ADAPTING

TO

CLIMATE CHANGE

Indur M. Goklany*

* The author is also Manager, Science & Engineering, Office of Policy Analysis, Department of the Interior. The views expressed in this paper are his alone and are not intended to reflect those of the U.S. Department of the Interior or the U.S. Government.

NOTE TO THE READER

The following paper, originally titled, *Adaptation and Climate Change*, was presented at the American Association for the Advancement of Science's Annual Meeting in Chicago, February 6-11, 1992. Changes and comments necessitated to the original paper because of new information in IPCC's 1995 Assessment are noted in italics within stylized parentheses, i.e., *{ }*. An Epilogue has been appended at the end of the paper which briefly summarizes whether, and how, the arguments and conclusions of the original paper ought to be modified in light of the new information. In addition, minor editing was undertaken to reduce the bulk of the original.

May 7, 1997

ABSTRACT

This paper deals with the often ignored issue of adaptation to human-induced climate change. Adaptation is not only inevitable but essential to fashioning the least-social-cost strategy to addressing climate change. The urgency for limiting climate change is inversely proportional to society's adaptability. Some mitigation strategies are incompatible with adaptation goals (e.g., reducing CO_2 rather than equivalent amounts of other greenhouse gases may compromise several adaptation goals) and climate change impacts -- and, therefore, benefits -- analysis must necessarily incorporate adaptation.

The paper provides criteria for evaluating policy options, and identifies options compatible with both mitigation and adaptation that would also help address current urgent problems.

INTRODUCTION

Most of the focus on policies dealing with human-induced climate change has been on curtailing the emissions of greenhouse gases. This paper, however, will focus on that stepchild of the policy debate on climate change: adaptation.

A fundamental principle of public policy is that we should deal with those problems first that are the most important and which can be reduced, if not eliminated, at the least net overall cost to society. Thus, it is necessary to establish the relative importance of climate change to mankind. To accomplish this, the paper will first address the following series of questions:

- Why is climate change important?
- What are the magnitudes and directions of the impacts of human-induced climate change on human and natural systems? How certain is our knowledge with respect to these impacts?
- How important is climate change compared to other agents of future global change (with respect to those systems which are sensitive to climate change)?

In addressing these questions, the paper notes that no assessments of the impacts of climate change are credible unless they consider those adaptations that would necessarily take place given, at the minimum, the current legal and institutional framework, and technological progress. It then addresses why good public policy demands consideration of adaptation options. The paper discusses the ability of human and natural systems to adapt to future changes. It identifies which options to limit climate change may, and which may not, be compatible with the goals of adapting to future global change. Next, it presents a set of generally applicable criteria for selecting specific options. It then lists options that will help society deal with climate change given:

- Its relative importance as an agent of change.
- The uncertainties in our scientific, technical and economic knowledge.
- That societies everywhere have a large -- and, seemingly, endless -- backlog of unmet but highly desirable needs.

Before a final discussion and summary of conclusions, the paper recommends broad strategies that would help societies cope with climate change without compromising their ability to deal with the other urgent problems facing them.

WHY IS CLIMATE CHANGE IMPORTANT?

Climate determines the abundance and distribution of natural resources upon which virtually all life depends. It determines where, when and how much water is available. Water, in conjunction with other climatic factors, affects health, abundance and distribution of crops and other plants which sustain all higher life forms (including fish, wildlife and human beings). Climate is key to our food security, and availability and access to forest and forest products. Through its effects on natural resources, it affects the well-being of all living things. Figure 1 is a simplified schematic diagram showing the interconnections between climate, natural resources and socio-economic conditions. If climate change were not to have any significant physical, biological or socio-economic impacts, it would be nothing more than a scientific curiosity, unworthy of being elevated to a public policy issue. Thus, whether or not the climate changes is not as important as what its effects are. Therefore, establishing that climate will change is a necessary, but not a sufficient, condition for policy changes which could have significant socio-economic impacts. A sufficient condition would be that the socio-economic (including environmental) consequences of action would be, on the net, more beneficial than inaction, and that the costs of action would be the best and highest use of society's resources.

In summary, climate is important only because of its effects on natural resources (e.g., water, land, plants, forests, habitats and other biological resources) and on human activities, such as agriculture, forestry, human settlements and recreation, which depend upon these natural resources. In the following, the term "natural resources" incorporates both the resource themselves as well as the activities that depend upon them.

IMPACTS OF HUMAN-INDUCED CLIMATE CHANGE

There is indeed a greenhouse effect. Naturally-occurring greenhouse gases warm the earth by about 33^{o} C. Without such warming, the earth would be much less hospitable to human beings and many other species.

Greenhouse gas concentrations have increased measurably since pre-industrial times. Continued increases will change the climate but, except for a few aspects (in particular, globally averaged temperature and precipitation), in ways that cannot, by and large, be currently estimated.

One aspect of which we are relatively certain is that globally-averaged mean temperature would, if anything, increase. Temperatures would increase more toward the poles than toward the equator; more in winter than in summer; and more at night, than in the day. However, the rates and magnitude of surface temperature increase are uncertain. Using the best available general circulation models (GCMs) which, nevertheless, have several shortcomings and significant uncertainties associated with them, the Intergovernmental Panel on Climate Change's Scientific Assessment (1990) estimated that the global mean surface temperature would increase about 1^{o} C. by 2025 and 3.3^{o} C. by 2100 (relative to today's "means"). Corresponding sea level increases were estimated to be about 18 cm. ($\pm$ 9cm.) for 2025, and between 30 cm. and 110 cm. (with a best estimate of 66 cm.) by 2100.

{*The IPCC (1996: 41) lowered the "best estimate" for 2100 to 2.4^{o}C for temperature change. The corresponding sea level rise was estimated to be between 13 cm and 94 cm, with a "best estimate" of 49 cm.*}

IPCC's IMPACT ASSESSMENT

Based on impact analyses that were available as of approximately early 1990, the Intergovernmental Panel on Climate Change noted that many impacts will be positive, while others will be negative. However, it is not yet possible to know whether the net impact will be in one direction or another. Nevertheless, some general features emerge from the IPCC Impacts Assessment (1990):

-- Both **water supply and demand** will be affected by climate change. Water is critical not only because it is a resource that is consumed directly by human beings but also because its availability (or lack of it) determines the productivity of crops, forests and other ecosystems, and their health, abundance and distribution. However, it is not possible to predict with confidence whether water supply would increase or decrease in a particular area (IPCC Impacts Assessment, 1990, p. 3).

-- It is unlikely that **global food security** will be harder to attain were climate to change (IPCC Impacts Assessment, 1990, p. 2) even though there may be some regional dislocations in agricultural production. Climate change per se will alter the productive potential of each area: however, whether production potential would be increased or decreased in particular areas can not now, in general, be foretold. Warmer temperatures would tend to increase productivity in currently cold areas. In the mid-latitude interiors of continents, lower soil moisture would tend to reduce productivity.

{The direct effects of carbon dioxide may help boost production of many crops, e.g., rice and wheat (IPCC, 1996a: 33). The geographical ranges of various insects, weeds and diseases may also vary and unless adaptation measures are taken, could reduce production.}

-- **Sea level rise** would have a net negative impact. A Dutch study for the IPCC indicates that protecting the world's coastlines against a 1-meter sea level rise (close to the upper limit according to the IPCC's estimate for 2100) would cost $500 billion (IPCC Response Strategies, 1990, pp. 152-153). This is the cumulative, undiscounted cost over the 110-year period, and is estimated to be about 0.04% of cumulative world GDP. Such an expenditure would help protect human settlements and associated infrastructure, but not necessarily preserve environmental values associated with the coasts.

-- **Forests** and **natural ecosystems** would be affected in ways we cannot now forecast. Increases in greenhouse gas concentrations and associated climate change would cause such ecosystems, which are constantly evolving, to evolve along a different path. It is unlikely that whole ecosystems would be translocated. Instead, each species would react differently, forming new assemblies and relationships. Changes in gas concentrations and climate would affect each species directly, and indirectly by modifying its competitive advantage relative to other species. The magnitude of impact will depend upon the rate of change in greenhouse gas concentrations and in critical climatic factors. Some fear too rapid a change could cause species die-back and/or species extinctions. On the other hand, other species may thrive. Productivity in the higher latitudes could increase; however, the net effect on global primary productivity is unknown (IPCC Scientific Assessment, 1990).

{-- ***Human health** could be affected either directly, because of increases in heat-stress (offset, at least partly, by reduced cold-stress), or indirectly, as the geographic ranges of vector-borne diseases (e.g., malaria, dengue, yellow fever and several forms of encephalitis) expand (IPCC, 1996a: 39*).}

As the discussion (below) on uncertainties indicates, there are good reasons to believe that the older analyses which form the basis of the IPCC impacts assessment overestimated the negative, and underestimated the positive, impacts of climate change through the next century.

RELATIONSHIP BETWEEN ECONOMIC RESOURCES AND VULNERABILITY TO CLIMATE CHANGE

Both the IPCC Response Strategies and Impact Assessment Reports note that developing countries are perhaps more vulnerable to climate change. This vulnerability is, however, due to their financial (and other) resource limitations which could preclude costly and elaborate adaptations -- and not because climate change is inherently expected to be greater in those nations. In fact, to the extent that temperature change is an indicator of changes in other critical climatic factors, it is expected that change will be least at the lower latitudes where most of the developing countries are located.

UNCERTAINTIES IN THE IPCC'S IMPACT ASSESSMENT

The IPCC 1990 Impacts Assessment (1990) notes that little confidence can be attached to current assessments of the impacts of changes in atmospheric concentrations of greenhouse gases and associated climate change. The following discusses the reasons for this lack of confidence. Where possible, the discussion also notes whether addressing specific uncertainties or omissions in the analytic approach would bias impacts assessments in one, or the other, direction.

Assumption of Equal Warming During the Day and Night.

Past impacts assessments have assumed equal increases in day and night temperatures. Analyses of past temperature trends for the U.S., U.S.S.R., China and Southeastern Australia which cover about 25% of the earth's land area, however, indicates that most of the measured increase has been during the night (IPCC Scientific Assessment, 1990; Karl et al., 1991 and 1992). This is consistent with theoretical expectations (IPCC Scientific Assessment, 1990, p. 153). This has significant implications for past assessments, because warmer nights mean that warming would preferentially increase minimum temperatures more than raise maximum temperatures. Hence, past assessments have probably overestimated evapotranspiration, days above, say, 90 degrees F., and days below freezing, and underestimated soil moisture. Higher night temperature would also mean longer growing seasons and higher survival rates of certain pathogens. The net result would be that the productivity of agricultural, forest and many natural ecosystems have likely been underestimated with both the negative impacts being overestimated and the positive impacts being underestimated.

IPCC's Impact Assessment Reliance on Analyses that Pre-dated its Projections.

The IPCC's 1990 Impact Assessment was based upon analyses that pre-dated its Science Assessment's calculations of "best estimates" for changes in globally averaged temperatures and sea level rise. These results were not re-calculated or adjusted per the IPCC's "best estimates". However, many of the analyses had used scenarios which assumed more rapid climate change and sea level rise. Because of this, there is an upward bias, in the IPCC's estimates of the impacts of climate change.

{To some extent this criticism is still valid. For instance, much of the sea level rise impacts in the 1995 Assessment were estimated for a 1m. rise. Similarly, one of the major global food impacts studies (Rosenzweig and Parry, 1994) used in this document relied upon older GCM runs from the 1980s, which project temperature changes between 4.0 and 5.2^{o} C, at the upper end of the IPCC projections.}

A substantial portion of the agriculture chapter was based on the EPA (1989) study of the potential impacts of climate change on the United States, and the International Institute for Applied Systems Analysis (IIASA) studies (Parry et al., 1988). The EPA study assumed that "normal" CO_2 was in the 300 to 326 ppm range (corresponding to measured levels for the 1950's and 1960's), and that climate change corresponding to equivalent doubling would generally occur by 2060. The three GCMs it used to calculate equilibrium temperatures estimated the globally averaged temperature increase corresponding to equivalent doubling (i.e., by 2060) to be 2.8, 4.0 and 4.2 degrees C. (EPA, 1989; p.63). Clearly, these translate to rates of increase significantly greater than IPCC's "best estimates" of 1^{o} C. by 2025 and 3.3^{o} C. by 2100.

The IIASA studies used a similar approach based upon the Goddard Institute of Space Studies (GISS) general circulation model (GCM) which estimated that the equilibrium globally averaged temperature would rise 4.2^{o} C. relative to a 1951 to 1980 baseline.

With respect to sea level rise, the IPCC Impact Assessment was based upon rises of the order of 1 to 2 m. By comparison, the IPCC "best estimate" was 0.65 m. by 2100 with lower and upper bounds of 0.3 and 1.1 m., respectively.

Omissions/Assumptions Resulting in Systematic Errors in the Rate of Climate Change.

The IPCC's "best estimates" did not consider the potential cooling effect of sulfates in the atmosphere (IPCC Scientific Assessment, 1990). It also did not factor into its estimates, the net cooling effects, over decades, of cumulative small and large volcanic eruptions. While they may be hard to model, they will no doubt occur, as evidenced by the number of volcanic eruptions over the past 110 years (which include a few major volcanic eruptions, e.g., Krakatoa, El Chichon, and Pinatubo, and many more minor ones). Even though an individual volcano's effect may not persist over a long period, the cumulative effect of several volcanic eruptions over the next 110 years (till 2100) could have a substantial influence on the rate of warming due to greenhouse gases.

Based on the best information available to it at the time, the IPCC had also significantly overestimated the net global warming due to CFCs. However, new findings (WMO, 1991) indicate that these past estimates for CFCs were probably too high. It seems that, in fact, a cooling due to the ozone depletion caused by CFCs could substantially cancel out any warming directly due to CFCs.

Counterbalancing some of the bias that would lead to lower estimates of climate change is the lack of consideration for tropospheric ozone levels.

{The IPCC (1996) Science Assessment corrected for the above oversights or simplifications, except for volcanic activity. This ought to be doable: the assumptions that would need to be made regarding probability distributions of frequencies, magnitudes and chemical composition of eruptions over the next century would be no less heroic than several other assumptions made in the impacts assessment.}

Finally, new information on methane indicates that while its annual rate of increase in the atmosphere has declined by about a third, its global warming potential may have been underestimated (Science Times, 1991). Because of these countervailing factors, the net direction of change (due to methane only) in the IPCC estimate is not clear.

{*The IPCC (1996: 22) Science Assessment attempted to correct for this, and other recent findings. However the recalculated global warming potential of methane was not significantly changed for the 20, 100 or 500 year time horizons*.}

In summary, new information combined with non-consideration of sulfates and volcanic activities would indicate that IPCC's earlier "best estimates" somewhat overestimate the rates of climate change and sea level rise.

{*And, in fact, the “best estimates” for global temperature and sea level rise by 2100 were lower in the 1995 Assessment. The former declined from 3.3^{o}C to 2.4^{o}C, and the latter from 66 cm. to 49 cm.*}

Projections of Future Socio-economic Activities.

We lack credible projections of the type and level of economic activities in the energy, agriculture, forestry and other sectors which would determine future emissions of greenhouse gases. Projections beyond 15 to 20 years are, at best, conjecture. Just as no one could have forecasted today's world a 100 (or even 50) years ago, it is equally unlikely that anyone will be able to forecast the world 50 to 100 years from now.

Among the reasons for some of the better known failures to forecast the future (e.g., Meadows et al., 1972 -- the Club of Rome Report; Global 2000, 1980) were the lack of appreciation for technological progress and human adaptability. See, e.g., Cole and Curnow (1973), Pavitt (1973) and Ausubel (1989). Cole and Curnow (1973) showed that incorporating a 2% per year improvement in natural resource productivity would indefinitely postpone the collapses projected by the Club of Rome Report.

The pitfalls of economic projections can be appreciated by evaluating, for example, the performance of the Global 2000 Project. It projected in 1978 that the U.S.'s energy consumption in 1985 (i.e., a mere 7 years time) would be between 90 and 102 quads. In actual fact it was 74 quads -- only slightly less than the 1976 level (Energy Information Administration, 1991). Its track record with respect to other commodities (iron and steel, copper, aluminum, etc.) was not much better. Some improvements in forecasts may be possible by explicit consideration of technological change and adaptation (see below); however, there are simply too many variables to even capture their full dimensions, let alone all the other variables that would determine future economic activity.

Waggoner and Schefter (1989) and Osborn et al. (1986) compared a number of forecasts of water use by the Senate Select Committee on National Water Resources and the U.S. Water Resources Council with what transpired in reality. The forecasts, which were for periods extending seven, twelve and twenty years into the future, usually missed the mark (defined by the investigators as being within twenty percent of the actual use). Often, when they did not, it was due to a cancellation of errors. Clearly, even the most august of groups are not immune from error.

It may be argued, in cases where cancellation of errors leads to an apparently "accurate" forecast, that as long as the overall forecast is accurate, getting the details wrong may not be all that consequential. This may well be the case for some activities, but for the issue of climate change, the details are critical. In fact, it is details that will determine whether impacts are positive or negative: details such as whether CO_2 would contribute 50% or 75% of the warming; whether there would be more warming during the day or night, in the higher or lower latitudes, in winter or in summer; whether there would be more or less precipitation in the growing season, in one area or another; whether a certain degree of warming would occur by 2050 or 2100; etc.

Inadequate Consideration of All the Climatic Factors Affecting Natural Resources.

Further complicating our ability to estimate the impacts of climate change, is that while much of the public policy debate on climate change has focused on temperature and global mean sea level rise, other climatic parameters are just as, if not more, critical to the health, abundance, distribution and well-being of human beings and other species. Water and its availability (measured in terms of both soil moisture and water available for irrigation) is probably more important for determining crop productivity and food security. Water is also critical for all other vegetation, habitats and life-forms that depend directly or indirectly upon vegetation for sustenance. Equally important are the climatic variability (on annual, seasonal and diurnal scales) and how that may change in the future; the predictability of climate; changes in the frequency and magnitude of extreme events (droughts and floods); cloud cover; and radiation at the earth's surface. A more detailed listing of these critical climatic factors is provided by McKenney and Rosenberg (1991).

With respect to these other critical climatic factors, as noted above, the seasonal and diurnal variability of temperature is expected to decline. The IPCC's Scientific Assessment (1990) notes that there is no reason to believe that the magnitude and frequencies of storms will vary. Notably, we cannot be confident of even the **direction** of change of many of these critical climatic factors at the regional level. Because of these uncertainties alone, one cannot state with confidence whether the net impact of change on any particular natural resource will be positive or negative.

Unavailability of Credible Estimates of Regional Climate Change.

The uncertainties regarding the rate and magnitude of surface temperature increases are magnified progressively as the geographical area of interest is reduced in scale to continents, regions, watersheds and river-basins. Thus, as both the IPCC Scientific Assessment (1990) and the Impacts Assessment (1990) note, there is little confidence in estimates of regional climate change. However, to estimate the impact of climate change on society and the environment, impact analysis must necessarily be first done at these smaller watershed and river-basin scales -- then they may be aggregated to higher levels. [In fact, to do impact analysis at these small scales would require obtaining predictions of critical climatic factors at an even finer scale.]

The inability to produce credible regional estimates of changes in critical climatic factors is independent of the ability to accurately forecast future emissions rates of sources and sinks.

<u>Inadequate Consideration of Direct Effects of Greenhouse Gases</u>.

Because any human-induced climate change will be a consequence of changes in the atmospheric concentrations of carbon dioxide (CO_2), chlorofluorocarbons (CFCs), halons, methane (CH_4) and other radiatively-active gases, the non-climate impacts of these gases must necessarily also be considered in estimating impacts of such climate change and in developing and analyzing policies. In particular, the **direct effects** of CO_2 and CFCs must be considered. For CO_2, these direct effects on vegetation (including crops) include stimulation of photosynthesis, increased plant water use efficiency and improved plant tolerance to drought, salinity and air pollution.

Because of the decade(s)-long time-lag between the build-up of atmospheric concentrations and associated climate change, the benefits of the direct effects of CO_2 would be manifested that much in advance of any effects, positive or negative, of any associated climate change.

Many of the agricultural studies the IPCC Impacts Assessment relied upon did not consider the direct effects of CO_2, e.g., the IIASA studies (Parry et al., 1988). Some that did, e.g., EPA (1989), assumed a more rapid rate of climate change than the IPCC "best estimate" -- as noted above. Moreover, it underestimated the CO_2 atmospheric concentration at the time the temperature increased by an amount equal to the temperature rise due to an equivalent doubling of CO_2 (see footnote 1, below).

{*Many of the agricultural studies that the 1995 Assessment drew upon included some of the direct effects of* CO_2*. IPCC (1996a: 33) suggests that under doubled* CO_2 *conditions, production of C3 crops, e.g., wheat and rice, may change from -10 to +80% only due to direct* CO_2 *effects, with a mean response of +30%. However, a close reading of one of the major global food and agricultural studies relied upon by the Assessment (Rosenzweig and Parry, 1994) suggests that the general criticisms in footnote 1 are still valid.*}

Analyses of impacts on forests and other terrestrial ecosystems had generally not included any direct CO_2 effects because, it was argued, while crops might gain from CO_2 fertilization, this phenomenon may only be of short term benefit for trees and natural vegetation due, possibly, to acclimation of carbon metabolism (Cure and Acock, 1986; Delucia et al., 1985: Tissue and Oechel, 1987). There is now more evidence that CO_2 fertilization can occur for trees and natural vegetation. First, some studies of photosynthetic response to elevated CO_2 show either an increase or no reduction in photosynthetic capacity (Arp and Drake, 1991; Ziska, et al., 1991; Drake and Leadley, 1991 and references there-in.) Data for cotton and soybeans suggest that canopy photosynthesis increases in elevated CO_2 if a carbon sink is available, and the relative effect of CO_2 is greatest at higher temperatures. Data collected over 4 growing seasons on 2 monospecific stands one dominated by a C3 sedge and the other by a C4 grass (in a salt marsh on the Chesapeake Bay) exposed to twice-normal CO_2 concentrations showed increased carbon accumulation of 88% and 40%, respectively. Drake and Leadley note that there is no evidence in that data that elevated CO_2 would result in downward regulation of photosynthesis, i.e., the data indicate elevated carbon dioxide should continue to increase carbon accumulation. Similarly, sour orange trees exposed to a less-than-doubling of CO_2 concentrations (a 300 ppm increase above ambient) for over 3 years under conditions of no moisture or nutrient stress, increased their above-ground carbon 2.8 times and below-ground carbon 2.5 times compared with trees exposed to ambient conditions (Idso and Kimball, 1991 and 1991a). Studies undertaken at Barro Colorado Island, Panama, over a three month period, also indicate that tropical species could be responsive to CO_2 fertilization (Ziska et al., 1991). Second, CO2 fertilization could explain the "missing" terrestrial sink suggested by Tans et al. (1990). Third, CO_2 fertilization is also indicated by the increasing amplitude of the seasonal swings in atmospheric CO_2 concentrations (Idso, 1991).

{Whether higher CO_2 *levels will increase photosynthesis in forest species significantly is still unsettled.}*

While the direct effects of carbon dioxide may be beneficial, CFCs -- by depleting the ozone layer and allowing more ultraviolet-b to reach the earth's surface -- can only have negative impacts. However, assessments of the impacts of increasing greenhouse gases rarely, if ever, account for these direct effects.

Incorporating direct CO_2 effects into impacts analyses to one degree or another will result in significant changes in the magnitude and, where impacts are otherwise negative, possibly even in the direction of impacts. In an analysis of wheat and corn yields in the Great Plains under potential climatic change, Rosenzweig (1989), which was one of the agricultural studies upon which the EPA (1989) impacts study was based, calculated that "[t]he direct effects of CO_2 ... compensate for or even ameliorate, the climate change impacts in many locations, but not in all".[1] Similarly, an analysis of crop yields in Missouri, Iowa, Nebraska and Kansas (MINK) (Easterling, et al., 1990) showed that the direct effects (DE) of increasing carbon dioxide concentrations from 350 ppm to 450 ppm could partially, if not totally, offset yield losses that might result by replacing today's climate with one that was similar to that of the great 1930's drought (referred to as the "analog climate")[2].

{As noted, under doubled CO_2 conditions, production of C3 crops, e.g., wheat and rice, may change from -10 to +80% due to direct CO_2 effects, with a mean response of +30%.}

In addition to accelerating the rate of photosynthesis, increased carbon dioxide also reduces water demand by crops and other vegetation. Methodological tools to calculate the magnitude of such effects are being developed only now. In their analysis, Easterling et al. calculated that the 100 ppm. increase in carbon dioxide would reduce irrigation requirements by about 10%.

Moreover, the effect of carbon dioxide on improving crops' water use efficiency would make more water available for all other water uses (including in-stream uses such as fish, wildlife, hydro-electric power generation, and recreation) because in the U.S., for instance, about 81% of surface water consumption is for irrigation (Foxworthy and Moody, 1985). Thus, even a small improvement in water use efficiency would have a significant benefit for other water users.

{*The water resources impacts chapter in the 1995 Assessment was based upon studies which ignored this factor (IPCC, 1996a: 479).*}

Uncertainties in Modelling Socio-economic Impacts.

Translating biological/physical effects into socioeconomic impacts is in its infancy. Because of the absence of such analyses, it is generally assumed that biological and physical impacts are a good surrogate for socio-economic impacts. In fact, the two are not equivalent. For example, food security is not identical to crop production. Yet, so far, few assessments of the impacts of climate change have made this distinction. [The difference between the two concepts is very well articulated in the IPCC's Resource Use and Management Subgroup (RUMS) Report (1990).] Among the reasons why the two should not be equated is that non-consideration of socio-economic impacts precludes full consideration of the ability of society to adapt and substitute resources, products and uses.

Neglecting Consideration of Adaptation.

---

[1]The analysis used the outputs of two GCMs -- the Goddard Institute of Space Studies (GISS) and the Geophysical Fluid Dynamics Laboratory (GFDL) -- for an equivalent doubling of CO_2 concentrations. These models estimated that at equilibrium, the globally averaged temperature would rise 4.2 and 4.0 degrees C., respectively, above the 1951 to 1980 baseline. The direct effects (DE) were modeled assuming concentrations of CO_2 increased from 330 ppm to 660 ppm. This study assumed that by the time the climate was identical to that under equilibrium with equivalent CO_2 doubling, the actual CO_2 concentration would also double. This was assumed to occur in 2060. By comparison, the IPCC "best estimate" was that there would be a 3.3 degree C. rise by 2100, by which time the CO_2 concentration would be about 850 ppm. *{Perhaps the last number would be closer to 700 ppm (IPCC, 1996: 23.)}*

[2]The MINK study is not necessarily consistent with the IPCC Scientific Assessment's projections. That indicates that by 2025 the atmospheric CO_2 concentration may be about 450 ppm. and the average global temperature may be 1^{o}C. higher than today's; and by 2100, the corresponding figures may be 850 ppm. and 3.3^{o}C. *{See comment on footnote 1}.*

Past impacts assessments have generally employed the usual, but invalid, assumption of a static world, i.e., the assumption that there is no technological innovation or adaptation that will take place over the 50-100 year (+) time frames that are selected for analysis to illustrate "impacts". This is particularly important for highly managed sectors and activities such as agriculture, forestry, public health and water resources where there is a long and successful history of technical and management innovation. This means that it would be incorrect to assume that the future situation in the absence of climate change would be similar to present day conditions. Moreover, farmers and water resource managers are constantly upgrading their expectations of the weather, climate and frequency and magnitude of extreme events based upon prior experience i.e., upon recent climate change. It should be expected that they would automatically adapt their management to steady changes in the climate. Thus, adaptation should be built-in both for the future "baseline" (i.e., non-climate-change) situation as well as the post climate change condition. The two sets of adaptations are not identical.

{The principle that "automatic" adaptations should be factored in prior to estimating climate change impacts has since been accepted, and is enshrined, in the IPCC's methodological guidelines for assessing impacts (IPCC, 1994; see also Frederick, 1994; Frederick, Goklany and Rosenberg, 1994). Some efforts have been made to include adaptations into agricultural impact studies but these efforts are incomplete (IPCC, 1996a: 33 and Box 13-1; Rosenzweig and Parry, 1994; Easterling et al. 1990). For other sectors, this principle is more honored in its breach. For instance, the water resources chapter of the 1995 Assessment is based upon studies that ignore adaptations (IPCC, 1996a: 474), and the estimate of increased potential for vector-borne disease (IPCC, 1996a: 11-12) is, by itself, not particularly useful in estimating probable impacts on death and disease since it is silent on adaptations and advances in medicine. Over long time spans, society can and has reduced major scourges to insignificance; consider, for instance, smallpox, polio, or water-related diseases in developed countries (Goklany, 1996). If we address malaria, dengue, etc., today, by 2100 they could well be mere footnotes to history. }

Ignoring adaptation possibilities will invariably lead to both overestimating the negative, and underestimating the positive, impacts of change, regardless of the agent of change. Another consequence of such a methodological oversight is that there would be virtually no difference in the impacts of a given "amount" of climate change whether it occurred as a sudden step function, as a gradual ramp function or even as an exponential function. This is counterintuitive. In fact one of the few items that most participants in the climate change debate agree upon is that the rate of climate change would determine the magnitude of the impacts (see, e.g., IPCC Impact Assessment, 1990). In spite of this unusual harmony, it is curious that the vast majority of existing current impact assessments methods are unable to produce this fundamental result.

The IIASA agricultural studies (Parry et al., 1988) considered farm level adjustments "that could be in place now". While this is a good start, that would not allow consideration of the full range of economically available options that would exist in, say, 2050 or 2100 due to technical change. For that reason, the results of those studies too would be sensitive to the magnitude -- but not the rate -- of climate change. Nevertheless, even those studies indicate that judicious switching to available cropping and management practices under a doubled-CO_2 climate would substantially increase crop yields above baseline in the Northern U.S.S.R., Japan, Finland and Iceland.

The previously quoted analysis of Easterling et al. (1990) attempted to capture the effects of technological change and adaptation in their analysis of climate change. Average yields in 2030 assuming the current climate and technological change, i.e., the "control case", increased 70-90% over the 40 year period compared to the use of both current climate and technology ("baseline"). [To check the plausibility of changes of such magnitudes, consider the experience of the previous 40 years during which time corn, wheat, soybeans and sorghum yields per acre increased 220%, 107%, 60% and 275%, respectively.[3]] Then using a climate analogous to that of the Great Drought and

[3]These figures are derived by comparing yields from 1984-88 (which included the 1988 drought year) with 1944-48. (U.S. Department of Commerce, 1975 and 1990).

incorporating direct effects of CO_2 at 450 ppm and technical changes,[4] they estimated yields would increase 18-23% above the control case for dryland wheat and alfalfa, and irrigated sorghum and wheat; about 10% for dryland sorghum and wheat; stay virtually unchanged for dryland soybean; and decrease 7% for dryland corn.

Interestingly the changes in yields due to the analog climate relative to the current climate were substantially smaller than the changes between 2030 and today due to technical change under the current climate. This would tend to confirm the arguments made below that, over the next century, relative to population and economic growth and technological progress, the effects of climate change alone -- or in conjunction with direct CO_2 effects -- may only be a small perturbation.

{Rosenzweig and Parry's (1994) global food impacts study indicates that in 2060, global cereal production would change by -11 to -20% due to climate change alone, relative to the non-climate change base for that year. (These could be overestimates because of the GCM results they employed.) With inclusion of direct CO_2 effects, the change could be -1 to -8%, also relative to that base. (However, see footnote 1, which suggests that the improvements could be underestimated.) Finally, with adaptations, the change would be from +1 to -2.5%. IPCC (1996a: 452) reports that more recent studies indicate a "far greater potential" for adaptation. Note that while global aggregate food supplies may be relatively unaffected, most studies indicate that developing countries would have larger food deficits under climate change. Thus, trade and economic growth are important, if not critical, for assuring food and nutrition security in developing countries (Goklany, 1995 and 1997)}

Finally, as noted in subsequent sections, the adaptability of systems will likely increase with time, barring any major changes in the legal and institutional framework that may discourage innovation.

WHAT ARE THE OTHER AGENTS OF GLOBAL CHANGE INFLUENCING NATURAL RESOURCES IN THE FUTURE?

The Intergovernmental Panel on Climate Change's (IPCC's) Scientific Assessment (1990) indicates that, relative to today's means, human-induced climatic change may increase globally-averaged mean temperatures by 1^{o}C. by 2025 and 3^{o}C. by 2100. However, over these time frames, climate change, whether human-induced or because of natural variability, is only one of several agents of global change determining future natural resource use and management. Other agents which may play an even more significant role include: population and economic growth, and technological progress.

Population growth will inevitably increase the pressures and demands on resources of all kinds. Over the next century, the world's population is expected to increase from the current 5.4 billion to between 11 and 15 billion. If all else stays equal, i.e., technology and its penetration as well as the average living standard were frozen, such an increase would increase pressures on natural resources two- to three-fold.

Economic growth can stimulate demand even as it makes resource and environmental protection more affordable. If the world population doubles by 2050, and the per capita economic growth increases at 2% per year until then -- all else being equal, i.e., technology and market penetration of different technologies were to remain frozen -- the demand on any natural resource would be about 650% of today's, i.e., it would increase by over five-fold.[5] [Alternatively, assuming that the per capita demand

---

[4]Adjustments incorporated into the analysis were: earlier planting in combination with longer season varieties for wheat and shorter season varieties for perennials, furrow diking for warm season crops, drought-resistant crops, and improved irrigation efficiency.

[5]World per capita GDP increased from $1,601 to $3,000 (in 1980 dollars) between 1960 and 1990 (United Nations Department of International Economics and Social Affairs, 1991). This translates into an annual growth rate of 2.1%. The 2.0% of growth rate assumed here is just shy of this historical 30-year average.

for natural resources increased at half the per capita economic growth rate, total natural resource demand would increase by over 250% over sixty years.]

However, slowing economic growth can not be a solution. Poverty -- a result of insufficient economic growth -- has been identified as one of the major causes of environmental degradation. Poverty has condemned hundreds of millions of people world-wide to malnutrition -- if not outright starvation -- and leads to inadequate clothing, shelter, sanitation, potable water and basic health care. In a recent report, the UN Department of International Economics and Social Affairs (1991) notes that each year, 3 million children die because of the unavailability (or lack of knowledge) of low cost oral rehydration therapy; an additional 4 million children die from six major preventable diseases of childhood (diphtheria, pertussis, tetanus, poliomyelitis, measles and tuberculosis); over 500 million are malnourished;[6] over 40% in a study of 89 developing countries lack safe drinking water; over 65% (in 65 countries) lack adequate sanitation.

The consequences of poverty are also reflected in statistics on infant mortality, and average life spans. Tables 1 and 2 which indicates that progress has been made in average living standards since the early 1950's, also shows that continued progress is necessary to narrow the gaps in these statistics between the poorer developing and richer developed countries. Compared to Africa, average life expectancy in Northern America is 45% higher; and infant death rate, 75% lower.

It is, therefore, no surprise that immediate concerns will determine the policies and actions of poorer societies. However, conservation and environmental protection are possible only when people can afford to take the long-term view, i.e., when people are sufficiently rich and secure so that "basic" and other important needs are first met. Moreover, poverty and lack of capital in many instances precludes acquisition of the latest generation of technology which, more often than not, is also more efficient. Thus reducing poverty, i.e., improving economic well-being, of such populations is an essential pre-condition for conservation and environmental protection. This is one of the pillars of the movement toward sustainable development (see, e.g., Lebel and Kane, 1987). Finally, economic growth seems to help nations reduce their birth rate by job creation, particularly for women, and by helping provide individuals with a safety net that does not rely totally upon each individual's family. In turn, any reduction in population growth would moderate some of the pressures on natural resources as well as dampen greenhouse gas emissions.

Technological progress, and human adaptation in light of that progress, will increase the demand for some resources while reducing it for others. Technological progress can improve the productivity and efficiency of all activities that use natural resources, as well as stimulate substitution of one form of natural resource for another. For example, introduction of synthetic fibers has reduced the demand for fiber crops, livestock and animal pelts. While this increased some forms of air pollution and pressures on landfills, it also reduced the demand for land for agriculture, grazing, hunting, and trapping. Both -- the reduction of demand for agricultural land as well as in the slaughter of wild and domesticated animals -- have benefits for conservation.

Perhaps the experience with agriculture provides the best illustration of the consequences of technological progress. In 1988, the U.S. harvested less than 300 million acres for domestic and export purposes. If technology were frozen at 1910 levels, then in 1988 the U.S. would have needed to harvest 1,220 million acres, rather than the 300 million actually harvested, just to maintain the U.S. population's food intake at the same level and quality as that in 1910, and provide the same level of exports in 1988 (Goklany and Sprague, 1991). One estimate pegs the amount of arable land in the U.S. at 540 million acres (Batie and Healy, 1983) -- substantially less than the 1,220 million acres that would have been needed absent technological change.
The 14-fold increase in farm productivity per unit of labor from 1900 to 1988 also served as an incentive to reduce the birthrate of rural areas because farmers no longer needed a large family as its labor force. (U.S. Department of Commerce, 1975; U.S. Department of Agriculture, 1984; 1990).

[6]Malnourishment is defined as having caloric intake less than 1.4 times the basal metabolic rate.

Technological changes contributing to this increase in productivity include: substitution of animal and human power by the internal combustion engine and electric power; greater use of fertilizers, pesticides and other chemicals; greater use of irrigation; improved storage and distribution of food products; and higher yielding seed varieties. Each of these has some negative impact on the environment; yet each also contributes to the more efficient use of land. Without these improvements in productivity, virtually all productive land would be in agriculture: little would be left over for parks, wilderness areas and conservation of wildlife habitat.

As these examples indicate, technological progress results in trading-off one set of risks to the environment and to natural resources for another. The world-wide increases in life spans and living standards attest to the fact that these trade-offs have, on the net, benefitted society: the world-wide life expectancy at birth increased from 47.5 years for 1950-55 to 63.9 years for 1985-90 (Table 1); over the same periods, world infant death rate declined from 155 to 70 per 1000 births (Table 2).

TABLE 1: LIFE EXPECTANCY AT BIRTH (in Years)

	1950-55	1985-90
Africa	37.7	52.0
Northern America	69.0	75.6
Latin America	51.9	66.7
Asia	42.0	62.7
Europe	65.8	74.4
USSR	64.1	70.0
Oceania	60.8	71.3
World	47.5	63.9

Source: United Nations, 1990.

TABLE 2: INFANT DEATH RATE (Per 1000 births)

	1950-55	1985-90
Africa	188	103
Northern America	29	10
Latin America	126	54
Asia	181	72
Europe	62	13
USSR	73	24
Oceania	68	26
World	155	70

Source: United Nations, 1990.

HOW IMPORTANT IS CLIMATE CHANGE COMPARED TO OTHER AGENTS OF GLOBAL CHANGE?

As the prior discussion on impacts of climate change indicates, the one thing we can say with confidence is that little confidence can be placed upon their analyses. Nevertheless, both the reports of the IPCC Impacts Assessment Work Group (1990) and the recent U.S. National Academy of Sciences' (1991, 1991a) Panels on the Policy Implications of Climate Change note that impacts will be both positive and negative. More important though, in terms of the issue raised, is that the magnitude of impact of climate change is, generally speaking, not in the several hundred percent range as is expected to result from the other major agents of global change.

This conclusion is robust and holds true even if one was to disregard the various reasons enumerated previously why past assessments tend to overestimate negative, while underestimating, positive impacts. Similar rationale had led the IPCC's Response Strategies Work Group Report to note that the effects of climate change could be a small perturbation compared to other factors.[7]

Moreover, as both the IPCC Resource Use and Management Subgroup (RUMS) and NAS (1991a) indicated, the ability to adapt, albeit at some cost, is quite high for many sectors and systems. The exception to this would seem to be natural and marine ecosystems.

{The 1995 Assessment and associated studies confirm that climate change impacts will likely be relatively small compared to the impacts due to other agents of global change:

- *Global cereal production could rise from 1,795 million metric tons (mmt) in 1990 to 3,286 mmt in 2060, an increase of 83%, in the absence of climate change; the net effects of climate change, direct CO_2 effects and adaptations are estimated to change production by -80 to +30 mmt, i.e., between -5 and +2% of merely the change in production between 1990 and 2050*

[7] IPCC Response Strategy Work Group Report (1990), p. 166.

in the absence of climate change (Rosenzweig and Parry, 1994; IPCC 1996a: 451). Thus, by comparison with the impacts of other global changes, climate change impacts on land conversion, habitat loss, land use, use of agricultural chemicals, and diversion of water for agricultural use will likely be relatively modest.

- *By 2050, climate change alone could increase global forest area by +1 to +9% over 1990 levels, while the combination of climate change, direct CO_2 effects and land use changes (mainly due to conversion to agricultural uses because of the increasing demand for food supplies) could decrease aggregate forest area by 25%. (IPCC 1996a: 494-495.)*

- *Annual malaria cases may increase 10-16% in 2100 relative to an "assumed base" of 500 million per year in 2100 . (IPCC 1996a: 12, 574.)}*

THE ROLE OF ADAPTATION

Previously it was noted that impacts assessments must necessarily incorporate adaptations that could occur given, at the minimum, the current legal and institutional framework, and technological progress[8]. However, the role of adaptation in climate change goes well beyond doing credible calculations of its potential impacts.

The ultimate **goal of public policy** is to deal with problems so that the net social and economic (including environmental) consequences are minimized. Thus, prior to any actions that go beyond the "no-regrets" stage we must be able to show: (a) that they will result in net social, economic and environmental benefits, even while taking into consideration the scientific, technical and economic uncertainties, and (b) resources expended on these actions would be the best use for society's scarce resources and would not reduce its ability to deal with more urgent problems.

To assure that social, economic and environmental disruptions are minimized, as the IPCC WG3 report points out, both **adaptation** and **mitigation** must be considered as an integrated package. The lower the costs of adaptation, the less should be the need for limitations, and vice versa. The least-social-cost strategy must necessarily consider adaptation. First, no rational analysis of mitigation options can proceed without estimating whether, and to what extent, the options reduce the net negative social, economic and environmental consequences of climate change. As noted, to accomplish this, adaptations have to be considered. Second, limitations and adaptations are not necessarily compatible and may work at cross purposes (see below). Third, it is essential to assure that the marginal costs of one do not exceed that of the other or the marginal benefits.

Finally, while the public policy debate has concentrated on limitations, adaptations are unavoidable because:

- Climate will change due to natural variability, whether or not there is human-induced climate change.

- If there is any human-induced climate change, the inertia of the climate system dictates further climate change even if atmospheric greenhouse gas concentrations were to be stabilized immediately.

---

[8]The phrase "at a minimum" is employed because even legal and institutional frameworks evolve, i.e., adapt, particularly if societies are faced with either real or imagined threats or opportunities. That this is so, can be easily seen by comparing virtually any society today with its forerunner as little as, say, fifty years ago. While such rapid evolution may be, historically speaking, a relatively recent phenomenon, it is likely to continue given that the world is shrinking into a global village and the speed of communications is, if anything, likely to increase further.

THE ABILITY TO ADAPT TO CLIMATE CHANGE

The history of civilization is also a chronicle of mankind's efforts, and ability, to adapt. Migrating poleward in the summer and toward the equator in winter, planting the first crop, building the first shelter, wearing the first garments and digging the first well were all manifestations of adaptation undertaken specifically to reduce society's vulnerability to the elements. It is no accident that those activities (agriculture, forestry, water resource management) that are most sensitive to climate change are among the most highly managed human systems and also have the longest and most successful history of adaptation.

It is the goal of all resource managers to make the resources as invulnerable to climate as is practicable. For instance, in the U.S., one of the Bureau of Reclamation's and the Army Corps of Engineers' goals is to minimize present and future disruptions to water supply due to fluctuations in the climate -- regardless of the cause of any climate change. For this they have constructed an elaborate infrastructure of dams, canals and other capital-intensive projects as well as an elaborate set of management rules and practices to deal with droughts and floods as well as more "normal" circumstances. Similarly, the Department of the Interior, as steward of the Nation's natural resources (including fish, wildlife, forests and other vegetation), has planning procedures that would help manage these resources now <u>and</u> in the future -- regardless of the cause of any significant impacts. This involves constant prediction of sources of change, and constant adaptation to them and their consequences.

It was against this background that the IPCC's RUMS (1990) noted that there is considerable ability to adapt to human-induced climate change:

- Human beings and other species have an intrinsic ability to adapt to some degree of climate change because climate is inherently variable at all time scales. Through the ages they have developed the capability, and a suite of responses, to adapt -- in many instances, successfully -- to extreme events (e.g., floods, droughts). Human beings should be significantly more adaptable than other species. The greater the rate of climate change, the greater their vulnerability.

- Economic and technological progress have made it easier to cope with climatic variability and extreme events through earlier warning systems, better infrastructure and greater financial resources. Continued economic and technological progress will further reduce society's vulnerability to climate change.

- The ability to adapt varies with the amount of economic resources societies can muster and their degree of technical sophistication. Thus, one would expect developing countries to be less able to adapt (assuming the degree of impacts are the same). In fact, as noted previously, both the IPCC Response Strategies and Impact Assessment Reports note that developing countries are perhaps more vulnerable to climate change. This vulnerability is due to their limitations of financial (and other) resource and technological ability -- and not because climate change is inherently expected to be greater in those nations. In fact, to the extent that temperature change is an indicator of changes in other critical climatic factors, it is expected that change will be least at the lower latitudes where most of the developing countries are located. Nevertheless, as the RUMS report indicates, the efficiency with which many countries have adopted new technology in these sectors, albeit often without adequate environmental assessment, suggests a considerable ability to adapt to new circumstances whatever their cause; however, the closer farming is to subsistence farming the less the likelihood that it would adapt without assistance and "appropriate design."

- Climate varies tremendously around the world from place to place. Yet human beings have cultivated crops, and managed livestock, forests, water and other natural resources under all these myriad conditions. This wide variation in current climate means that there already exists a fund of knowledge that will help us adapt to future climate change. Thus, one should expect that an area would attempt to draw upon experiences and practices from area(s) whose present climatic conditions most closely approximate its future expected conditions. The degree of success in employing such an analog would depend not only upon the correspondence of the climatic and physical conditions, but also on legal, economic, cultural and other institutional factors which may reduce (or aggravate) barriers to transferring practices from one locale to another.

- o Economic development will further reduce a nation's vulnerability to climatic change because historically we see that with such development the fraction of gross domestic product (GDP) dependent on natural resources (and, hence, sensitive to climatic change) declines. For instance, in developed nations, less than 5% of GDP is attributable to agriculture; whereas in many developing countries this exceeds 25% (see, e.g., World Resources Institute, 1990). Clearly the latter set of nations would be more vulnerable to climatic change. Similarly, with less than 2% of GDP coming from farms nowadays versus about 11% in 1926-30 (prior to the 1930's drought) and 24% in 1889-93, the U.S.'s vulnerability to climate change has declined substantially (see U.S. Department of Commerce, 1975 and 1990).[9]

- o The ability to adapt -- which is greatest for the heavily-managed sectors (agriculture, forestry, public health and water resources) -- is likely to accelerate with the introduction of biotechnology, genetic engineering and the information revolution which speeds up the dissemination of knowledge. For instance, because agriculture is in most nations, the major user of water, introduction of more drought tolerant species via these techniques will help society cope with both future water resource and food security problems.

It is considerations such as those outlined above that have led Ausubel (1991) to ask, perhaps only partly tongue-in-cheek: Does climate still matter?

In summary, while adaptation to climate change may be problematic for natural ecosystems, the ability to adapt is, paradoxically, highest for those economic sectors and human activities which are most sensitive to climate change. Moreover, for these sectors/activities the ability to adapt successfully is a direct function of a society's wealth (i.e., sustainable economic growth) and technological progress.

COMPATIBILITY OF MITIGATION AND ADAPTATION RESPONSES

Mitigation and adaptation strategies may or may not be compatible with each other.

Examples of potential non-compatibility between adaptation and mitigation (and their respective goals) include:

- -- Monoculture plantation forests. Such forests may be the most efficient sinks for CO_2, yet widespread reliance on them could have potential negative impacts on biodiversity.

- -- CO_2 controls may not only reduce any potential climate change but, as the previous discussion on the direct effects of CO_2 implies, it would also reduce many of the positive impacts on water supply and availability, agriculture, forests and other ecosystems resulting from elevated CO_2 concentrations. Thus, CO_2 limitations would also reduce the adaptability of human and natural systems.

---

[9]The entire food and fiber sector, however, is about 10 times larger than the farm sector. In 1987, the former contributed 15.8% of the value added to the domestic economy, while the farm sector added about 1.3%. [The food and fiber sector includes food processing, manufacturing, transportation, trade and retailing, eating establishments in addition to farms.] Between 1975 and 1987, the value added by the food and fiber sector shrank from 20.4% to 15.8%. (U.S.Department of Commerce, 1990).

The trade-offs between the opposing outcomes must be based upon more complete analysis of the social, environmental and economic analysis of mitigation options prior to any decisions.

Adaptation and mitigation options that would reinforce each other include increasing the productivity (or efficiency) per unit of land used for agriculture, timber and forest products and human settlements, consistent with environmental safeguards; elimination of agricultural subsidies (see below); afforestation, reforestation and reductions in deforestation; and reductions in tropospheric ozone concentrations and CFCs.

CRITERIA FOR SELECTION OF OPTIONS ADDRESSING CLIMATE CHANGE

Notwithstanding the uncertainties in our knowledge about the social, economic and environmental consequences of climate change, it would seem that other agents of global change are more significant. Moreover, the ability to adapt to many, though not all, of the adverse consequences of climate change is relatively high. Furthermore, there are substantial uncertainties regarding the social, economic and environmental consequences of any specific response strategies. Finally, there are several competing demands on society's resources including the vast backlog of unmet needs for, e.g., better public health and safety. Given all this, can we justify major expenditures dealing with climate change? Would it be rational to select policies solely because of climate change? How can we assure that scarce societal resources spent on dealing with this issue are well spent in light of the wide spectrum of unmet societal needs? Which mix of response options would maximize socio-economic and environmental well-being?

To address these issues, each option should be evaluated based upon the following criteria:

- <u>Flexibility</u>, i.e., it should be adjustable at relatively low cost in light of new knowledge as science improves and uncertainties are reduced. The option should be successful whether or not climate changes.

- <u>Timeliness</u>, considering how long it takes to formulate and effectively implement the options, as well as how long before effects on natural resources become evident.

- <u>Feasibility</u>, considering the various institutional, economic, legal and cultural barriers to successful implementation and the degree of difficulty in overcoming them.

- <u>Compatibility</u> with other climate-related responses and socio-economic objectives.

- <u>Economic justifiability</u>, on grounds other than climate change. Because of the uncertainties related to the impacts of climate change, it is impossible to determine whether particular actions taken now to specifically address these impacts will necessarily result in net benefits to society. Hence, these strategies should focus primarily on options which would:

    - Address high priority <u>current</u> problems that seem likely to be intensified by climate change,

    - Help society better cope with future change, regardless of the agent of change, and

    - Provide net benefits to society whether or not human-induced climate change is significant, i.e., the options should be justifiable on their own merits. This includes ensuring cost-effectiveness and economic efficiency, and consideration of opportunity costs -- aspects that are likely to be met if it provides other non-climate-related benefits.

In most instances, options would have to be analyzed and implemented at the national or subnational levels because impacts of climate change, the ability to adapt and the consequences of adaptation will all vary considerably from place to place. Each nation should decide the precise mix of response options that would maximize its net socio-economic (including environmental) well-being based upon its specific social, environmental and economic situation. This will inevitably involve determining the necessary balance between various competing societal objectives (of which dealing with climate change is but one) and allocating limited financial, technical and human resources among them. In some instances, such options analysis would need to be done on a national or even on a bi- or multi-national basis (e.g., for rivers crossing international boundaries).

OPTIONS FOR ADAPTATION

Options that could be implemented in the short-term include:

o Improving the knowledge base to allow reasoned judgments to be made on natural resource use and management. This includes:

- -- developing inventories, data bases, and monitoring systems of the current state of resources;
- -- cataloguing current management and use practices across the wide range of climates existing on the globe;
- -- improving methodological tools for assessing the impacts of increasing greenhouse gas concentrations and associated climate change;
- -- estimating the sensitivity and adaptability of natural resources to different scenarios of climate change;
- -- estimating the sensitivity and adaptability of natural resources to different scenarios of greenhouse gas controls.

o Increasing the efficiency of the use of all natural resources by increased productivity and fuller utilization of the "harvested" component of resources and by waste reduction. In general, actions designed to achieve these goals fall into the following categories:

- -- increased research and development;
- -- removal of unnecessary barriers to the dissemination and adoption of new technologies and practices;
- -- adoption of an economic system and associated institutions which would ensure that such improvements are rewarded.

Specific measures include the development and adoption of technologies which would increase the productivity or efficiency (per unit of land and water) of crops, forests, livestock, fisheries and human settlements consistent with the principles of sustainable developments. It would alleviate the major causes of conversion of natural ecosystems and loss of biological diversity. In addition to alleviating pressures on land, such measures would also help reduce emissions of greenhouse gases. On the other hand, in areas where carrying capacities are strained or extended, appropriate measures to expand carrying capacities should be considered, e.g., by implementing pollution control measures, improving access to potable water or transportation infrastructure. Examples of options to increase efficiency include more efficient milk and meat production per unit of product; development of drought resistant crop varieties; improved food storage and distribution; and better irrigation water management practices and drainage which would allow water supplies to serve greater areas.

o Acceleration of economic development efforts in developing countries. Because these countries have largely resource-based economies, efforts improving agriculture and natural resource use would be beneficial. Such efforts, would help formation of such capital as, and when, it may be necessary to adapt to climate change, and generally make sustainable growth and development more feasible. It would also help moderate future population growth by providing jobs for women and helping shift social security needs from individual families to broader based programs.

- o Reviewing and, where appropriate, removing subsidies for inefficient use of land, agriculture, forests, water and other natural resources. This would reduce inappropriate exploitation of marginal lands and other resources, as well as their over-exploitation in other (non-marginal) areas. World-wide reduction in such subsidies would particularly benefit developing countries. The direct environmental benefits would be accompanied by a strengthening of their economies which are heavily dependent upon natural resources. In turn, stronger economies would make both adaptation and sustainable development more affordable further reducing environmental degradation. Finally, this would also decrease greenhouse gas emissions by limiting land conversion that would otherwise result from excessive land clearing, livestock and agriculture.

- o Developing methods whereby local populations and resource users gain a stake in conservation and sustainable resource use, e.g., by investing resource users with clear property rights and long-term tenure, and allowing voluntary water transfer or other market mechanisms.

- o Decentralizing, as practicable, decision-making on resource use and management, while assuring coordination with adjacent jurisdictions and incorporating mechanisms whereby interests of the broader society are also considered.

- o Promoting and strengthening of resource conservation and sustainable resource use in those highly vulnerable areas where climate change may further exacerbate conditions. Assessments of the potential impacts of climate change might help identify which are likely to be further stressed. Various initiatives could be explored for conserving the most sensitive and valuable resources including strengthening conservation measures, managing development of highly vulnerable resources, and promoting reforestation and afforestation.

- o Continuing and improving national and international agricultural and natural resource research/extension institutions.

- o Strengthening mechanisms for technology transfer and development.

REDUCING THE VULNERABILITY OF SOCIETIES TO GLOBAL CHANGE

As noted previously, both the IPCC Response Strategies and Impact Assessment Reports note that developing countries are perhaps more vulnerable to climate change because their financial (and other) resource limitations preclude costly and elaborate adaptations -- and not because climate change is inherently expected to be greater in those nations.

For these nations, it is particularly important to concentrate on those options which would, as noted above, address the highest priority current problems that would also help society cope better with any climate change -- if and when it occurs.

Because the fundamental reason for concern for developing nations is the lack of sufficient capital and human resources (rather than climate change per se), it is imperative to try to expand the level of these resources. This can only be done through:

- o Sustainable economic growth, which will reduce poverty, one of the main causes of environmental degradation; help reduce population, and therefore emission, growth rates; make more affordable any other greenhouse gas controls, if and when they become necessary; and improve the ability to adapt to future changes, regardless of the agent(s) of change; and

- o Technological change, which will help meet present and future societal needs with lower expenditures of financial, natural and human resources.

U.S. actions that help in this regard include:

- o Its espousal of world-wide elimination of subsidies on agriculture (in the GATT negotiations). This is economically justified on its own merits, and it would have direct environmental benefits in subsidizing nations. Equally importantly, it would stimulate economic growth in developing nations (because generally their agricultural sectors contribute relatively more to their national economies than they do in developed/industrialized nations).

- o Bi- and multi-lateral aid to developing nations designed to generally improve economic development, efficiency and productivity of agriculture and other natural resource based activities, and technological cooperation.

- o Its example -- and encouragement for adoption -- of a free market economy based upon the principles of individual property rights, decentralized decision-making and rewards for individual efforts and entrepreneurship. These are the key elements to ensuring that resources available to deal with society's problems expand even as the problems themselves become more intractable and costlier to address. These same elements are the necessary ingredients for assuring continued technological change. Spreading these ideas may be the most important contribution the U.S. can and has made to helping other nations.

Finally, continued growth of the U.S. economy also directly benefits other nations. First, even though the U.S. economy is less dominant on the world scene than it used to be in past decades, it still absorbs a lot of goods and services from elsewhere. A slowdown in its economy will also be a drag on other nations, especially developing nations with significant exports to the U.S. Second, a strong U.S. economy also makes possible the flow of aid to other nations.

DISCUSSION AND CONCLUSIONS

It is a fundamental principle of public policy that we should deal with those problems first that are the most important and which can be reduced, if not eliminated, at the least cost to society. Accordingly, this paper addressed the question: how important is climate change compared with other agents of future global change? It then dealt with the role and importance of adaptation in dealing with climate change. It listed options for adaptation, and criteria for their evaluation, before recommending approaches that would help society cope with climate change with the least disruption to society.

The following summarizes the paper's conclusions.

THE IMPORTANCE OF CLIMATE CHANGE

- o Climate is important only because of its effects on natural resources (e.g., water, land, plants, forests, habitats and other biological resources) and on human activities, such as agriculture, forestry, human settlements and recreation, which depend upon these natural resources.

- o Population and economic growth and technological progress are the other agents of global change influencing natural resources in the future.

- o Based upon existing assessments, over the next 100 years, climate change will be much less important to the state and condition of natural resources than these other agents of global change.
- o Furthermore, because of new information and methodological inadequacies, there is good reason to believe that existing assessments tend to overestimate negative, while underestimating positive, impacts of climate change. Reasons for this include: incomplete and,

often, non-consideration of such adaptation as will necessarily take place given the current legal and institutional framework, and technological progress; inadequate consideration of the direct effects of increased carbon dioxide which would benefit agriculture, forests and other ecosystems that depend upon photosynthesis for food and energy, and water resources; use of scenarios that assume a more rapid rate of climate change than expected by, e.g., the IPCC; the past assumption that there would be equal warming in the day and the night; the new finding that the net effect of CFCs on warming may have been overestimated; lack of consideration of cooling due to sulfates and volcanic activity in the calculations of the best estimates of climatic change, counterbalanced to some degree by similar non-consideration of tropospheric ozone.

{*More recent climatic change projections correct for many of these items though not for volcanic activity. Direct CO_2 effects are considered in a number of studies on agricultural impacts and, to a smaller extent, forest impacts. However, except for agriculture, adaptations are rarely considered in estimating climate change impacts, and even for that sector, the adaptations considered are limited*.}

THE ROLE OF ADAPTATION IN DEALING WITH CLIMATE CHANGE

There can be no rational analysis of climate change that ignores adaptation:

- No assessments of either the impacts or benefits of limitations can be credible if they do not incorporate adaptation.

- Adaptation is inevitable because climate will change from natural, if not man-made, causes.

- Some mitigation strategies, e.g., control of carbon dioxide, may compromise society's ability to cope with global (as opposed to climate) change. Others, e.g., CFC control, may reinforce adaptability. Hence, evaluation of mitigation strategies should explicitly analyze their impacts upon the future adaptability of natural resources to global change. This should be the least that should be expected of a "comprehensive" approach towards human-induced climate change.

THE ADAPTABILITY AND VULNERABILITY OF SOCIETIES TO CLIMATE CHANGE

While adaptation to climate change may be problematic for natural ecosystems, the ability to adapt is, paradoxically, highest for those economic sectors and human activities which are most sensitive to climate change. This is because, in recognition of their sensitivity to climate, these systems have always been very heavily managed. They have a long history of successful and rapid adoption of technological and management innovation. In fact, the pace of such innovations is expected to accelerate over the next several years due to breakthroughs in biotechnology, genetic engineering and in information dissemination.

Both the IPCC Response Strategies and Impact Assessment Reports note that developing countries are perhaps more vulnerable to climate change. This vulnerability is due to their financial and other resource limitations, not because climate change is inherently expected to be greater in those nations. The paucity of capital and other resources would preclude costly and elaborate adaptations.

CRITERIA FOR EVALUATING STRATEGIES AND OPTIONS

While the limitations of society's human and economic resources and lack of sufficient technological progress are most evident in developing nations, these factors are no less important to developed nations. In fact, the only reason that many nations (whether developing or developed) have not further reduced greenhouse gas emissions is that, given other societal needs, the social costs of such limitations are -- rightly or wrongly -- perceived as too high given available technology and economic and human resources. Given this, can we justify major expenditures dealing with climate change? How can we assure that societal resources spent on dealing with this issue are well spent given that there is a wide spectrum of unmet societal needs?

However, because of the uncertainties and systematic biases in most available impact assessments, it is unclear whether actions taken now to address climate change or its location specific impacts will result in net benefits to society. Hence, these actions should focus primarily on options which would:

- Address high priority current problems that seem likely to be intensified by climate change,
- Help society better cope with future change, regardless of the agent of change, and
- Provide net benefits to society whether or not human-induced climate change is significant, i.e., the options should be justifiable on their own merits.

There needs to be greater emphasis on actions that help meet both adaptation and mitigation goals. These include increasing the productivity or efficiency (per unit of land or water) of crops, livestock, forests, fisheries and human settlements consistent with the principles of sustainable development; elimination of subsidies for agriculture and, where appropriate, other natural resources; reforestation, afforestation and reduced deforestation; and, possibly, CFC controls (if that does, in fact, have the net effect of slowing potential warming). Adaptive strategies must, in general, be tailored to national or sub-national situations.

REDUCING THE VULNERABILITY TO GLOBAL CHANGE

The fundamental reason for concern, particularly for developing nations, is insufficient capital and human resources, rather than climate change per se. Accordingly, it is necessary to continue to stimulate:

- Sustainable economic growth. This will also reduce poverty, one of the main causes of environmental degradation, and help reduce population, and therefore emission, growth rates.
- Technological change. This will help meet present and future societal needs with lower expenditures of financial, natural and human resources.

Most importantly, both are compatible with satisfying other, more urgent societal needs such as better health, sanitation, safety and education. They would also make more affordable any greenhouse gas controls, and improve the ability to adapt to future changes, regardless of the agent(s) of global change.

Many actions which are compatible with both mitigation and adaptation would also contribute to stimulating sustainable economic growth and technological change. Such actions include: increasing the productivity or efficiency (per unit of land or water) of crops, livestock, forests, fisheries and human settlements consistent with the principles of sustainable development; elimination of subsidies for agriculture and, where appropriate, other natural resources; reforestation, afforestation and reduced deforestation.

What is true for developing nations also holds for the United States. It, too, has real constraints on available resources to deal with its outstanding problems. While that may seem odd, the reality is that as societies get richer and many urgent needs are met, the ones that are not met prove to be more intractable and costlier to address. Hence, the U.S. too needs to continue to expand its economy and ensure that the pace of technological change is not unnecessarily dampened. Continued growth of the U.S. economy also directly benefits other nations.

ADAPTATION: A "DO-NOTHING" POLICY?

Some have labeled adaptation as a "do-nothing" policy. While a "do-nothing" policy may be rationally justified, given the inability to show even qualitatively that any real costs (no matter how small) would result in any net benefits (save as insurance), pursuit of adaptation in fact requires "affirmative" action -- as this paper indicates. Society will have to work at being prepared for global change. Successful adaptation requires specific actions, many of which would also help limit greenhouse gases, that will stimulate sustainable economic growth and continued technological progress, as well as avoid actions that would impose or raise barriers to attaining these twin goals. As the experience of the centrally-planned economies proves, neither economic progress nor innovation are inevitable: wrong choices affecting the legal and institutional framework can halt progress toward these goals. In that case, it would be better, in fact, to do nothing -- because meeting the twin goals of sustainable growth and technological progress is also critical to ensuring that limitations of greenhouse gases, if and when they become necessary, cause the least disruption to society.

{

EPILOGUE

This paper was essentially completed toward the end of 1991. Since then, new studies have confirmed the general validity of its central arguments and conclusions.

One conclusion was that the original IPCC estimates of temperature and sea level rise were most likely overestimated because they did not, among other things, account for ozone depletion, sulfate aerosols and the cumulative effects of such volcanic activity as will undoubtedly take place before 2100. In fact, the IPCC (1996) reanalysis concluded that:

- *The "best estimate" temperature rise would be 2.4°C by 2100, as compared to 3.3°C using the IPCC 1990 estimate.*

- *Over the same time period, sea level could rise between 13 and 94 cm. with a "best estimate" of 49 cm., compared to the IPCC 1990 range of 30 to 110 cm. with a "best estimate" of 66 cm.*

However, the new estimates are also fraught with considerable uncertainty. Moreover, they do not include any cooling due to average or "expected" volcanic activity which could change results significantly: Hansen (1987) calculated that the cumulative effect of volcanic activity can cause significant cooling, reducing globally averaged temperatures by 0.5°C to 1.0°C by 2019.

While lowering the magnitude of climate and sea level changes should provide more breathing room, the precise estimates are, themselves, less critical to the conclusions and recommendations of this paper than the following arguments and conclusions which seem quite robust, barring a substantial upward revision in the speed or magnitude of change or a major omission regarding adverse impacts:

- *Relative to other agents of global change, the impacts of climate change will be small. The IPCC 1995 Assessment confirms this. For instance, by 2060, the impacts of climate change on global food supplies will likely be an order of magnitude less than the effects of other global changes. Land conversion due to other global changes will also overwhelm any climate change impacts on global and tropical forest areas, with potentially much larger effects on many "unmanaged" ecosystems. Thus, a higher priority ought to be placed on the various measures previously outlined to reduce land conversion and water diversions while meeting human needs.*

- *Adaptations can and will reduce the impacts of climate change, particularly for managed systems. Thus, when adaptations are included, we see little effect on aggregate global food supplies. Similarly, when, and if, human health impact studies factor adaptation and technological change over the next century into their estimates, we should also see those impacts drop.*

- *Numerous current problems, particularly in developing countries, should have a higher priority than limiting climate change. Dealing with some of these problems, moreover, will also advance adaptation to climate change (Goklany, 1995). Consider, for instance, that about 2 million people will almost certainly die from malaria <u>this</u> year (WHO, 1997). By comparison, the mortality due to climate change is estimated at 140,000 in 2100 (IPCC, 1996b: 204).*

Even assuming this to be a fact rather than an estimate, human welfare would be better advanced if we first dealt with malaria. Moreover, if malaria incidence increases 10-16% in 2100 as suggested by IPCC (1996a), focusing on malaria today would help humanity adapt and cope better with the impacts of climate change when, and if, they occur. This is as close to a perfect "no-regrets" action as one can devise. Using the same rationale, society would probably be better off by first attacking all the infectious and parasitic diseases that could be aggravated by climate change. These, and efforts to cope with the other agents of global change, should keep humanity busy for some decades. Other higher priority items include reduction of local air pollution, sewage treatment, and improved access to safe water. In the meantime, we could further refine our understanding of the science and, more importantly, develop more credible impact assessments before weighing, perhaps once a decade, whether, or which, climate change mitigation and adaptation options would be the best use of scarce human and fiscal resources considering not only their costs and benefits but, more importantly, remaining unmet needs. Such a deliberate approach could reduce the cost of mitigation without appreciably adding to the costs of climate change (see Wigley, Richels and Edmonds, 1996).

- *Economic growth coupled with technological change increases the likelihood that, in the long run, both population growth and pollution will be reduced (Goklany, 1995, 1996 and 1997a).*

However, adaptation continues to get short shrift in the climate change policy debate and in its access to resources for research and actions. For instance, globally about $170 million (or less) is spent annually on malaria research by the public and private sectors (Nature, 1997). Of this, the U.S. government spends about $25 million (in 1994),less than half what it spent (in real terms) in 1985. By contrast, the U.S. Global Change Research Program cost $1,600 million in FY 1996, of which $4 million went to Health and Human Services for health related research.

Despite the official lack of attention, there are several encouraging developments along the lines recommended in this paper:

- *Economic liberalization, freer markets and reduced trade barriers worldwide, and particularly in Asia and Latin America.*

- *Reductions in agricultural subsidies, particularly in OECD nations.*

- *Greater acceptance of private property rights, water marketing and other marketing schemes.*

By stimulating economic growth and making societies more amenable to technological change, these actions help reduce total fertility and population growth rates, which continue to decline. They will make both adaptation and mitigation more affordable. More importantly, they will provide the means and ability to reduce the vast backlog of unmet needs. Each time an urgent problem is reduced, if not eliminated, climate change will move up in the priority list. And one of these days, it could be at, or near, the top of that list, but based upon a review of the IPCC's 1995 Assessment, today other public health, global change, and environmental problems ought to take precedence.}

ACKNOWLEDGMENTS

This paper is a substantially expanded version of a paper produced for the American Geophysical Union's 1990 Fall Meeting. Both versions draw heavily upon the report of the Resource Use and Management Subgroup (RUMS), Response Strategies Work Group of the Intergovernmental Panel on Climate Change, June 1990. The author, who served as the Rapporteur of that Subgroup, gratefully acknowledges the contributions of its members and participants. However, he alone bears full responsibility for any errors and views expressed here. Finally, portions of this paper were delivered elsewhere (Watson, Bach and Goklany, 1991).

REFERENCES

Arp, W. J. and B.G. Drake. 1991. Increased photosynthetic capacity of Scirpus olneyi after four years of exposure to elevated CO_2. Plant, Cell and Environment. Volume 14, October.

Ausubel, J. H. 1991. Does climate still matter? Nature 350: 649-652.

Ausubel, J. H. 1989. Regularities in Technological Development: An Environmental View, in Technology and Environment, Washington, D.C., National Academy Press.

Cole, H. S. D. and R. C. Curnow. 1973. An Evaluation of the World Models in Models of Doom: A Critique of the Limits to Growth, H. S. D. Cole, C. Freeman, M. Jahoda and K. L. R. Pavitt, eds., with a reply by the authors to The Limits of Growth, New York, N.Y., Universe Books.

Cure, J.D. and B. Acock. 1986. Crop responses to carbon dioxide doubling: a literature survey. Agriculture and Forest Meteorology. 38: 127-145.

Delucia, E. H., T. W. Sasek, and B. W. Strain. 1985. Photosynthetic inhibition after long-term exposure to elevated levels of atmospheric carbon dioxide. Photosynthesis Research. 7: 175-184.

Drake, B.G. and P. W. Leadley. 1991. Canopy photosynthesis of crops and native plant communities expand to long-term elevated CO_2. Plant, Cell and Environment, v. 14, October 1991.

Easterling III, W. E., M. McKenney, N.J. Rosenberg and K. Lemon. 1990. Working Paper IIB-A Farm-Level Simulation of the Effects of Climate Change on Crop Productivity in the MINK Region, Processes for Identifying Regional Influences of and Responses to Increasing Atmospheric CO_2 and Climate Change -- the MINK Project. Draft Report, by Resources for the Future for U.S. Department of Energy, Washington, D.C.

Energy Information Administration. 1990. Monthly Energy Review. March 1990. DOE/EIA-0035(90/03). Washington, D.C.

EPA. 1989. The Potential Effects of Global Climate Change on the United States. J.B. Smith and D. Tirpak, eds. Environmental Protection Agency, Washington, D.C.

Frederick, K. D. 1994. Integrated Assessments of the Impacts of Climate Change on Natural Resources: An Introductory Essay. Climatic Change. 28: 1-14.

Frederick, K. D., I. M. Goklany and N. J. Rosenberg. 1994. Conclusions, Remaining Issues, and Next Steps. Climatic Change. 28: 209-219.

Global 2000 Report. 1980. The Global 2000 Report to the President of the U.S.: Entering the 21st Century, V. 1, 2 and 3, G. O. Barney, Study Director, A Report Prepared by the Council on Environmental Quality and the Department of State. Elmsford, N.Y., Pergamon Press.

Goklany, I. M. 1997. Conserving Habitat, Feeding Humanity. Forum for Applied Research and Public Policy. Forthcoming.

Goklany, I. M. 1997a. The Federal Role in Improving Environmental Quality in the United States: Evidence From Long Term Trends in Air Pollution. Presented at the American Society of Environmental History Conference on Government, Science, and the Environment, Baltimore, MD, March 6-9.

Goklany, I. M. 1996. Factors Affecting Environmental Impacts: The Effects of Technology on Long

Term Trends in Cropland, Air Pollution and Water Related Diseases. Ambio. 25: 497-503.

Goklany, I. M. 1995. Strategies to Enhance Adaptability: Technological Change, Sustainable Growth and Free Trade. Climatic Change. 30: 427-449.

Goklany, I. M. and M. W. Sprague. 1991. A Different Approach to Preserving Biological Diversity: Increasing the Efficiency and Productivity of Land Utilization. Draft report, U.S. Department of the Interior, Washington, D.C.

Hansen, J. E. 1987. Testimony to the Senate Energy and Natural Resources Committee, November 9.

Idso, S. B. and B. A. Kimball. 1991. Effects of two and a half years of atmospheric CO_2 enrichment on the root density distribution of three year old sour orange trees. Agric. For. Meteorol. 55: 345-349.

Idso, S. B. and B. A. Kimball. 1991a. Downward regulation of photosynthesis and growth at high CO_2 levels. No evidence of either phenomenon in three year study of sour orange trees. Plant Physiol. 96: 990-92.

Idso, S. B. 1991. The aerial fertilization effect of CO_2 and its implications for global carbon cycling and maximum greenhouse warming. Bull. Amer. Meteor. Soc. 72: 962-65.

IPCC. 1996. Climate Change 1995: The Science of Climate Change. Cambridge, U.K., Cambridge University Press.

IPCC. 1996a. Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Cambridge, U.K., Cambridge University Press.

IPCC. 1996b. Climate Change 1995: Economic and Social Dimensions of Climate Change. Cambridge, U.K., Cambridge University Press.

IPCC. 1994. IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations. Department of Geography, University College, London.

IPCC Resource Use and Management (RUM) Subgroup Report. 1990. Available as Chapter 6 of the IPCC Response Strategies.

IPCC Response Strategies Report. 1990. Climate Change: The IPCC Response Strategies. Washington, D.C. Island Press.

IPCC Impacts Assessment. 1990. Climate Change: The IPCC Impacts Assessment. W. J. McG. Tegart, G. W. Sheldon and D. C. Griffiths, eds., Canberra, Australia. Australian Government Publishing Service.

IPCC Scientific Assessment. 1990. Climate Change: The IPCC Scientific Assessment. J. T. Houghton, G. J. Jenkins and J. J. Ephraums, eds., Cambridge, U.K., Cambridge University Press.

Karl, T. R., et al. 1991. Global Warming: Evidence for Asymmetric Diurnal Temperature Change. Geophys. Res. Lett. 18: 2253-2256.

Karl, T. R., et al. 1992. Correction to "Global Warming: Evidence for Asymmetric Diurnal Temperature Change." Geophys. Res. Lett. 19: 219.

Lebel, G. G. and H. Kane. 1990. Sustainable Development: A Guide to Our Common Future: The Report of the World Commission on Environment and Development. Geneva, Switzerland: The Center for Our Common Future.

Meadows, D. H., D. L. Meadows, J. Randers, W. W. Behrens III. 1972. The Limits to Growth, New York, N.Y., Universe Books.

National Academy of Sciences. 1991. Policy Implications of Greenhouse Warming -- Synthesis Panel. National Academy Press, Washington, D.C.

National Academy of Sciences. 1991. Policy Implications of Greenhouse Warming: Report of the Adaptation Panel. National Academy Press, Washington, D.C.

Nature. 1997. Malaria Briefing. April 17, available at http://www.nature.com.

Foxworthy, B. L. and D. W. Moody. 1985. National perspective on surface water resources. In National Water Summary 1985 -- Hydrologic Events and Surface-Water Resources. United States Geological Survey, Water Supply Paper 2300. Washington, D.C., U.S. Government Printing Office.

Osborn, C. T., J. Schefter and L. Shabman. 1986. The accuracy of water use forecasts: evaluation and implications. Water Resources Bulletin. 22: 101-09.

Parry, M. L., T. R. Carter, and N. T. Konijn, eds. 1988. The Impact of Climate Variations on Agriculture, Volume 1: Assessments in Cool Temperate and Cold Regions. The International Institute of Applied Systems Analysis, Vienna, Austria.

Pavitt, K. L. R. 1973. Malthus and other economists: Some doomsdays revisited, in Models of Doom: A Critique of the Limits to Growth, H. S. D. Cole, C. Freeman, M. Jahoda and K. L. R. Pavitt, eds., with a reply by the authors to The Limits of Growth, New York, N.Y., Universe Books.

Rosenzweig, C. 1989. The Potential Effects of Climate Change on Agricultural Production in the Great Plains: A Simulation Study, in the Potential Effects of Global Climate Change on the United States, Appendix C, V.1, J. B. Smith and D. Tirpak, eds. Environmental Protection Agency, Washington, D.C.

Rosenzweig, C. and M. L. Parry. 1994. Potential impact of climate change on world food supply. Nature. 367: 133-138.

Science Times. 1991. Methane Gas Buildup Appears to Be Slowing. In The New York Times, June 18.

Tans, P. P., I. Y. Fung and T. Takahashi. 1990. Observational constraints on the global atmospheric carbon dioxide budget. Science. 247: 1431-38.

Tissue, D. T. and Oechel, W. C. 1987. Response to Europhorum vaginatum to elevated CO2 and temperature in the Arctic tussock tundra. Ecology. 68: 401-410.

United Nations. 1990. World Population Prospects. New York, N.Y., United Nations.

United Nations Department of International Economics and Social Affairs. 1991. Overall Socioeconomic Perspective of the World Economy to the Year 2000. New York, N.Y.

U.S. Department of Commerce. 1975. Historical Statistics of the United States: Colonial Times to 1970, Part 1, Bureau of the Census, Washington, D.C.

U.S. Department of Agriculture. 1984. Agricultural Statistics 1984, Washington, D.C.

U.S. Department of Commerce. 1990. Statistical Abstract of the United States 1990, Bureau of the Census, Washington, D.C.

U.S. Department of Agriculture. 1990. Agriculture Statistics 1990, Washington, D.C.

Waggoner, P. E. and J. Schefter. 1989. Future Water Use in the Present Climate, in Climate Change and Water Resources, P.E. Waggoner, ed., New York, N.Y., John Wiley and Sons.

Watson, H. L., M. C. Bach and I. M. Goklany. 1991. Global vs. Climate Change. United States/Canada Symposium on the Implications of Climate Change for Pacific Northwest Forest Management, October 23-25, 1991, Seattle, Washington.

Wigley, T. M. L., R. Richels and J. A. Edmonds. 1996. Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations. Nature. 379: 240-243.

World Bank. 1992. Development and the Environment. World Development Report 1992. Oxford University Press, New York 10016.

WHO. 1997. Fifty Facts From the World Health Report 1997. Available at http://www.who.ch/whr/1997/whr-e.htm, May 5, 1997.

WMO. 1991. Scientific Assessment of Ozone Depletion. Global Ozone Research and Monitoring Project report No. 25, World Meteorological Organization, Geneva, Switzerland.

World Resources Institute. 1990. World Resources 1990-91. Washington, D.C.

Ziska, L. H., K. P. Hogan, A. P. Smith and B. G. Drake. 1991. Growth and photosynthetic response to nine tropical species with long-term exposure to elevated carbon dioxide. Oecologia. 86: 383-89.