all the household's service producing activities face the same set of climate characteristics while purchased goods are used in specific activities. The particular usefulness of this approach is that it can be reasonably tied to household activities (production of services) and expenditures related to climate and allows for some activities to benefit from a specific climate change whereas other activities would suffer from the same change. I.e. depending on the activity,

$$\frac{\partial g_t}{\partial C_t} >=< 0 \text{ for j= 1,...,s and k=1,..,l.} \qquad 10$$

Thus, whether a particular climate or a particular climate change was a positive or a negative net effect for the household as a consumer would depend on the net effect on all the service flows.

The above approaches are unable to consider non-use values, those benefits, independent of any specific activity such as recreating in the area, that individuals may derive from knowing that a specific ecoystem or species that is threatened by climate change exists. Randall (1991) discusses different concepts of non-use value. Contingent value surveys, where individuals are asked how much they are willing to pay for environmental goods, are the principal method for deriving non-use values. These have proved controversial and difficult to implement for relatively well-defined environmental changes such as oil spills (see, for example, Arrow, et. al., 1993). Issues of particular additional difficulty for analyzing climate change using contingent valuation is that unless questions are narrowly defined, respondents may inlcude assessment of both use and non-use values. Thus, it may be inappropriate to sum contingent valuation estimates with estimates derived from market studies. For example, households may include an estimate of how much more they would have to pay for air conditioning, water, or food or how much less they would have to pay heating. On the other hand, narrowly designed questions regarding losses of specific environemntal goods--a coastal wetland or specific tundra area in Alaska--depend on how climate change would affect other wetlands or tundra areas. Moreover, the list of possible environmental changes is nearly endless and extremely uncertain.. Thus, any specific set of changes may not include the changes that many people value highly.

4.3 Closing the Loop--Households in a General Equilibrium Context

In the context of general equilibrium, households are both consumers and owners of resources (land, labor, and investment capital). The full impact of climate change on consumers includes the direct effects of climate as it enters utility, plus the effects of changes in prices of goods whose production costs change because of climate change, plus changes in income as affected by changes in the prices of inputs owned by the household. To the extent that climate change affects employment opportunities and hence wage rates in a nation or region, the full impact of climate change on the household both as a consumer and as an owner of resources will depend on climate's effect on household income as well as household consumption. In equations 7, 8, and 9, $\overline{Y}$ is replaced by Y, which is now a function of climate by virtue of the fact that wage rates change in response to changes in labor demand stemming from changes in production induced by climate change. For large areas (big countries) with a diverse set of production activities, it is probably unlikely that wage rates would change because climate sensitive production sectors are a small component of the economy (e.g. Nordhaus, 1991a, Kokoski and Smith, 1987). Appeal to large areas is, however, in some sense, misleading because within large areas there may be many areas that are more seriously affected. Scenarios leading to human migrations could involve, for example, loss of beach resort areas and consequent loss of jobs associated with tourism or significant loss of agricultural in an area heavily dependent on agricultural production and a consequent loss of income earning potential for residents. Such losses occur at geographic scales of 1-50 mile radius areas and thus are unlikely to be observed in economy-wide measures. The fundamental difficulty in assessing the potential costs in such a situation is determining whether out-migration would occur or instead whether new industry and employment opportunities would develop to replace lost opportunities.

4.4 Dynamic Production and Consumption Models

Economic modeling of adjustment cost to climate change can be addressed within straightforward economic models. The key aspect of adjustment is a slowly adjusting stock where the economic agent (producer or consumer) decides to adjust the stock level on the basis of current and future prices, resource availabilities, and technical constraints. Empirical work is most advanced in considering capital investment in this context where the stock is physical plant that can be augmented through investment and which depreciates over time. (The basic dynamic model for production is given in, for example, Hyashi, 1982.) Some work in agriculture (e.g. Hyami and Ruttan, 1985) has considered technology in this context, where annual research and development expenditures play the role of investment and the sum of research and investment expenditures through time (sometimes depreciated for obsolescence) is taken as a measure of the stock of knowledge at any given time. An advantage of the household production representation in equation 9 is that long-lived consumer purchases such as homes or vehicles are directly interpretable as capital stocks which depreciate and can be augmented through investment. Thus, it provides a relatively firm foundation for considering adjustment costs within households. The theoretical construction is applicable to other aspects of adjustment frequently raised in the context of climate change such as cultural resistance to change, the need for learning and education on the part of individual households, or the resistance to change that might be brought on by preferences and tastes acquired from having lived for many years in a particular climate and environment. The difficulty here is in defining measurable stocks for many of these concepts. Education and learning can be measured through schooling, but much relevant education with regard to adapting to climate may be informal. A possibility for regional analysis is to consider some measure of the mobility of a population as a stock of knowledge living in other climatic and resource conditions. Thus, an area where the population travels extensively and where many may have lived elsewhere at some point would have a far larger stock of knowledge regarding how to live in a changed climate than a less mobile population. The more mobile population may thus face lower psychic adjustment costs for a similar change in climate. Such an approach would be a way of quantifying the frequent observation that the poor in developing countries would find it harder to adjust than those in developed countries. It would interact with the fact that the poor may also be less able to afford adaptive responses (such as moving). Formally, the dynamic analog to equations 1 and 9 are:

$$\max\left\{\int_{t=o}^{T}\left(P_t\cdot f\left(X_t,C_t,K\right)-\sum_{t=1}^{n}r_tX_t-\Psi\left(K_t,I_t\right)\right)e^{-rt}dt:\dot{K}_t=I_t-\delta K_t\right\} \quad 11$$

and

$$\max\{ \int_{t=0}^{T} U\left(g_1\left(Qd_{t1},C_t,K_1\right),\ldots,g_s\left(Qd_{ts},C_t,K_s\right),\Omega\left(K_{t1},\ldots,K_{ts},I_{t1},\ldots I_{ts}\right)\right)e^{-rt}dt: \quad (12)$$

$$\overline{Y} \le \sum_{j=1}^{m} P_j \cdot QD_j + \sum_{j=1}^{m} \Psi_j\left(K_{tj},I_{tj}\right): \dot{K}_{tk} = I_{tk} - \delta_k K_{tk} \ \}$$

where X (inputs), C (climate characteristics), and Qd (consumer demands) are vectors of length n, l, and m, r is the discount rate, t is time with T being a terminal date possibly ∞, and K, K_i and I and I_i for i=1,..,s are stocks of capital (or other stocks) and investment (or augmentation of stocks). $\dot{K}, \dot{K}_i$ are the rate of change over time of K and K_i. ψ and ψ_j describe the cost of adjustment as a function of the capital stock and the level of investment and would generally be seen as increasing in I and decreasing in K. In the consumer problem, adjustment costs are represented as part of the constraint that expenditures not exceed income and are within the utility function, allowing for the fact that adjustment costs may involve both pecuniary costs and psychic costs. It is possible that for some types of stock variables (culture or religion which may rule out some adaptations such as eating different foods), the relevant I and δ are 0 making K a fixed stock. Based on these representations, demands for each period conditional on the stock of capital in that period can be derived as well as the path of augmentation of the stocks. Because there is a cost or resistance to adjustment, the actual stock level will only slowly adjust toward the optimal stock. Because of the slow adjustment, there will be greater costs associated with the dynamic problem than under the assumption of full adjustment.

4.5 Measuring Damages Under Uncertainty

No one disputes that the potential changes in climate are highly uncertain. There are many ways in which uncertainty affects damage estimates. The gap between theoretical approaches and practical empirical approaches is greatest in this area. Among the issues are irreversible environmental losses which have been broadly discussed but not applied to climate change (e.g. Arrow and Fisher, 1974; Fisher and Hanemann, 1990), the closely related area of option value for investment which illustrates how adaptive investment decisions may be affected by climate uncertainty (e.g. Pindyck, 1991); interaction with common pool resource management issues (Walker and Gardner, 1992). Environmental irreversibilities are most frequently discussed in terms of loss of species or ecosystems. Uncertainty issues that have been brought to bear specifically on aspects of climate change include consideration of risk averse behavior on the part of farmers (Yohe, 1992a), the interaction of asymetric loss with uncertainty in the case of sea level rise (Yohe, 1992b) and the possible impacts of increased frequency of storms on insurance markets (Viscusi, 1992). The usual protocol for crop response studies, by simulating crop response models over a 30 year record of realistically varying climate, captures the asymetric losses in agriculture that stem from drought or similar events (see for example, Parry et al.,1988, or for an example in the context of an economic model see, Kaiser, et al., 1992) that Yohe captures through specification of a specific distribution for sea level. Agent learning and the ability to detect a climate change signal within a normal very variable climate is closely related.

5.0. APPROACHES AND ESTIMATES FOR SPECIFIC SECTORS AND SYSTEMS

The number of studies of potential impact of climate change on biological and physical systems has burgeoned. The IPCC (Tegart, et al., 1990; Houghton, 1992) provides references to many studies. Extensive bibliographic sources on potential climate change impacts include Scheraga (1991), Handle and Risbey (1992), IPCC (1990), EPA (1993) as well as the Climate Change Impact Database of the Institute for Environmental Studies at Free University of The Netherlands which contains information on approximately 500 research projects focusing on impacts.

As noted above, the broadest attempts to identify <u>all</u> potential economic activities affected by climate change include Kates, et al., (1985) and Nordhaus (1991), shown here as tables 1 and 2. Below we discuss selected works which make projections in the sectors of agriculture, forests and ecosystem change, fisheries, water resources, sea level rise and coastal effects, and community and household effects. As suggested earlier, most of these studies are not integrated (for example, climate effects on water resources are generally not incorporated into projections of agricultural yields.) Many different methodologies are used to anticipate impacts in the various sectors. Most frequently, GCMs, historical data, or geological records are used to project the equilibrium conditions which will exist at a designated point in time, usually benchmark double CO2 equivalent atmospheric concentrations, and adaptation or mitigation strategies are applied to this perturbed climate. Most studies are qualitative, and the few which quantify monetary costs usually utilize percentages or trends from reports of the IPCC (1990) and the EPA (1989) and apply these to industry output projections or GNP (e.g., Nordhaus, 1991b; Cline 1992a, b).

5.1 Forest and Ecosystem Change

Spatial dimensions of GCMs are coarse when compared with the dimensions of the range of ecosystems (Joyce et al., 1990). Models which combine the transient effects of atmospheric and ecological interaction are in developmental stages. Therefore GCMs or historical pollen records are most generally used to project equilibrium conditions, and existing ecological models are then applied to these conditions to determine species abundance and distribution.

According to Joyce, et al. (1990), ecological models can be characterized as:

1) physiological-based plant models which measure the response of individual plants to changing conditions;

2) population models which examine plant establishment, growth, seed production and death;

3) ecosystem models which focus on biogeochemical processes of fixation, allocation, and decomposition of carbon, and the cycles of nitrogen, phosphorus, sulfur and other elements;

4) regional or global models which correlate vegetation distribution with climatic variables of temperature, precipitation (Smith et al., 1992) and soil type (Prentice et al., 1992).

Gap phase models are a widely used type of population model that predicts the establishment, growth and death of species and accounts for competition for light, water, and nutrients (Botkin et al., 1972; Shugart, 1984). For the most part, the various ecological response models have not been integrated, although there have been attempts to incorporate nutrient cycling of ecosystem models into gap-phase models in forests (Pastor and Post, 1988).

Table 1. Economic Activities According to Their Sensitivities to Climate Change

Sector	Activity's Percent of Total National Income	Impact for CO_2 Doubling (billions 1981 $)
Severely impacted sectors		
Farms	2.78	
Impact of greenhouse warming and CO_2 fertilization		-10.6 to 9.7
Forestry, fisheries, other	0.32	Small
Total	3.10	
Moderately impacted sectors		
Construction	4.52	Positive
Water transportation	0.26	?
Energy and utilities		
Energy (electric, gas, oil)	1.90	
Electricity demand		-1.7
Nonelectric space heat		1.2
Water and sanitary	0.24	Negative
Real estate-land-rent component	2.12	
Sea level rise damage		
Loss of land		-1.6
Protection of sheltered areas		-0.9
Protection of open coasts		-2.8
Hotels, lodging, recreation	1.05	?
Total	10.09	
Negligible effect		
Mining	1.87	
Manufacturing	24.08	
Other transportation and communication	5.49	
Finance, insurance, and balance real estate	11.38	
Trade	14.47	
Other services	13.47	
Government services	13.96	
Earnings on foreign assets	2.08	
Total	86.81	
TOTAL	100.00	-$6.2

NOTE: A positive number indicates increase in output; a negative number indicates a loss.
Source: Data from Nordhaus (1991b) as appearing in NAS (1992), p. 600.

TABLE 2. ECONOMIC ACTIVITIES CONSIDERED IN CLIMATE IMPACT ASSESSMENTS[1]

	Sensitive area[2]	Maunder 1970	CIAP 1975	Aspen Institute 1977	CSIRO 1979	WMO 1979	DOE AAAS 1980	CEAS 1980	SCOPE 1984	EPA 1989	IPCC 1990	Nordhaus 1991	Cline 1992	EPA 1993
1	Agriculture	X	X		X	X	X	X	X	X	X	X	X	X
2	Forests and forestry	X	X		X	X	X	X		X	X	X	X	X
3	Pastoral activities				X		X	X	X		X			X
4	Fish and fisheries	X	X			X	X	X	X	X	X			
5	Ecosystems						X							X
6	Environmental conservation									X				
7	Water supply, demand		X	X	X	X			X	X	X	X	X	X
8	Energy supply, demand	X	X	X	X	X		X	X	X	X	X	X	
9	Manufacturing operations, location of plants	X	X		X			X			X			
10	Offshore operations					X								
11	Mining (extractive industries)				X						X			
12	Transportation: water, air, rail, highway	X		X	X			X			X	X	X	
13	Construction	X		X	X			X		X				
14	Materials weathering		X											
15	Esthetic costs		X											
16	Trade	X						X						
17	Public expenditures		X					X						
18	Communications							X						
19	Insurance	X			X						X			
20	Financial planning and institutions			X				X						
21	Recreation and tourism	X			X			X				X	X	
22	Sea level rise, coastal zones						X			X	X	X	X	X
23	Health: mortality, morbidity	X	X			X	X	X	X	X	X		X	X
24	Migration							X			X		X	
25	Social concerns, crime	X	X				X	X	X					
26	Military planning and operation													
27	Political systems and institutions	X	X				X							
28	Legal systems and institutions	X					X							

Source: Updated from Kates, et al. ,1985, p. 88.

[1] To be checked here, topic must be treated explicitly or extensively.

[2] List includes 2 topics (6 and 26) not covered in studies listed, but covered in other studies.

The global and regional models are currently the most widely used to assess the gross effect of climate change upon ecosystems. These models evaluate steady state conditions: predicted vegetation patterns are those that would occur only after the ecosystems have adjusted fully to a new climate that has been "stable" over a long enough period for the system to adjust. There are no obstacles to species migration. Because species migrate at different rates (Davis, 1981) and migrating species are faced with anthropogenic barriers (Flather and Hoekstra, 1989) the steady state assumption is unrealistic (EPA, 1993). Additionally most modeling scenarios do not include disturbances such as fire, insects, disease and pollutants. Fundamentally, the issue of stability of climate over such long periods and the concept of equilibrium of ecosystems or climate are open to question as past "stability" and "equilibirum" have included variability and change on many different time scales.

Quite extensive work has been done in the United States to apply global & regional models to climate change, and quite often the use of different methodologies yields different results (Joyce et al., 1990). For example Botkin et al., (1988) and Solomon and West (1987) completed independent analysis of climate change for the Lake States. Both studies for two GCMs scenarios (NCAR and GISS) projected total biomass to decline, but the species and their relative abundance's in the future ecosystems were quite different.

Emanuel et al., (1985b), Solomon and Sedjo (1989), Prentice and Fung (1990) and Smith et al., (1992) have utilized variations of the Holdridge Life Zone Classification System in order to simulate potential ecosystem distribution under climate change. The Holdridge system correlates temperature and precipitation parameters with 37 “life-zones” (alternatively, “eco-climate zones”) ranging from polar desert to wet tropical rainforest. The primary objective of the studies by Prentice and Fung and of Smith et al., were to assess sensitivity of terrestrial carbon storage under climate change. Each eco-climatic zone was assigned a level of carbon storage. These zones were then superimposed on a 2 X CO2 climate and the change in global vegetation distribution was estimated. Up to 50% of current world-wide eco-climate zones changed to a new eco-climate zone under a perturbed climate. These studies suggest that total vegetation would increase, acting as a net carbon sink. Again, these studies are limited by their assumption that vegetation and climate are in equilibrium. Conversely, studies in the US by Solomon (1986) and Neilson et al., (in press), that consider problems of adjustment, indicate that climate change at the predicted rate could result in forest dieback and a net release of CO2.

The IPCC (1990) synthesizes a number of site specific, regional and global studies by various contributors to conclude that “current forests will mature and decline during a climate in which they are increasingly poorly adapted ... and large losses from parasites and direct climatic effects can occur... increased mortality owing to physical stress is likely... and losses from wildfire will be increasingly extensive.” For natural ecosystems, rates of change are likely to be faster than the ability of some species to respond ..... [resulting] in a reduction in biological diversity.”

In an attempt "to address the potential impacts of climate change on forested systems at regional and global scales under an array of possible climate change scenarios" a comprehensive study has been done by EPA (1993). The study focused upon the impacts of climate change on the global distribution of two forest systems, boreal forests and tropical forests, "in order to represent contrasting cases of the interaction of human and biological constraints on the potential response of forest ecosystems to climate change." In addition, case studies were utilized in order to provide a more comprehensive assessment of impacts at the regional level in an effort to include land use and transient effects which would facilitate a more detailed evaluation of potential impacts and adaptation strategies. Results indicate that climate change could have a major impact on ecosystem distribution and composition. In the case study of Costa Rica, for example, a moderate climate change scenario (+2.5° C change and 10% precipitation increase) projected that 38% of the country's land area would change from one eco-climate zone to another. A more extreme scenario (+3.6 C and 10% precipitation increase) projected a 47% change. An increase in spatial resolution of the models increased the land area change to 43% and 60% respectively (Tosi et al., 1992). Overall, the study projects that the "ability to select suitable species for plantation forestry may enable the forestry and fuelwood sectors to offset potential declines in production of native forests, however, the impacts on naturally maintained forests and nature conservation could be severe."

Few attempts have been made to quantify financial loss associated with possible decline in forested area. Cline (1992) synthesizes EPA's (1989) projections to predict a loss of $3.3 billion annually for the US logging industry. This is based upon extrapolation of the EPA's estimated 40% loss of US. forests. The approach neglects possible price impacts and therefore possible consumer wlefare losses but relatively crduely adjusts logging industry revenues for the value of other inputs and thus may overestimate producer welfare losses.

5.2 Agriculture

Most estimates of agricultural impacts of climate change use crop response models, detailed models of plant growth as determined by temperature, moisture, sunlight, and nutrient levels. The models reflect understanding of physiological response and are based on experimental crop growth experiments. The models run at time increments of less than one day and simulate growth of the plant over the season. As such they require very detailed climate data. Rosenzweig, et al.,(1993) and US EPA (Smith and Tirpak, 1990) used detailed models specifically designed for individual crops including corn, wheat, soybeans, and rice. The Erosion Productivity Impact Calculator (EPIC) model (Williams, et al., 1989, used by Easterling, et al., 1992) is somewhat less detailed and the model can be parameterized to represent different crops. The climate change crop study protocol is to choose a specific site or representative farm, develop a representative climate history with and without climate change for a number of years (e.g., 30), simulate the crop response models for each year under the "with" and "without" climate change scenarios, and summarize the yield impacts as a comparison of the 30 years average yields.

Different methods are used to generate representative climates. Rosenzweig, et al., (1993) and Parry et al., (1988) use historical climates (usually for the period 1950-1980) and create the climate change scenario by adding temperature and precipitation differentials from GCM runs to the daily (or hourly climate records). Easterling et al., (1992) use an analog climate (the 1930's dust bowl) contrasted with more recent decades of normal climate. Kaiser, et al., (1992) developed a statistically based climate generator which stochastically creates realistic climates where the means and variances of key climate measures, precipitation and temperature, can be altered to reflect the type of changes that might be expected for the region based on, for example, GCM scenarios. The Kaiser, et al., approach provides the most flexibility. The approach used by Easterling, et al., is least flexible; its application is appropriate only for regions that have specific climate change analogs and only for those analogs. The Rosenzweig et al., and Parry, et al., approach carries with it the specific climate pattern of the historical period used and requires a historical data series with the requisite daily detail.

Where these results are connected to economic models the projected yield impacts are used to shift supply or yield and profitability on representative farms which are the foundation of the economic model. Kaiser, et al., comes closest to linking crop response models with farm-level management models where operators choose crops and production practices to maximize returns based on expected prices and resource conditions. Easterling, et al., use output changes to shock an input-output table for the region. Somewhat surprisingly, even with the significant yield changes sometimes projected for major crops like corn or wheat, economic models that attempt to consider whether it is optimal to shift to crops that are better adapted to drier or hotter climates (e.g., sorghum) conclude that no crop shift is indicated (Kaiser, et al., 1992; Yohe, 1992) unless there is a considerable value to reducing year-to-year variability if, for example, farmers display relatively high levels of risk aversion. Economic modeling based on supply changes due to crop response models range from the farm level (Kaiser, et al.,1992) to the regional level (e.g. Easterling et al., 1992, Dudek, 1990, Liverman, 1992; Mooney and Arthur, 1990; Arthur, 1988), national level (several reported in Parry, et. al, 1988; Adams, et al., 1990) and the global level (Kane et al., 1992; Tobey, et al., 1992; and Rosenzweig, et al., 1993). Some efforts have focused on the particular vulnerability to food shortage of populations in developing countries (Downing, 1991).

Nearly all results have shown the potential for significant yield losses for some areas (on the order of 30 or 40 percent) but inclusion of the positive effects of carbon dioxide fertilization, adaptive responses such as changed cultivars and cropping practices, and inclusion of broader geographic regions where effects are positive have led to some scenarios where the net effect of climate change is positive. One workshop that relied on experts to develop estimates over the course of the workshop developed results that were very positive ranging from 15 to 40 percent yield increases but this effort did not consider regionality in precipitation effects (NCPO, 1989). Nordhaus (1991b), largely on the basis of Adams, et. al results, summarized the net effect as zero.

A few efforts have used cross-section statistical approaches to assess the implications of climate change for agriculture. These include, for example, Mendzhulin (1992); Hansen (1992); and Nordhaus, Mendelsohn and Shaw (1992). These efforts rely on the variation of climate across geographic regions to estimate agricultural conditions under a changed climate. Mendzhulin uses cross-sectionally estimated yield equations to evaluate climate change assuming that paleoclimates serve as useful analogs for climate change. He finds extremely positive effects on yields in the areas of the former Soviet Union and in the United States. Most climatologists do not believe that paleoclimates are useful analogues. Mendzhulin's yeild equations could be used with climate scenarios derived from GCMs or other means. The other studies of this type listed here do not develop projections of the impact of climate change but the statistical models were estimated with the intent to do so. Hansen estimates a statistical model of corn yields for the United States corn belt. The unique aspect of the study is that it includes both 30-year climate averages and the contemporary weather to develop separate estimates of the short term effect of weather and the longer-term adjustment to climate. Mendelsohn, Nordhaus, and Shaw [1993], and Mendelsohn and Shaw (1992), estimate the impact of climate and climate variability in the US assuming that land values represent agricultural returns after correcting for other effects. By estimating the impacts on land values they argue that they implicitly estimate the full range of adjustment including impacts on and shifts among minor crops and to nonagricultural uses. They find that estimated impacts are smaller then detailed production estimates. Mendelsohn, Nordhaus, and Shaw argue further for a weighting by crop value rather than land. They find that this reweighting yields positive effects for much of the United States because many high-valued minor crops are likely to benefit from warmer climates.

These efforts do not consider the effects of carbon dioxide fertilization because it does not show geographic variability, although Mendzhulin adjusts yields for carbon fertilization based on crop response studies. Such adjustment is more feasible in the case of yield estimates than for a measure such as land value. The reduced form estimate of land value depends on the specific pattern of relative prices of crops at the time of estimation and thus cannot consider the effect of changes in world prices induced by climate change. An alternative that has not been applied to global change directly is an approach used to assess global food production potential (MOIRA) in the 1970s. This effort used a far more aggregated biomass production capability based on soils and broad climate zones. In many ways it is closely related to the Holdridge life zone approach used for ecosystem modeling.

Only Kaiser, et al., consider a dynamic path of climate change made possible by their unique climate generator but the approach is limited to a representative farm. All of these approaches have limited themselves to considering the affects of climate on existing agricultural land. In principle, the approaches could be extended to consider opening up new land but validation and verification of the models for such areas would be difficult. Additionally, remote areas of little current agricultural interest generally have poorer data.

5.3 Coasts

Coastal damages are almost exclusively linked to sea level rise. Ocean or surface air temperatues are likely to have effects on coastal ecosystem effects but these have not been evaluated. Sea level rise resulting from climate change associated with a benchmark CO_2 doubling has been estimated to range from 0.5 to 3.5 meters (EPA, 1989, IPCC, 1990, Hoffman, 1983). Societal concerns include the possibilities that such increases may inundate developed areas, flood low-lands, destroy wetlands and estuaries, and lead to salt water intrusion into coastal ground water supplies. The most recent evaluations of potential sea level rise suggest, however, that the rise over the next 100 years could be considerably less (from 35 to 55 centimeters)(Wigley and Raper, 1992) due, at least in part, to the lagged ocean response to air temperature increases. The actual apparent sea level rise for a specific coastal area would differ depending on whether the coastal area is itself subsiding or rising. Subsidence or rising can be on the order of magnitude of the sea level rise now expected over the next 100 years.

Many industrialized countries have assessed the costs and impacts associated with sea level rise including significant studies in the US (Titus et. al, 1991) and the Netherlands (Rijkswaterstaat, 1990). Comparatively little work has been done on developing countries but studies are forthcoming from the EPA (1993) and Rijkswaterstaat (1992). Additionally, the World Coastal Convention sponsored by NOAA, US , EPA, and Rijkswaterstaat is planned for November 1993 in an attempt to synthesize world knowledge. Studies of sea level rise damages have centered upon defense costs, i.e., the costs of sea walls, dikes, or beach nourishment. There have been fewer attempts to integrate the effects that a rise may have on other sectors, such as salinization of freshwater supplies, recreation, and coastal ecosystem effects.

The IPCC (1990) estimates the capital cost for protection of cities, harbors, beaches and cultivated low-lands against 1m sea level rise for 181 countries to be $500 billion. This is the cost to prevent inundation and erosion. Individual country projections include The Netherlands at $12 billion and Japan at $74 billion. The study may underestimate coastal protection because it assumes that the frequency and severity of floods and storms remains the same. Nor does it consider the costs of responding to saltwater intrusion and "therefore costs will be considerably higher." The IPCC projections will be updated to include some of these secondary effects.

The US EPA estimate, which includes incorporation of some wetland and dryland loss in conjunction with defense mechanisms, is projected to be $200 to $475 billion for the United States (Titus et al., 1991). This number allows for inland migration of wetlands which may be unlikely due to the speed at which sea level may rise as well as the presence of anthropogenic barriers impeding mitigation.

Some developing country studies have taken place, most significantly those of Egypt and Bangladesh (Broadus et al, 1986; Milliman et al, 1989). These countries are seen as particularly vulnerable because they are characterized by large low-lying areas with high rates of subsidence combined with sedimentation loss which collects in upstream dams. These studies projected quite significant impacts for a 1 meter rise including 8 -10 million people displaced and 12 - 15% loss of arable land submerged for Egypt. Nicholls and Leatherman (EPA, 1993) provide more detailed results of these countries and indicate that loss could be significantly greater. Obviously small low-lying island nations are particularly vulnerable to a rise in the area of a 1 to 2 meters or greater (Pernetta, 1991).

The forthcoming EPA (1993) study was conducted to provide more information on developing countries. The study utilizes three possible scenarios, a .2 meter rise, .5 meter rise, and 1 meter rise by 2010. Generally, these studies did not consider local uplift or subsidence. National overviews are given for Bangladesh, Brazil, China, Egypt, Malaysia, Nigeria, India and Senegal. In-depth case studies were done for Bangladesh, the North China Coastal Plain, Shanghai area, Hong Kong, Alexandria Governate (Egypt) and the Lower Pampas, Argentina. National assessments using aerial videotaping techniques were done for Argentina, Nigeria, Senegal, Uruguay, and Venezuela. The authors indicated difficulty in including factors such as wetland migration and land valuation and therefore these were often excluded from calculation. The three responses considered were: 1) no protection, 2) developed areas protection, and 3) total protection including areas of both high and low levels of development. Wetlands are not protected in any of these situations.

The numbers generated from the IPCC (1990) and the EPA (1989) have been used by some to calculate costs for specific regions. Rijserberman (1991) used the figures to assess the costs to the OECD countries and concluded that such costs would "be manageable."

Cline (1992) uses the EPA figures of 49% wetland loss (6,440 square miles) and dryland loss of 6,650 square miles in addition the midrange EPA estimate for capital costs of $370 billion (halfway between the EPA estimates of $275 to $475 billion) to calculate a value of $7 billion in annual costs for the US. To arrive at these calculations he values wetland at $10,000 per acre, extrapolating from current wetland conservation costs of $30,000 per acre. He calculates the value of coastal dryland at $4,000 per acre, twice the US median land rate of $2,000 per acre to allow for greater value near the coast. To these values he attaches a real land rental rate of 10% to reach an annual value of $4.1 billion and $1.7 billion for wetland and dryland loss respectively and adds this to an average annual capital outlay for construction of defense measures of $1.2 billion. The appropriate value of land potentially lost due to sea level rise is difficult to establish. Land values typically exhibit a gradient with declining values as distance from the shoreline increases. If this gradient simply moves back with sea-level rise, the actual lost value is perhaps more appropriately represented by the value of land further inland. Generally, the valuation of an ecosystem like wetlands on the basis of the cost of conserving them is problematical as it assumes that the policy (if one exists) forcing conservation or reestablishment accurately reflects demand for the ecosystem.

Yohe (1990) has produced a scale of cost relative to sea level rise which increases non-linearly. This scale shows a rise of 13 to 200 cm corresponding to a cumulative vulnerability of between $36.3 billion and $909.4 billion respectively. These cost are based upon the value of lost structure, the value of lost land, and the lost social "services" delivered from existing coastline.

5.4 Fisheries

Few generalizations have been made describing the possible impacts that climate change may have upon fisheries. The distribution and abundance of fisheries is based upon complex interactions of many variables which include physical, chemical, and biological processes as well as economic and management factors. Climate change has the potential to effect any and all of these variables and as the understanding of the interactions is limited so is the ability to make predictions. Additionally, GCMs do not offer sufficient spatial resolution to predict future regional conditions. Ocean models are not coupled to climate models nor do they have the spatial resolution to predict changes in upwelling or other phenomena that are important for fish reporduction and growth. The discussions of climate change and fisheries have therefore centered upon forecast by analogy; analyzing the effects that climate and environmental trends have had upon specific commercial fish stock in the past.

Fisheries management has primarily been limited to a relationship of stock depletion and recruitment. It is recognized that this approach is limited and that the rise and fall of various fish populations is often dependent upon subtle environmental changes. Studies that tie these changes to fish yields are now being called upon to improve fisheries management. Additionally, they are being used as analogs to anticipate possible fluctuations in stock under changing environmental conditions due to climate change.

Such studies include a description by Southward (1980) and Southward, Hoalch, and Maddock (1988) of the climate induced alterations in the ocean circulation pattern in the western English Channel. These alterations resulted in the replacement of populations of herring, a cool water fish, by pilchard, a warmer water species, when changing currents resulted in an increase in sea temperature. Kawasaki (1992) considers a correlation of sardine populations with anomalies in the median sea surface temperatures between the years 1876 - 1987. He finds that when temperature anomalies were positive, populations were relatively high. Ware and Thompson (1992) illustrate that commercial fisheries of the Pacific hake and the Pacific sardine have varied over the past 200 years from a high of 24 million metric tons to a low of 1.4 million metric tons. The abundance of these fisheries rise and fall in phase with rise and falls in phytoplankton and zooplankton production. The population of the plankton similarly fluctuate on a 40 to

60 year time scale in response to a long-period change in wind patterns that determine the extent of coastal upwelling.

Francis and Sibley (1991) point out that biological responses to climate change may differ according to geographic location. They discuss the fluctuations of salmon populations in the North Pacific. They illustrate that the periods of highest and lowest catch for pink salmon in the Gulf of Alaska and the coho salmon in the Washington/Oregon/California region are reversed. This may be explained by research of Wickett (1967), Tabata (1984, 1991) and Hollowed and Wooster (1991) which indicates that physical variables such as temperature or coastal upwelling and biological responses of fish and zooplankton are similarly out of phase for the two regions.

Sibley and Stickland (1985) offer an array of possible impacts which may arise from climate change. They present six climate-related abiotic effects; increased mean water temperature, increased vertical stability at surface due to warming, decreased and seasonal sea ice extent, weakening and poleward and seasonal shifts in storm tracks and surface turbulence, weakening and poleward and seasonal shifts in wind-driven surface currents and coastal upwelling, temperate decrease and high latitude increase in net precipitation and runoff. These abiotic effects will have impacts upon biological processes which will influence the distribution and abundance of fisheries. For example, increased mean water temperature could increase "growth and development rates and metabolic demands of species," as well as "poleward and seasonal shifts in productivity and predator/prey distributions" these could in turn "increase the survival and yield [of fisheries] subject to changes in predator/prey abundance and poleward shifts of ranges and migration patterns subject to suitable habitat."

Bakun (1990) points out that on a global scale there are two competing abiotic processes that can significantly impact fish populations. Warming could dampen the temperature contrast between oceanic tropical and polar regions and therefore slow the currents of the ocean and atmosphere above it. On the other hand, increased contrast in temperature between the oceanic and continental temperatures may intensify currents. "Many of the consequences of global climate change to marine ecosystems and also to marine-influenced terrestrial systems could depend on the relative importance, in each local situation of these competing effects."

Conclusions of a study by Fogg (1991) perhaps offer an indication of the current state of knowledge of climate change and fisheries on a general level. He anticipates little change in overall productivity but indicates that "drastic rearrangements" of marine organisms and fisheries may occur. "However in dealing with such an infinitely complex system as the marine biosphere some important factor will almost certainly have been overlooked" and we therefore can not place much confidence in prediction.

5.5 Water Resources

Accurate forecasting of the effects of climate change on water resources would require fairly specific information about air temperature, precipitation, cloud cover, wind speed, and humidity. Again, reliable information on this level is not available. In particular, water runoff that determines river, lake, and reservoir levels depends on the intensity and timing of storms and whether precipitation falls as snow or rain. GCM predictions are particularly uncertain regarding precipitation because clouds are poorly represented. Forecasts focus on three approaches: 1) hypothesizing the effects of a range of changes in air temperature and precipitation, 2) utilizing GCMs to estimate conditions, 3) utilizing paleoclimatology studies of warm epochs (IPCC 1990).

Perhaps the most useful models are those which utilize rainfall-runoff scenarios based on historical data in conjunction with GCM projections. Notable studies include those of Gleick (1987), Nemac and Schaake (1982), and Flashka et al., (1987). Gleick, for example, utilizes a model for the Sacramento basin in California to estimate that a 4° C temperature rise combined with a 10% increase in precipitation would decrease summer runoff by 55%. A 10% decline in precipitation at the same temperature would yield a 65% decrease in summer runoff. In both of these scenarios, winter run-off will increase as a result of reduced snow pack, however not enough to offset summer loss. The EPA (1989) estimates a 7 to 16% decrease in water delivery in California's central valley basin by the year 2100.

Cline (1992) uses a water price of $250 dollars per acre-foot (the estimated price of water in California as indicated by the New York Times, 6 March 1991) to estimate a cost of $750 million annual loss for California. Cline then estimates the possible repercussions for the whole of the US:

> "Nationwide withdrawals of water amount to 0.378 billion acre-feet annually. Assuming $250 per acre-foot for domestic and industrial use (59%) and $100 for irrigation (41%), the annual value of water withdrawals is on the order of $70 billion annually. If water availability were to decline by 10% (based on the Gleick and the EPA-California estimates), the annual cost would amount to $7 billion." (Cline, 1992, pg. 124)

The IPCC (1990) surveys various individual basin studies and suggests that developed countries are less sensitive to changes in water resources than developing countries. Waggoner et al., (1990) offer a comprehensive survey of how climate change may effect water resources in the US, and recommend flexibility and foresight in future planning of water resources. The IPCC suggests that "relatively small climatic changes can cause large water resource problems .... especially in semi-arid regions and those humid areas where demand or pollution has led to water scarcity." Water availability is expected to decline in areas such as the Sahelian zone in Africa. One scenario suggests that a 10% reduction in precipitation will lead to a 40-70% reduction in annual run-off in this area.

The EPA (1993) emphasizes that because "river basins vary markedly in hydrological sensitivity, development, management capacity, and potential for further development" universal statements can not be made. They indicate that negative effects could be mitigated and positive effects enhanced. Their study assessed potential impacts and adaptations of five river basins shared by developing countries; the Indus, Mekong, Uruguay, Zambezi, and the Nile. They conclude that the water management of "the Nile and the Zambezi would have to be changed substantially to accommodate global warming. The worst-case scenario for the Nile (the GFDL 80% reduction in river flow) portends economic disaster," but the study suggests that with an emphasis on river basin management, vulnerability to climate change can possibly be mitigated.

5.6 Community and Household Effects: Infrastructure, Health, Energy and Amenities

The potential effects of climate change on communities and households are perhaps the most difficult to assess and have, not surprisingly, received less attention than the sectors discussed thus far. Within this category we include climatic effects on household purchases (e.g. energy), direct climate effects on well being (e.g. health), and community or regional impacts that would result if, for example, climate changes led to out- or in-migration. The difficulty in estimating the effects of climate change on households is that many of these effects are not well-defined.

The IPCC (1990) indicates that "among the most significant of all the potential impacts of climate change are the possible effects on human settlement, a broad term meant to encompass (i) housing or shelter, (ii) the surrounding community, neighborhood, village or relevant social unit in which individuals live, (iii) the supporting physical infrastructure (e.g.. water and sanitation services and communication links) and (iv) social services (e.g. health services, education, police protection, recreational services, parks, museums etc.)." Included in the IPCC chapter are climate change effects upon the energy, transport and industrial sectors; human health; air quality, and changes in ultraviolet-B radiation. The studies range from illustrations of the positive effects that climate change may have for ice-free water-way transport and lower costs of material damage due to reduction in winter salt use, to the negative impacts of warmer weather on the wool clothing industry and infrastructure destruction in China due to the melting of permafrost.

The study suggests that populations in developing countries are relatively more vulnerable to climatic effects than developed countries. Possible adverse effects include: drought induced reduction of biomass which accounts for a large proportion of energy supply in developing countries, sea level inundation of low lying areas displacing populations (14% in the case of Egypt), and degradation of agricultural lands. Additionally, increased stress on already overburdened cities is projected as "environmental refuges" are forced to move off of degraded land. Health effects of climatic change were also considered. Risks to human health focused upon increased mortality from heat stress and air pollution, decreased water quality and quantity, and the possible spread of vector borne-diseases. In its discussion of the energy sector, the IPCC refers to the US EPA study (1989) suggesting a demand increase in the US of 14%-23%, however for other countries such as the Federal Republic of Germany demand is projected to decline by 9%.

In the recent EPA (1993) study it is suggested that "global climate change could have mostly negative impacts on developing countries although, in some cases, effects could be positive..... Findings for developing countries overall include, generally reduced crop production, increased hunger, increased rates of death from heat stress in some cities, land loss in coastal areas from sea level rise, particularly in deltas and wetlands, potential increases in floods and water scarcity in some river basins, potential dieback of tropical forests and disruption of ecosystems in nature reserves, with possible increase in extinction of local species." The section on agriculture, for example suggests that an additional 63 to 369 million people in developing countries could go hungry by 2060. Additionally, a warming of 4° may increase death from heat stress in Cairo from 4.5 to 19.3 (per 100,000 people) and in Shanghai from 6.2 to 69.8, while the same change could increase mortality in New York from only 2.7 to 6.5. The study further indicates that the adverse effects of climate change could be partially or completely mitigated but at "significant economic, social, and environmental costs."

Similar to the studies above, EPA's (1989) study of the US suggests possible adverse effects from air pollution, increased morbidity due to heat stress, and possible spread of vector borne diseases. In consideration of infrastructure, the EPA utilized various case studies to investigate economic effects. For example a study of Cleveland, Miami, and New York City by The Urban Institute, estimated a $5.9 million savings in road maintenance and snow removal for Cleveland. The study suggests further that most urban infrastructure will turn over in the next 35 to 50 years, potentially allowing cities to adapt to change at lower costs. In general, northern cities may face increased costs for air conditioning but this may be offset by reductions in heating fuel, snow and ice control and road maintenance. Southern cities will probably show increased costs due to cooling requirements. The study recognized the importance of climate variability as an important factor to be considered however on the basis of mixed GCM model results the "assumption of no change in variability in the scenarios used for this report must be recognized as reasonable, given the current state of knowledge." (EPA, 1989)

Cline (1992) utilizes the EPA's (1989) data on energy to estimate increased energy costs of $11.2 billion annually for the US under benchmark CO2 doubling, partially offset by a $1.3 billion saving in heating costs. Nordhaus uses the same EPA data to reach a cost of $1.63 billion in increased costs for energy demand against a $1.16 savings from heating costs. (A recent study by Rosenthal and Mendelson (forthcoming) indicates that there could actually be a net reduction in US energy demand under climate change). Using a non-agricultural wage average of $17,994 in 1990, a working life span of 45 years and a 1.5% discount rate, Cline estimates a mortality cost of $5.8 billion per year, migration costs are estimated at $0.5 billion per year (based on increased costs of services), $0. 8 billion for increased costs from hurricane damage (based upon a 40%-50% increase in severity of storms as referenced from Emanuel, 1987), $1.7 billion in loss of leisure activities (based upon 60% fewer ski days), $100 million in urban infrastructure costs (extrapolation from EPA, 1989 case studies), and $3.5 billion dollars in increased costs for tropospheric ozone control (due to Clean Air Act enforcement costs). Cline notes that "personal comfort" could conceivably improve from "very mild global warming" up to about 2.5° C, however under very long term warming (for example his estimate of 10°) disamenity could be severe. Cline also sites a study by Mearns et al., (1984) that holding variance of daily temperatures constant an increase of 1.7 C could have a multiplicative effect on the frequency of heat waves (a threefold increase in the study area of Des Moines, Iowa). Cline suggests that if people are willing to pay just 0.25 percent of personal income to avoid such sharp increases in heat waves or other effects of a CO_2 doubling, such disamenity could stand at $10 billion annually.

Mendelsohn (1987) reviewed the literature on three other methods used to assess the value of non-market goods. He highlighted the strengths and weaknesses of using partitioning, hedonic and index models to assess the demand for outdoor recreation. These models have been used to measure the value of a variety of resources and activities, from additional ski areas in California (Cichetti, et al., 1976) to the size of steelhead populations in Washington (Brown and Mendelsohn, 1984). In few cases have these techniques been used to measure the potential impacts of climate change. One example, however, is a study by Englin (1993) which utilized the hedonic property value technique to estimate the amenity value of rainfall. Utilizing property values on the Olympic Peninsula in Washington, where per annum rainfall has a spatial variance of 100 to 16 inches within a distance of 40 miles, his estimated model showed that both annual rainfall and its seasonal distribution affected property values. Less rainfall that was seasonally concentrated was associated with higher property values.

Incidental to a survey designed to consider consumers willingness-to-pay to avoid oil spills, Kemp and Maxwell (1993) asked about household willingness-to-pay to minimize the risk of the greenhouse effect. In their survey, respondents expressed a willingness to pay of \$595±\$182 for all social and environmental programs and allocated \$8.80±\$4.10 to the greenhouse effect. With about 90 million households, this implies a total willingness-to-pay in the United States of about $.8 billion dollars which is less than one-tenth Cline's estimate. Notably, the survey by Kemp and Maxwell did not request that respondents limit their answers to only non-market effects of climate change. Hence, their estimates should be interpreted as willingness-to-pay to avoid both market and non-market effects. The estimates of Nordhaus (1991b) which suggest optimal carbon taxes of \$2 to \$10 dollars per ton of carbon (low and medium damage estimates) based largely on the order of \$2.6 to \$13 billion dollars in the United States given current emissions of 1.3 billion tons of carbon. The actual social cost might be on the order of 1/2 the revenues because inframarginal reductions would be less expensive than the tax rate. The "optimal" cost per household based on estimated market damages would be on the order of \$28 to \$140 per household. And, this optimal tax would avoid very little of the expected total damage due to climate change because it would not stabilize concentrations of gases. While subject to different interpretations, the wording of the Kemp and Maxwell survey suggests that the estimated amount is what households are willing to pay to avoid most of the damage. Thus, households appear willing to pay far less than what would be needed to avoid even estimated market damages. Any number of explanations exist for such a discrepancy:

Consumers may have different expectations regarding market damages, they may see warming as having net beneficial amenity value offsetting market losses, or they may discount damages at a higher rate than that rate used by Nordhaus. More likely, the reliability of damage estimates is so poor and consumers have so little information on what climate change would entail that both approaches provide only highly speculative estimates.

Most impact assessments center upon changes in mean temperature. Several studies (Mearns et al., 1990, Rind, 1989, Katz and Brown, 1992) have focused on the effects of climate change upon extreme events, but little has been done to integrate these extremes into economic analysis. These studies suggest that "assessments that rely on scenarios of future climate involving only changes in mean values or that infer changes in frequency of extreme events from only changes in means (i.e., holding the variability climate constant) are suspect" (Katz and Brown, 1992) and that variability must be addressed.

Some studies suggest amenity benefits from global warming (National Research Council, 1978 as cited in Nordhaus, 1991b). Others indicate that amenity assessments are conjecture and perhaps misplaced. In the words of Thomas Schelling, "a mistake hard to avoid is superimposing a climate change that would occur gradually in the distant future on life as we know it today--today's habitations and transport, today's agriculture and construction and fishing, today's urban complexes, today's working hours and living standards, diet and warmth, indoor and outdoor activity." He goes on to illustrate that climate change is only one of many future uncertainties that we face and that through migration, changes in life style, and new technologies we are not strangers to adaptation. He suggests that in our "calm" assessment of climate change we may be overlooking "things that should alarm us." For example if one is concerned about the welfare of developing countries, the concentration should be on immediate economic contributions to the country's standard of living and economic growth rather than possibly dictating a tax to curb CO_2 emissions (Schelling, 1983).

6.0. AN IMPACT CLASSIFICATION SYSTEM

6.1 "Portraits" of Alternative Conditions of Adaptation and Damage

Across the studies reviewed above, there are widely divergent views on whether climate change will seriously affect society and what society can do about it. Those views stem from more fundamental characteristics about society's interaction with climate. Identifying these fundamental characteristics provides a guide to organizing research to evaluate effects of climate change. Further, different economic sectors, social systems, and natural systems exhibit different combinations of these fundamental characteristics. The distinct combination of characteristics of a system, its portrait, determines the system's vulnerability to climate change, suggests what broad class of adaptive measures would (or would not) be useful, helps identify critical research needed to resolve differences regarding effects, and provides guidance for the development of impact estimates.

In considering climate change damages, seven considerations are repeated in the literature;

1. Is the system naturally flexible, autonomously and quickly adjusting to change?[1]

2. Does the system flexibility require specific action's by individuals or institutions?

3. Do these individuals or institutions currently have the knowledge and capacity needed to undertake these actions?

4. Is the system naturally (autonomously) flexible but only if given time to adjust?

5. Is the system flexible but only over the long run and with specific actions by individuals or institutions that take time and/or involve irreversible capital investment?

6. Do these individuals or institutions currently have the knowledge and capacity to plan for and undertake irreversible investments needed to adapt to climate change?

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[1] The specific time frame of short-run and long-run is dependent on the speed of climate change. The more rapid is climate change, the shorter the period over of time before one might consider adjustment to be slow and costly. Given the expected rates of climate change, adjustment that could occur within 3-5 or even 10 years almost certainly should be considered the short-run whereas adjustment that takes more than 50 years should almost certainly be considered the long-run. For more conventional problems, the short-run is frequently considered one-year or less whereas 10 years would usually be considered the long-run. If climate change is higly nonlinear at the local level where adjustment must occur then for purposes of adjustment climate change should be considered more rapid even though the global average may approximate a smooth, near linear trend.

7. Are there climatic effects on the system that remain after individuals and institutions have taken all feasible adaptations?[2]

As structured, each of these 7 questions can be answered with a simple yes or no.[3] Our shorthand references for these considerations or system characteristics are:

1. Short-Run Autonomous Flexibility; SRAF.
2. Short-Run Non-Autonomous Flexibility; SRNAF.
3. Knowledge/Capacity for Short Run Flexibility; KSR.
4. Long Run Autonomous Flexibility; LRAF.
5. Long-Run Non-Autonomous Flexibility; LRNAF.
6. Knowledge/Capacity for Long Run Flexibility; KLR.
7. Climate Matters; CM.

The specific time frame of short-run and long-run is dependent on the speed of climate change. The more rapid is climate change, the shorter the period over of time before once might consider adjustment to be slow and costly. Given the expected rates of climate change, adjustment that could occur within 3-5 or even 10 years almost certainly should be considered the short-run whereas adjustment that takes more than 50 years should almost certainly be considered the long-run. For more conventional problems, the short-run is frequently considered one-year or less whereas 10 years would usually be considered the long-run.

Underlying the taxonomy developed here is the assumption that each characteristic has 2 basic states, 0 (no) or 1 (yes), which implies $2^7 = 128$ possible combinations. Further, it is assumed that the flexibilities are not additive but are alternatives.[4] Thus, for example, if there is short-run autonomous flexibility (SRAF), human intervention does not increase flexibility further in either the short- or long-run nor does the system become more flexible over time. In such a case, SRNAF, LRAF, and LRNAF are essentially redundant because flexibility has achieved its full value of 1 in the short run without any specific action. It is also possible to rule out a number of the possible outcomes by considering the role of

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[2] A first question is, of course, whether climate has any affect on the system even without adjustment? If not, then none of these seven consideration matter. But, it is a useful precaution not to conclude too quickly that climate does not matter at all because many of our observations may confuse climate not mattering at all with climate not mattering because the system can adjust and has had enough time to do so.

[3] As yes or no questions, these are highly simplified. The flexibility concepts are closely related to economic putty-clay models of capital investment.

[4] It is straightforward to consider adding together the various flexibilities and in some sense scoring the outcomes. With data on degree of flexibility, timing, etc., this would form the approach for numerically estimating effects but for the time being the intent is to develop conceptual portraits to help simplify the modeling problem where there is agreement on some features.

knowledge. To do so we assume the state of knowledge/capability only matters if there exist potentially feasible approaches for increasing flexibility.

Given these different categories and assumptions, only 20 of the 128 possible combinations remain (Table 3). An asterisk (*) denotes a point where the 0/1 flexibility assumption eliminates a set of possible outcomes. The pound sign (#) indicates points where the knowledge assumption eliminates a set of possible outcomes.

Each of these portraits is distinct and each has different implications for system vulnerability, for the class of adaptive measures that would (or would not) be useful, and for the direction for critical research needed to resolve differences regarding effects. Considering the full portrait is important: in some of the portraits where climate fundamentally matters, for example, the policy implication is that society can do nothing to adapt the system and/or that the ability to provide a detailed climate forecast is irrelevant to reducing climate damages. In contrast, in some portraits where climate fundamentally does not matter, the costs of climate change could be high and more research and improved climate forecasts have extremely high returns in reducing potential damages.

Table 3: Sector/System Response Portraits

		SRAF	SRNAF	KSR	LRAF	LRNAF	KLR	CM
I	1	Y	*	#	*	*	#	Y
	2	Y	*	#	*	*	#	N
	3	N	Y	Y	Y	*	#	Y
	4	N	Y	Y	Y	*	#	N
II	5	N	Y	Y	N	*	#	Y
	6	N	Y	Y	N	*	#	N
	7	N	Y	N	Y	*	*	Y
	8	N	Y	N	Y	*	*	N
	9	N	Y	N	N	Y	Y	Y
III	10	N	Y	N	N	Y	Y	N
	11	N	Y	N	N	*	#	Y
	12	N	Y	N	N	*	#	N
	13	N	N	#	Y	*	*	Y
	14	N	N	#	Y	*	*	N
	15	N	N	#	N	Y	Y	Y
IV	16	N	N	#	N	Y	Y	N
	17	N	N	#	N	Y	N	Y
	18	N	N	#	N	Y	N	N
V	19	N	N	#	N	N	#	Y
	20	N	N	#	N	N	#	N

While there are a variety of ways to group the 20 portraits, 5 broad categories have been identified and are discussed in outline form below The numbers in parentheses refer to individual portraits as identified by the numbered rows in table 3.

I. (1,2) **The sector or system responds quickly without conscious human intervention and human intervention is unable to augment the adaptation that already exists.** Neither research on adaptation nor improved climate forecasts have any value. There are no actions one would take in response to an improved forecast and no prospects for discovering new adaptation measures. Knowing the specifics of climate effects is like knowing the date of one's inevitable death. The rate of climate change is not important because the system responds rapidly. There are 2 variants:

A. (1) **Climate matters.** That is, responses of the system are noticeable (e.g., agriculture and natural ecosystems will relocate, people will migrate, etc.). There will be lots of change in systems that humans value; but in valuing the change society may see it as good, as bad, or be indifferent. Regional effects of climate change are highly dependent on the current climate of the region; e.g., if the region is too cool relative to optimal production, then warming will be a benefit, if it is too warm, warming will make it worse. (The presumption would be that tropical developing countries would be worse off while northern areas would be better off.) The basic characteristic, that adjustment is a natural part of the system and is not significant in itself, means that the differential regional effects are themselves not a serious consequence (e.g., agriculture moves and changes in response to demand and technology anyway, people will relocate anyway--climate change considerations may change their destination, but relocation costs would exist in any case). The research question is to evaluate whether the change is desirable, undesirable, or nets out. (E.g., Are there fewer good places left to grow crops or to move to or are there more?) If the overall assessment is that climate change is damaging then the only way to prevent damage is to halt climate change altogether. Cross section evidence on the success of the systems under different climates is directly relevant because adjustment occurs rapidly.

B. (2) **Climate does not matter**. Climate change is not a problem because, recognizing the system's natural adjustment mechanisms, the system is not sensitive to the climate within the projected range. Any cross-section evidence on climate sensitivity is likely incidental correlation. The ability of society to deal with short term variation of weather within a given climate provides a good analogy for how society would respond to climate change. The presumption that society is not that sensitive to climate is bolstered by the observation that temperature varies by 10's of degrees over seasons or that people move across broad climate zones without ill effect.

II. (3,4,5,6) **The system can respond quickly but specific human actions are needed.** These adaptive actions are currently known and as long as society is aware of the changes in climate as they occur and takes action, the rate of change does not matter. Spatially detailed monitoring of climate and conveying this information to those who must take actions to adapt is useful. Such efforts have value whether the ultimate effects of climate change are judged to be beneficial or detrimental. Without such effort opportunities to take advantage of improved climate will be missed, as will opportunities to mitigate losses. Those better prepared fair relatively better. Detailed projections of climate for specific regions are not particularly valuable because the system can respond rapidly once the actual change is observed. Research on adaptation is not needed. Cross-section evidence on climate response can be misleading because it presupposes that decision makers will be aware of climate and take the actions needed.

A. (3,4) **Even if society fails to respond, the system has resiliency**. It will adjust by itself but the slowness of the natural response will mean that society will bear adjustment costs. In this eventuality the rate of change of climate **does** matter and there is an *a priori* bias toward the effects of climate change being detrimental because adjustment costs would be incurred. The value of concerted action is to avoid adjustment costs rather than improve overall response.

1. (3) Climate matters; see I. A. as long as decision makers respond.

2. (4) Climate does not matter; see I.B. as long as decision makers respond.

B. (5,6) **There is no natural resiliency if society fails to respond**. Monitoring climate and organizing for adaptation and education about the potential for climate change has added urgency. The rate of change does not matter because the system either adjusts quickly or does not adjust at all and hence suffers the full effects of climate change. Those who fail to take action will fall ever further behind the better prepared.

1. (5) Climate matters; see I.A.

2. (6) Climate does not matter; see I.B. but this portrait is one that can create considerable regret because failure to act can lead to ever growing losses even though these could be avoided.

III. (7,8,9,10,11,12) **There are things that society can do to create flexibility but society must fund an applied research program to develop these options and/or establish the capacity to react to climate change.** The concept of adapting to climate change is new but once this idea is institutionalized the rate of climate change is not important. This makes it important to buy time early so that this research program has an opportunity to pay off. In a similar vein, recognizing that climate change is a reality before change is evident is important because this provides a period to get adaptation research and capacity-building institutionalized. A concerted program of research on how to adapt is useful as long as one expects climate changes to occur. Any evidence drawn from time series data is biased because it fails to consider the effect research can have on developing new adaptive responses. Yet, cross section evidence may be biased as in II.

A. (7,8,11,12) These portraits are directly parallel to 3,4,5 and 6 respectively after considering III.

B. (9,10) If society fails in its research program, it has well-known options but these take time. Similar to portraits 7 and 8, respectively but long run adjustment does not occur spontaneously and requires specific action.

IV. (13,14,15,16,17,18) **Adjustment is costly; whatever adaptation that is needed will be disruptive.** The more rapid the change in climate, the greater the damage. Slowing climate change will reduce costs in any of the portraits. Neither cross-section nor time series evidence is particularly informative because the fundamentally important aspect of climate change is the rate over time. Cross-section evidence provides no information on the cost of change. Time series evidence does not contain evidence on different climates but only on the response to variability of weather. Response to variability has little or nothing to do with the response to climate. Because the rate of change is critical to determining damages, analyses that examine future costs in an equilibrium climate without considering when the climate change will occur seriously underestimate the full damages. Regional inequities will stem from the uneven projected rate of change (e.g., climate change will affect northern regions more seriously because temperature increases more)

A. (13,14) There is nothing society can do to speed up adjustment or limit the ultimate effects of climate change. As a result, neither research into improved adaptation nor an improved forecast of climate is useful.

1. (13) See I.A. but now the adaptation required by climate change exceeds the natural rate. (E.g., farms relocate at considerable cost as they fail; population migration rates increase.) The economic burdens on individuals harmed by climate change can be alleviated through compensation schemes but someone in society must bear the cost.

2. (14) The fact that climate change does not matter is somewhat irrelevant to estimating damages from climate change because change will require adjustment that is costly; the economic burdens on individuals harmed by climate change can be alleviated through compensation schemes but someone in society must bear the cost.

B. (15,16) Society can take relatively well known actions to limit effects or respond to new opportunities. Further research on adaptations is not useful but better climate forecasts help because these will provide the basis for investing in anticipation of change. Once the inevitable adjustment costs are considered, portraits 15 and 16 are similar to those in II but whether climate matters is best described by IV.A.1. and IV.A.2. The possibility that needed actions will not be taken (or at least not in a timely manner) becomes more likely because they require planning, large scale investment, and anticipation of climate change. The ability of decision makers to detect a trend in climate from the noise of climatic variation and/or have access to improved climate forecasts is important

C. (17,18) Similar in nearly all respects to portraits 15 and 16, the additional consideration is that adaptation research is critical. Successful adaptation depends heavily on the research community delivering in a timely manner both in terms of improved climate forecasts and improved adaptation measures. If these are not forthcoming, the effects of climate change will be more severe.

V. (19, 20) **There is no resiliency in the system and no ability to create it.** Neither improved climate forecasts nor adaptation research has any value.

A. (19) Climate matters: The inability to adjust means that it is not possible to take advantage of even potentially beneficial change thus there is little possibility other than that climate change is a serious problem. This view would reconcile the current ability of societies to prosper in varying climates as only due to the fact that they developed over 100's of years and this development has itself created a structure that cannot be changed unless one virtually rebuilds society from scratch. The only choices are to stop climate change or suffer severe damages.

B. (20) Climate doesn't matter. While society is fragile, the projected amount of change is far too little to be of any concern. The implication here is identical to that of portrait 2 but for different reasons.

6.2 Classification of Expected Impacts of Climate Change

Table 3 provides a framework for considering climate change interactions with specific economic sectors or systems. As an example, a few sectors usually considered as potentially affected by climate change are discussed below.[5]

Crop agriculture. Most see crop agriculture as quite dependent on climate, and most also see a considerable ability to adjust. Most would argue that the specific technologies for adapting already exist in the form of crop variety and farming practices as they exist across climate zones. To the extent there is debate about the agricultural effects of climate change it is centered on the contrasts among portraits 1 and 3. As a result climate change may be either beneficial or detrimental to agriculture. There are likely to be strong regional effects on agriculture if it is heavily dependent on the current conditions in the region and on how climate will change. Will the agricultural sector respond autonomously to climate change or are specific actions required? Support for the autonomous adjustment view comes from, for example, the existence of crop development stations across the United States where crops that succeed are selected and sold to farmers in the region. The specific role of climate in the success of certain crops or varieties need not be known, we need only continue testing a wide variety and selecting those that do best. Further, these

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[5] The sector portraits developed here are in the same vein of "nature myths" developed in anthropology. For a discussion as applied to climate change see Ausubel, et. al. (1992). Ausubel et. al. identify 4 nature myths, where individuals view nature as fragile, robust, resilient, or capricious. For a broader discussion, see, for example, Douglas and Wildavsky (1983). The focus here is on features of social and natural systems that can be evaluated whereas the nature myths describe beliefs of different groups which give rise to different moral imperatives and, thus, difficulty in reaching consensus.

crops are selected and developed over periods of the order of a few years and farmers respond to many changes, expanding acreage, replacing machinery, etc., over quite short periods. Markets reinforce adaptation (profits for success and losses for failure).

The principal argument against this view is that adaptation will be slow and costly. If so, portraits 13, and 15 would characterize agriculture. The major concern in this regard is whether climate change would require opening of new lands and building new infrastructure to support production in these new areas only to be rendered obsolete as climate advances further. To consider this hypothesis, one should consider whether relocation is a likely implication of climate change or whether, existing agricultural areas will remain agricultural areas only with a different mix of crops.

Natural ecosystems: Rainforest The tropical rain forests offer a strong contrast to the agricultural sector. The widely held view is that they are characterized by portrait 19. Climate matters, the rain forests are not very flexible, and cannot be made flexible. Climate changes of the type projected are likely to cause significant loss of rain forest. Given this view, one would consider the amount of loss by considering the current area of rain forest and determine if, under climate change, any of that area would remain within the climate bounds of rain forest. Because the rain forest cannot migrate or be moved, the fact that other areas might become climatologically suitable for rain forest is irrelevant. Better understanding of rain forests is largely irrelevant to saving them and the rate of change does not matter because no adaptation occurs even with time (for practical purposes). The only alternative for reducing damage with this characterization is to reduce the amount of climate change.

The only alternative scenarios are those of portrait 13 or an extreme of portrait 20. Portrait 13 allows that there is some adjustment with enough time (e.g., through natural migration) . Important considerations in evaluating damages are whether the climate shifts gradually (warm, moist areas move slowly across geography as opposed to a sudden movement of precipitation because the storm track changes), whether there are barriers (natural or manmade), and the overall rate of climate change. The extreme of portrait 20 would hold that within a wider range than the climate change anticipated rain forests are largely insensitive as far a society values them. Despite the wide differences among these portraits, there appears to be agreement that human intervention is unable now or in the conceivable future to substantially increase the adaptation potential of rain forests.

Water reservoir and supply systems. The literature suggests characterization of these as row 15. Water manager systems can adapt and there is general knowledge of the steps needed but these adaptations will always involve fairly large investments. Rapid change will render water resource infrastructure obsolete requiring new investments. The rate of change will be important. Regional differences will stem from regional variation in the rate of change. Because climate is important, there are better or worse climates so some regions will deteriorate in terms of water supply while other regions may be better off. Nearly all areas will suffer costs, however, because, whatever the change, adjustments will be required:--i.e., expand reservoirs, build new reservoirs, change transportation systems to meet changing locations of supply, damns for flood control, etc. Because adjustment costs may predominate, the rate of climate change is a major factor in determining costs. Good long-term forecasts of climate change would be valuable in planning water systems.

Recreation and "consumptive" enjoyment of natural systems.[6] Depending on what recreation activities are important and how people enjoy them, one can arrive at very different category assignments and hence it is difficult to generalize. Thus in order to evaluate these activities, a further disaggregation is necessary. There are a number of ways people use natural system amenities. An intensive use of natural systems is an extended vacation that involves significant travel. In such a case individual recreationers have the short run flexibility to determine their destination. In doing so, they can likely overcome significant climate changes. This component of recreation use is likely to be characterized by portrait 1 or 3, the difference being whether existing information sources (ski reports, beach reports) already create autonomous response to changing climate or not. If one must plan the vacation a number of months in advance, the specific act of planning may depend on knowledge of the climatological trend that is not included in daily weather forecasts. In any case, repeated poor experience with a vacation site would lead one to autonomously adjust (i.e. go somewhere else next time).

Recreation activities that involve short day trips. In such a case, the geographic area may be limited such that climate change could lead to migration of systems away from populations that currently enjoy them or may reduce the probability of conditions that favor the recreation activity (more years without natural snow or worse snow conditions for skiing, receding lake levels for swimming or fishing, changing prevalence of animal or plant species in habitat areas). Adjustment in this case, could require moving to areas where these activities were within a day trip. In such a case, portrait 13 would be most applicable. If, however, one views individuals as flexible in enjoying natural systems with different characteristics (e.g. hiking or camping without observing or particularly recalling how animal or plant life may have changed from a previous visit) then portrait 2 might best apply.

7.0 Conclusions

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[6] "Consumptive" enjoyment refers use values (as opposed to non-use values as discussed earlier). Specifically, it includes recreation activities ranging from, for example, watching sunsets to gardening, bird watching, skiing, fishing, hunting, and camping. It is not meant to be limited to activities that "use up" the environmental good--many of the recreation activities have the public good characteristic where one person's consumption does not reduce availability of the good for others. However, the spatial aspects of enjoying these goods means that they are, at a minimum, probably congestible public goods. Non-consumptive uses of the environment includes existence values that may involve ethical considerations about other systems.

The number of studies on impacts of climate change have increased significantly. Many of these studies investigate specific case studies and analogies. The weakest element of broad assessments of climate change have been assessments of impacts. Current international assessments of the impacts of climate change, by far the most prominent being the Intergovernmental Panel on Climate Change, at best describe the damage in economic or physical terms associated with a particular level of climate change. Analysis of agriculture and coastal impacts is most advanced; for these sectors estimates of impacts associated with a doubling of climate change for specific climate scenarios thought to be possible scenarios of increased carbon dioxide have been made. For other sectors, studies are limited to 1) understanding climate sensitivity (arbitrary changes in climate parameters unrelated in a specific way to the magnitude or direction of change that could occur) or 2) studies of specific geographic areas chosen for convenience or because they are suspected of being particularly sensitive to climate change.

These approaches offer severe limitations for evaluating whether aggressive action to limit climate change should be taken. Accepting for the time being that estimates of damages for agriculture and coasts are accurate, the relevant question for climate change policy is how much of the damage would be avoided by a specific limitation on emissions. Policies that stop short of controlling concentrations will only avoid a portion of the damage. For information on other sectors to be relevant for decision making some effort is needed to relate impacts to actually possible or likely scenarios. For case studies to be relevant, effort is needed to define the representativeness of the case. Put another way, one might attempt to define the relevant population that a set of case studies could reasonably represent. There is a tendency for research to be fairly narrow in arguing that the case study applies only to the specific case, but for assessment to use a few case studies as representing a broad population such as the entire world or all developing countries.

The need for a damage function is recognized in the few attempts to model the problem from the perspective of integrated economic analysis. Published efforts employ extremely simplified versions of the physical and climate systems. Damage functions in these analyses are represented as an aggregate global value represented as a function of global average temperature. Not necessarily unreasonable but heroic assumptions have been made to assume that estimates for some sectors of the United States are representative of the share of GNP that might be associated with climate change in other countries and through time. The current value of emissions control is highly dependent on the near-term (next 50 years) of damages yet "fitting" of these functions rely on estimates for damages associated with equilibrium climates changes from present associated with doubling of trace gases since the pre-industrial period. Such climates are unlike to be observed for nearly 100 years or more. Interpolation, when there are 100 years between data points, gives rise to substantial possibility for error.

Theoretical constructions in economics exist that can in principle be applied to evaluate damages and estimate functional relationships of damages to climate variables. Applied work has, however, made extreme simplifications with regard to interactions between climate and economic activity. The principle limitation in improving models of impacts developing reasonable estimates of parameters. Many relationships are merely hypothesized with little evidence on the magnitude or sign.

Impact sectors reviewed herein included 1) Forests and Ecosystems, 2) Agriculture, 3) Coasts, 4) Fisheries, 5) Water Resources and 6) Community and Households. Community and households subsumes a diverse set of impacts. These include direct effects of climate on households and individuals and the indirect effects that result from changes in resource prices and resource-dependent product prices. Ultimately migration decisions depend on a households balancing of all of these effects compared with changes that are occurring at the same time to possible target destinations. A feature of climate interaction with regard to effects on society and the economy is that the relationship between damages and any given climate variable is not monotonic over the range of current geographic climate variation. Thus, it is not possible *a priori* to determine whether a particular climate change is beneficial or damaging without information on the current specific state of the impact site. Aggregate damages depend critically on how the population at risk is distributed with regard to the current climate state. Without such data there is little ability to estimate aggregate damages. As crude as is climate model resolution, global economic models have far coarser resolution. As a result, very ad hoc aggregation assumptions from site specific impacts to regional economic impacts are made. Until this situation is improved, accurate, spatially detailed climate forecasts will do very little to improve decisionmaking with regard to climate change policy because there will be no ability to convert these climate forecasts into economically and socially relevant forecasts.

Based on existing studies of damages and criticisms of them, 7 separate considerations that affect the vulnerability of a sector to climate are identified. These 7 considerations involve whether climate matters or not, whether the system can adjust autonomously or requires specific recognition and human action to adjust, whether adjustment can occur quickly or requires time, and whether the capacity and knowledge to adjust currently exists. Combinations of these considerations give rise to 20 separate portraits of sector response capability. Consideration of how a sector relates to these portraits can provide guidance on possible biases in existing studies, possible approaches for estimating relationships, and the degree to which improved climate forecasts can improve adjustment.

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