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STAFF DRAFT - APRIL 26, 1990

A WORLD OF DIFFERENCE

REPORT OF THE NATIONAL GOVERNORS' ASSOCIATION

TASK FORCE ON GLOBAL CLIMATE CHANGE

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APRIL 26 DRAFT

NGA STAFF DRAFT

REPORT OF THE TASK FORCE ON GLOBAL CLIMATE CHANGE

OUTLINE AND TABLE OF CONTENTS

EXECUTIVE SUMMARY AND STATEMENT OF GOALS

The atmosphere acts like a greenhouse around the earth. Certain gases, most of which naturally occur in the atmosphere in minute quantities, trap the sun's heat and warm the planet. Without this natural occurrence, the planet would be some 60 degrees Fahrenheit colder than it is now, the seas would be permanently frozen, and life as we know it could not exist. (EPA Options, p. 1) We literally owe the habitability of our planet to the phenomenon commonly known as "the greenhouse effect."

In recent years, evidence that human activities are changing the composition of the atmosphere has caused increasing concern. The world energy system, industrial and land use practices, agriculture, and population growth are adding certain greenhouse gases to the atmosphere faster than they can be removed by natural processes. As concentrations of greenhouse gases increase, the heat-trapping properties of the atmosphere also increase, like a more efficient blanket around the globe. Almost all scientists believe that this increase in greenhouse gases results in a theoretical increase in average global temperature. However, there is debate about the extent, rate, and timing of future temperature and climate changes. The U.S. EPA and others have predicted that a doubling of atmospheric carbon dioxide or its equivalent in some combination of greenhouse gases -- expected by the middle of the next century -- could raise the earth's average temperature by 3 to 10 degrees Fahrenheit (1.5 to 4.5 degrees Celsius). (EPA Options, p. 4) In January 1990, the National Academy of Sciences estimated that 4 degrees Fahrenheit (2 degrees Celsius) is the most likely temperature rise.

Although the implications of such a temperature increase are not well understood, they could include an increase in the frequency and severity of climate extremes such as droughts and storms; changes in rainfall patterns; rising sea level with consequent shoreline and beach erosion, flooding of estuaries, and loss of wetlands; desertification; and migration of agricultural and forest zones, among others. Some scientists believe that a warmer world could bring some benefits, such as lengthening the growing season in northern regions.

For several reasons, global climate change may be the most complex environmental and economic problem humankind has ever faced. First, there is substantial scientific uncertainty about the rate, magnitude, and regional effects of future climate change, and this uncertainty is likely to persist for some time. This scientific uncertainty and the difficulty in accurately predicting climate change are compounded by the existing natural variability of meteorological and biological systems. Second, the social and economic costs of the measures that might reduce the threat are not yet well understood, and a comprehensive assessment of the available options has only recently begun. Finally, mitigation and adaptation to climate change is an issue that can be effectively addressed only with the cooperation of all nations. It is likely that unilateral measures by any one country will be quickly overwhelmed by events elsewhere if other nations do not cooperate in a coordinated response. Some maintain that unilateral actions now could reduce American bargaining power in future international negotiations.

To address this important issue, NGA Chairman Governor Terry Branstad created the Task Force on Global Climate Change. The task force was charged with developing recommendations for the nation for the decade of the 1990s, and illuminating the role that states can play in addressing the problem of global climate change. To accomplish this mission, the task force met with senior scientists and policymakers from several nations, and engaged in constructive dialogue with business and environmental leaders, whose support is crucial in any response to this problem.

After careful deliberation, the task force makes the following findings:

First, atmospheric concentrations of greenhouse gases are increasing due to human activities. Over the last 100 years, atmospheric concentrations of carbon dioxide have increased by about 25 percent. (EPA Options, p. II-10) Concentrations of methane have increased by approximately 140 percent since the middle of the nineteenth century, and there have been significant increases in concentrations of other greenhouse gases, including chlorofluorocarbons (CFCs) and nitrous oxide. (EPA Options, p. II-22)

Second, a broad scientific consensus has developed that increasing the concentration of carbon dioxide and other greenhouse gases will increase the atmosphere's heat-trapping ability and warm the climate to some degree. There is debate and uncertainty, however, about the magnitude and timing of the warming and the implications of that warming for the earth's climate system, environment, and economies.

Third, controlling emissions is central to reducing potential climate change. For carbon dioxide, change in energy policy is the primary strategy for stabilizing or reducing emissions. Other measures, such as slowing the loss of forests, are also critical.

Fourth, states have an important role to play in addressing this problem because of their authority over utilities, land use, transportation, taxation, and other means of affecting change in the environment.

Fifth, any effective solution or response to global climate change must necessarily include sustained action by the federal government and the international community. Developing nations, whose emissions may grow rapidly in the future, must be full partners in the international negotiations.

The central question facing policymakers -- and the primary issue facing the task force -- is whether enough is known about global climate change to warrant taking action now to reduce it. Although considerable uncertainties must be acknowledged, some scientists and government agencies in several countries have predicted that significant global climate change could be evident within the next several decades.

The social and economic costs of the measures that may be necessary to reduce greenhouse emissions are still being evaluated. Economists have estimated these costs for the United States to range from virtually nothing to 5 to 6 percent of gross national product. (c.f. Williams, 1989; Mann and Richels, 1989) Overreaction could have serious effects on the economic well-being of the nation, depending on the actual cost. The next generation deserves to inherit the healthiest possible economy as well as the healthiest possible environment.

The costs of responding to the threat of climate change must be weighed against the possibly severe environmental and economic consequences associated with global warming and the risks associated with delay. Because greenhouse gases can remain in the atmosphere for centuries, emissions have a cumulative impact on the climate. Although the magnitude and timing are uncertain, today's emissions are likely to "commit" the planet to some degree of warming. In its 1989 report on global warming policy options, EPA found that early governmental response to global climate change would result in less severe problems in the next century. Assuming a policy response starting in 1990, the severity of the problem could be reduced by about 40 percent, compared to the same policies initiated in 2010. (EPA Options, p. 42)

Considering the evidence and the risks of both over- and under-reaction, the task force recommends taking steps now that provide a reasonable return on investment and offer other social and economic benefits. These prudent measures should be undertaken even if ~~new~~ [the presence of] scientific [uncertainty] ~~evidence reduces the urgency of addressing global climate change~~.

In view of these findings, the task force embraces seven key goals for the United States in the 1990s. They include the following:

ONE: **Develop an international agreement to protect the atmosphere.** The United States cannot significantly reduce the rate or magnitude of global climate change through unilateral action; the cooperation of all nations is required. It is particularly important that U.S. reductions in carbon dioxide emissions are not offset by net increase in other countries. America should use its preeminent position to lead the development of appropriate agreements as soon as possible to assure a coordinated international approach to the threat of climate change.

TWO: **Utilize cost-effective energy conservation and efficiency measures to stabilize U.S. emissions of carbon dioxide.** Between 1973 and 1986, the U.S. economy grew by more than one-third with no significant increase in carbon dioxide emissions, due largely to increases in energy efficiency. The United States should take cost-effective steps to extend that record by improving the efficiency of energy generation and use sufficiently to allow economic growth while stabilizing carbon dioxide emissions. States have numerous opportunities to reduce their carbon emissions through utility regulation reform that encourages efficiency. Building, lighting, appliance, and transportation efficiency measures also can yield substantial reductions in carbon emissions by reducing the amount of fuel we use.

THREE: **Stop production of and recycle chlorofluorocarbons, and use cost-effective strategies to stabilize or reduce other greenhouse gases.** The Montreal Protocol should be amended to eliminate the production of chlorofluorocarbons and to require that those already in use be recycled so they are not released into the environment. In addition, steps should be taken wherever possible and cost-effective to stabilize or reduce U.S. emissions of methane, nitrous oxide, ozone, and other greenhouse gases. Methane recovery from waste should be encouraged. Research in agriculture and animal diets has discovered ways to reduce greenhouse gases from these sources. Implementation of these discoveries should be encouraged.

FOUR: **Develop and commercialize alternative energy systems, including**

clean fossil, renewable energy sources, and nuclear power. Federal and state governments should take steps to ensure that clean and renewable energy sources make the maximum possible contribution to the nation's energy needs. A wide array of energy sources that would reduce carbon emissions from current levels is available, including clean fossil technologies, cogeneration, solar energy, wind power, geothermal, biomass fuels, hydroelectricity, and a new generation of safe nuclear power. These alternative energy systems should be further developed and marketed so that the energy needs of the nation can be met without increasing greenhouse gas emissions.

FIVE: **Implement forestry programs to reduce the effects of global climate change.** The severity of climate change can be reduced by taking steps to remove greenhouse gases from the atmosphere. Planting trees, particularly in urban areas, can help reduce the severity of climate change because they take up carbon dioxide as well as provide shade. Responsible management and expansion of our existing forest resources can improve the quality of forest ecosystems, increase our production of wood, and reduce atmospheric carbon dioxide.

SIX: **Plan and act now to adapt to a changing climate.** Some degree of future climate change due to human activities or natural phenomena appears likely. A planned response to this change should be developed promptly. Particular attention should be given to problems related to water resources, sea level rise, and agricultural and forestry practices. The task force recommends that programs in these areas consider the possibility for future global climate change.

SEVEN: Pursue an aggressive research program to reduce key uncertainties about global climate change. The world's response to the threat of global climate change must be based on the best possible science. We must enhance our ability to understand, monitor, and predict the forces that are shaping the climate. As the world's leader in scientific research, it is imperative that the United States support a program of research to better define the potential magnitude and timing of future climatic changes; the possible ecological effects of such changes; and the cost and effectiveness of various response options, including changes in energy sources.

In embracing these goals, the task force believes the federal government bears a special responsibility for assisting states or industries that may be adversely affected by a move to a less energy- and carbon-intensive economy. The federal government must plan for and provide a transition so that our national goals do not become unreasonable limitations on the growth and development of particular states or industries.

Finally, the task force recognizes that our lifestyles, the actions we take as consumers, and our attitudes toward the natural world directly affect the planet. Continued economic growth must occur within a framework that recognizes the long-term need for sustainability. The task force supports the development of environmental education programs and other efforts to provide greater insight into the ways in which our actions knowingly or unknowingly affect the environment. We must foster an environmental ethic promoting stewardship of the earth for present and future generations.

The following chapters examine these goals in greater detail and suggest strategies that could be used to achieve them.

STATEMENT OF THE PROBLEM

Through the millennia, the earth has been changing. Great ice sheets have developed and disappeared, forests and grasslands have migrated across the globe, even the oceans have advanced and retreated in response to global forces unknown to the primitive humans who witnessed these changes. Now, human forces may be changing the earth. There is great concern among some scientists around the world that human activities may be altering the atmosphere enough to cause "global warming" and serious changes in climate.

The phenomenon of greenhouse warming was first described in 1827 by the French mathematician and physicist Jean Fourier, who suggested that the earth's temperature is the result of certain greenhouse-like properties of the atmosphere. These properties permit solar radiation to reach the earth's surface and limit its escape again into space, thus warming the planet. Without the greenhouse effect, as these properties have come to be known, the earth would be cold and lifeless.

By 1896 global warming was well enough understood that the great Swedish chemist Svante Arrhenius was able to demonstrate that the traces of certain gases found naturally in the atmosphere -- principally carbon dioxide and water vapor -- account for the greenhouse effect. Moreover, Arrhenius was able to calculate the temperature increase that could be expected if the combustion of fossil fuels doubled concentrations of carbon dioxide in the atmosphere. He predicted that such a doubling would raise the global average temperature by about 10 degrees Fahrenheit, consistent with several recent predictions of 3 to 10 degrees Fahrenheit.

In the ensuing decades, however, little thought was given to Arrhenius' prediction, not because scientists doubted the nature of the greenhouse effect, but because few expected that human activity could appreciably raise concentrations of atmospheric carbon dioxide. Then, in the International Geophysical Year of 1958, American scientists began to take highly accurate annual measurements of atmospheric carbon dioxide at Mauna Loa, Hawaii. Since then, annual measurements have shown that carbon dioxide and other greenhouse gas concentrations are increasing rapidly. Other gases in the atmosphere, such as methane, nitrous oxide, and chlorofluorocarbons, also have greenhouse properties and are increasing. These gases differ in their concentration, atmospheric lifetime, and climate effect.

SUMMARY TABLE OF GREENHOUSE GASES

GREENHOUSE GAS	CURRENT CONTRIBUTION TO WARMING (percent)	MAJOR GLOBAL SOURCES (percent)	ATMOSPHERIC CONCENTRATION (parts per million)	ANNUAL INCREASE (% per year)	LIFE SPAN (years)	CLIMATE EFFECT (CO_2=1)
Carbon Dioxide	49		351.3	0.4	100	1
Fossil Fuels	35-45	75-90				
Deforestation	4-15	10-25				
Methane	18		1.675	1.0	11	25
Natural Wetlands		20-40				
Rice Paddies		12-35				
Ruminant Animals		12-20				
Landfills		6-15				
Natural Gas Drilling		5-10				
Coal Mining		3-9				
Chlorofluorocarbons	14		.000225	5.0	75-111	15,000
CFC-11			.000226	4.0	75	
Foams		55				
Aerosols		31				
Refrigerators		8				
CFC-12			.000392	4.0	111	
Refrigerators		49				
Aerosols		32				
Foams		13				
Nitrous Oxide	6		.31	0.2-0.3	150	230
Natural Soil and Ocean Releases		50-60				
Fossil Fuels		7-20				
Deforestation		7-15				
Fertilizer Use		2-17				
Tropospheric Ozone	?		.02-.1	?, but increasing	hours	2,000
Carbon Monoxide	?		.20	2	.4	NA
Fossil Fuels		10-25				
Deforestation		8-35				
Oxides of Nitrogen	?		.01-1.0	?	1-7	NA
Fossil Fuels		28-55				
Deforestation		16-25				

Source: EPA Policy Options; IPSEP Report on Greenhouse Policy; Worldwatch Report

GLOBAL CARBON DIOXIDE BALANCE

	10^9 tons CO_2/year	Percent
Natural Sources		
Oceans (Ocean-atmosphere interactions, Upwelling from deep oceans)	381	60
Land (Biological decomposition releases from soils, forest fires)	216	36
Total Natural Sources	597	96
Human Sources		
Fossil fuel use (Utilities, automobiles heating, etc.)	18	3
Land use (Deforestation)	7	1
Total Human Sources	25	4
Total from all Sources	622	100
Sinks		
Ocean (Ocean-Atmosphere interactions photosynthesis, biological activity)	392	63
Land (photosynthesis)	220	35
Total Sinks	612	98
Atmospheric Accumulation	10	1

Source: International Project for Sustainable Energy Paths (IPSEP), p. I.3-28.

THE GREENHOUSE EFFECT

The total effect of all the known greenhouse gases has already brought the atmosphere halfway toward the doubling of atmospheric carbon dioxide that Arrhenius used as the bench mark for his calculations. The growth of global emissions of greenhouse gases is directly related to human activities, and is dependent upon population growth, the level of economic activity, and other factors impossible to predict with confidence. EPA and others have estimated that, at current rates of emissions, atmospheric concentrations of carbon dioxide will have doubled from preindustrial levels by around the middle of the next century. Because carbon dioxide is the predominant greenhouse gas, a doubling of carbon dioxide from preindustrial concentrations has become the bench mark for estimating changes in temperature and climate.

Although in the earth's distant past, there were periods of high atmospheric carbon dioxide corresponding with high global temperature, neither the historical record nor direct observation can tell scientists exactly what effect such a doubling in carbon dioxide concentrations will have on global temperature. To estimate future temperature, scientists must use complicated mathematical models that reflect the physical laws governing the behavior of gases, and formulas expressing the interaction of the atmospheric system with the oceans and land masses. Many of these interactions are not well understood. Among other uncertainties, the role of clouds -- which both reflect sunlight back into space, cooling the earth, and trap infrared energy, warming the atmosphere -- is a major source of uncertainty in mathematical climate models. Modeling ocean currents, a crucial part of the climate system, also has proven difficult.

Another limitation is the incomplete understanding of the interaction of various greenhouse and non-greenhouse gases. For example, sulfur dioxide in the atmosphere brightens clouds and causes acid precipitation. Brighter clouds reflect more of the sun's radiation and may cool the earth. Temperature records for the northern hemisphere over the last fifty years show little change, a fact that some scientists attribute to increasing sulfur dioxide emissions. They hypothesize that sulfur dioxide, a principal cause of acid rain, may be delaying global warming.

In addition, there is uncertainty about other various effects that counteract or reinforce increases in the global temperature. For instance, it is possible that carbon dioxide fertilization, which makes plants grow faster, increases their uptake of carbon dioxide and removes more carbon from the atmosphere. Similarly, increased activity by soil microbes in response to higher temperatures may increase natural emissions of nitrous oxides. There may be hundreds or thousands of such feedbacks, each acting to enhance or reduce the magnitude of global climate change; their number and the net effect on the climate are unknown. Because these relationships and the overall sensitivity of the world's climate system are not well understood, the magnitude of climate change as the result of doubled carbon dioxide remains subject to considerable uncertainty.

The timing of any change in global temperature is also highly uncertain. Models can predict a new average global temperature for the climate in equilibrium, but cannot estimate how long it will take to realize that new temperature or whether the climate will change smoothly or abruptly. The atmospheric system and the oceans take a long time to warm up due to thermal inertia. There is an unknown lag time that occurs between a change in the atmospheric composition and a change in surface temperature. Thus scientists speak of increased levels of greenhouse gases resulting in a "commitment" to higher temperature without certainty about when it will actually occur.

Finally, current models necessarily focus on a large geographic scale, while regional or local effects remain uncertain. Scientists expect that temperatures will increase more at higher latitudes than closer to the equator. Even a modest increase in global average temperature can include dramatic and economically important regional events, some positive and some negative, such as increased growing seasons, changes in rainfall patterns, heat waves, or storms.

Increases in atmospheric concentrations of certain greenhouse gases during the last century are known, so it should be possible to directly test the models -- if the global average temperature in the last century can be established to provide a base line. Two scientific groups -- one in the United States and one in England -- have independently surveyed the historical record and found a temperature increase of about one-half a degree Celsius over the last 100 years (Schneider, Scientific American, Sept. 89, p. 72). This increase is about half the levels predicted by most models, based on observed increases in greenhouse gases. The discrepancy between observed and predicted temperature increases over the last hundred years keeps most scientists from stating with confidence that global warming has been observed.

Despite these uncertainties, scientists do not dispute the increase in atmospheric concentrations of greenhouse gases or the basic physics of the greenhouse effect. Several climate models developed and used independently in different countries have resulted in roughly similar estimates of future global temperature increases, in the range of 3 to 10 degrees Fahrenheit, assuming the greenhouse gas equivalent of doubling preindustrial levels of carbon dioxide. Such a warming would be unprecedented in human history. At the upper end of this range, it would approximate the temperature increase since the depths of the last ice age and would occur several hundred times faster.

GLOBAL CLIMATE CHANGE

Policymakers worldwide have noted these predictions and the severe consequences of a global warming of this magnitude. The principal concern is not global temperature increase alone, but rather the fact that the global temperature governs the earth's weather and climate in fundamental ways. Climate is determined largely by ocean and atmospheric currents, which in turn are driven by differences in temperature between warmer and cooler parts of the oceans, land masses, and atmosphere. The complex interactions of the earth's climate system are directly fueled by the planet's energy balance. If global temperature changes, so too must the climate.

While the science of global climate change is relatively new, studies have been conducted to examine the potential effects of a global temperature increase. These studies indicate that a doubling of atmospheric carbon dioxide could result in far-reaching -- even disastrous -- changes in the earth's climate. EPA's report to Congress, The Potential Effects of Global Climate Change on the United States, compiles data from numerous studies and analyzes the results region by region and sector by sector. The vast array of effects described in the report suggest that global climate change may be among the greatest threats humanity has ever faced.

WATER RESOURCES

Significant global temperature increases could cause more frequent and more severe droughts and floods. It is not yet known whether an increase or decrease in average rainfall is likely to result from the green- house effect, but most predictions point to increases in extreme weather events such as droughts and floods. (EPA Effects, p. 8-1) The regional and seasonal distribution of rainfall may also shift. Several studies suggest that mid-continental areas -- such as the American Midwest -- will become drier.

Other effects could include:

- Greater demand for water and decreasing supply. Irrigation and electric power production could be adversely affected in many areas.

- Lower river flows, negatively affecting hydropower, navigation, aquatic ecosystems, wildlife, and recreation.

- Earlier winter melts and the replacement of snow with rain, exacerbating seasonal flooding problems.

- Greater variability in the levels of rivers and lakes between months and years, which greatly complicates water management.

- Decreased water quality due to lower river flows and lake levels.

As mentioned earlier, today's state-of-the-art climate models cannot confidently predict regional climate change effects. The regional data that exists indicates that areas which currently experience water supply difficulties would face even greater problems associated with global warming.

AGRICULTURAL CHANGES

The effects of global climate change on agriculture are uncertain but potentially serious. (EPA Effects, p. 10.1-3) The stress from increased heat, lower moisture, irrigation pressures, and expanded pest ranges must be balanced against any potential improvements in plant growth that result from increased concentrations of carbon dioxide and longer growing seasons. EPA studies suggest that:

- Yields of corn, soybeans, and wheat would probably be reduced in all but the northern-most regions of the United States, which could have a longer growing season. If the "fertilization benefits" of carbon dioxide on crop yields are significant, some areas might overcome the negative effects of climate change. However, these fertilization benefits under field conditions are still uncertain.

- There may be a small-to-moderate aggregate reduction in agricultural output. This reduction should not threaten domestic food supplies, but it could negatively affect world food supplies and the U.S. trade balance.

- Farmland dependent upon natural rainfall could become less reliable, and the demand for irrigated acreage is likely to increase. This could put stress on regional water demand and lead to further degradation of surface and groundwater.

- Higher temperatures probably will increase the range and survivability of agricultural pests. More pests will survive winter, produce more than one generation per year, and affect crops earlier in the growing season. Pesticide usage probably will increase to combat the growing pest population.

In the aggregate, EPA studies suggest that the United States would probably not suffer a large net loss in agricultural production as the result of climate change. Any benefits of climate change, however, would not be uniform. Severe changes would necessitate continued technological improvements in agriculture. The shift of growing regions northward may be impeded by different soil conditions. The shifts in agriculture necessary to accommodate a change in climate would burden many farmers and threaten the economies and ecosystems of some agricultural regions.

At the Task Force' regional hearing in Burlington, Vermont, speakers expressed serious concerns over the ability of local agricultural economies to adapt to fundamentally different climates. The Vermont maple syrup industry, for example, has suffered from the combined effects of acid rain, ozone pollution, and heat stress. According to industry representatives, areas in Canada which produced no maple syrup twenty years ago are now enjoying bumper crops. It is likely that the predicted climate change will push the southern boundary of sugar maples and many other crops further northward, causing further economic disruption in Northeastern agricultural communities.

SEA LEVEL RISE

As water warms, its volume increases. Global warming in the range of most predictions could raise the ocean level from one and one-half to six feet over present levels by the year 2100, though recent estimates suggest the probable actual increase would be one to two feet. (EPA Effects, 9-1; Nature, January 1990) During the last ice age, when global temperatures were about 9 degrees Fahrenheit lower than today, sea level was more than 300 feet lower than it is now. Conversely, during the last interglacial period (100,000 years ago) when temperatures were about two degrees warmer, sea level was approximately twenty feet higher. (EPA Effects 9-2) Land-based glaciers, which store huge amounts of water, also influence sea level by slowly growing and shrinking. While most global warming predictions include declining glaciers, recent satellite data indicates that some glaciers are growing.

More frequent tropical storms and higher storm surges would exacerbate any increase in average sea level. While predictions suggest global warming could cause the loss of several hundred feet of shore or more, most U.S. recreational beaches are already less than 100 feet wide at high tide (see Figure___).

Many beaches and barrier islands could require massive adaptive efforts or face complete destruction. Flooding could increase along the coast as higher sea levels boost storm surges, reduce coastal drainage, and raise the water table. In the face of a three-foot sea level rise, EPA estimates it would cost $73 billion to $111 billion to protect barrier islands and developed mainlands through 2100. This estimate only measures the cost of shore protection. The financial losses of coastal industries such as tourism and fishing could be much higher.

EFFECT OF A ONE-FOOT SEA LEVEL RISE

Area	**Beach Erosion (in feet)**
Northeast to Maryland	50-100
Carolinas	200
Florida Coast	100-1000
Louisiana	several miles
California	200-400

Note: These numbers represent averages for the coastal regions listed; local beach erosion could be considerably higher where it coincides with other erosion problems.

Source: EPA Effects, p. 9-8

A rise in sea level also would allow saltwater to infiltrate farther into rivers, bays, wetlands, and aquifers. Increased salinity has already damaged oyster harvest in the Chesapeake Bay and pressured water supplies in Florida and New Jersey. According to EPA, a three-foot rise in sea level could eliminate up to 82 percent of continental U.S. wetlands, a crucial ecological resource. In addition to changes in the level of the sea, some scientists predict that major changes could occur in ocean currents such as the Gulf Stream, with virtually unpredictable effects on fishing or local weather.

At a regional hearing in New Orleans, Louisiana, the task force Governors heard evidence from experts on the potential climate-related devastation expected in the region. In Louisiana, shorelines are already retreating at a rapid pace; climate-induced sea level rise is expected to intensify this destruction.

IMPACT ON FORESTS

Forests are particularly sensitive to climate and rainfall. Climate change could force the southern ranges of many forests northward by hundreds of miles. Unfortunately, forest migration will probably occur too slowly to keep up with favored climate conditions and large areas of forest could die. Temperature increases of the magnitude predicted would make forests more susceptible to fires, pest attacks, and replacement with low-value trees, grasslands, and shrubs. In addition, changes in forests could reduce their biological diversity, aquifer recharge, wildlife habitat, and recreational uses. Precipitation runoff and soil erosion could increase in many areas. (EPA Effects, 11-1)

Scientists at Task Force Regional Meeting in Burlington discussed the implication of climate change for forest ecosystems. The intricate relationships between climate and forest growth, insect ranges, and diseases complicate predictions of forest impacts. But several scientists feared that the multitude of pressures on forests, including climate change, could cause a widespread die off of whole ranges of tree species. According to the United States Forest Service, valuable commercial forests stretching from Texas to Virginia have experienced declining growth in recent years. Trees have the unique ability to absorb CO_2 from the atmosphere as they grow. This benefit to the climate could be reduced by heat stress, which stunts tree growth and reduces CO_2 uptake.

EFFECTS ON BIOLOGICAL DIVERSITY

Unlike most other effects, the loss of a species is irreversible. Many species of plants and animals live within narrowly prescribed climate bands and may not be able to migrate or adapt quickly enough to adjust to climate changes. Reduced biological diversity could have serious implications, and untapped resources for research in agriculture, medicine, genetics, and industry could be irretrievably lost. Changes in habitat, location of wintering ground for migratory birds, and breaks in the food chain could cause ecological devastation. (EPA Effects 12.1-2)

CHANGES IN AIR QUALITY

Higher temperatures speed the reaction rates among chemicals in the atmosphere. As a result, the formation of ground-level ozone, which is the result of reactions of oxides of nitrogen and volatile organic compounds, would increase in many areas. Emissions of hydrocarbons, nitrogen, and sulfur oxides from human and natural sources also would increase with temperature. Under higher temperatures, sulfur and nitrogen oxides would oxidize more rapidly, increasing the formation of acid rain and snow in the atmosphere. EPA estimates that in the Midwest and Southeast, a seven-degree Fahrenheit temperature increase could triple the number of areas exceeding the National Ambient Air Quality Standards for ozone. (EPA Effects, 13-27)

HUMAN HEALTH EFFECTS

It is possible that deaths related to extreme temperatures could be increased in the summer and decreased in the winter. At present, the United States experiences more weather-related deaths during summer than in the winter months. Changes in temperature may be linked to higher infant mortality, outbreaks of malaria and Dengue fever, heart attack, stroke, and respiratory diseases. In addition, populations and ranges of disease-spreading vectors such as mosquitoes and ticks may increase. Lung cancer has been linked to increases in ozone levels, which are likely to increase as temperatures increase. In general, EPA reports that "unless the U.S. population becomes fully acclimated to higher temperatures, climate change will be associated with a rising number of summer deaths." (EPA Effects, 14-2)

CHANGES IN CLIMATE EXTREMES

The most common prediction of global climate change is expressed in terms of average temperature, but the global average masks great variation from place to place and season to season. In particular, summer heat waves could intensify considerably. The number of days in which an area reaches a certain temperature threshold would be greatly increased in some areas. Some predict these changes will be enough to become noticeable to the population within the next decade. For example, one prediction shows that the average number of days in a year when the temperature exceeds 100 degrees would increase from three to twenty-one in Omaha, assuming a doubling of atmospheric carbon dioxide. (Hansen, et. al. p. 45) Furthermore, the changes may come in the form of sudden climate jumps rather than following a smooth curve.

METEOROLOGICAL EVENTS

One of the first effects likely to be felt is an increase in weather variability from season to season and year to year. This change could bring more frequent and intense droughts and floods. Many sectors of the economy, particularly those relying on water resources, depend on reasonably predictable rainfall patterns. In addition, the warmth of ocean water is a determinant of the strength of hurricanes. Under the global warming scenarios studied, hurricanes would become more frequent, violent, and widespread. Winter snow melts would occur earlier and rain would replace snow in some areas. (EPA Effects, p. 17-5, 17-7, 17-9-11)

ENVIRONMENTAL REFUGEES

These effects may make some parts of the world much less hospitable than at present. Increased desertification, sea level rise, or flooding could require evacuation of some areas. America's Pacific Trust Territories, for example, could be hard pressed to support their current population due to low elevation and susceptibility to damage from tropical storms. Indeed, some nations, especially low-lying or island countries, could cease to exist if sea level rises as much as some have predicted. These changes could result in an international flood of environmental refugees -- people fleeing not from political or economic systems, but from ecological disaster.

OTHER EFFECTS

Urban infrastructures may well be affected by increasing temperatures. The net effect is difficult to predict; some cities might have lower snow removal and street repair costs, but higher air conditioning costs, for example. During the heat wave of 1988, Amtrak was forced to close major sections of track as a result of heat damage that warped the rails. (EPA Effects, p. 15-4) Annual costs of new electric facilities needed to meet increased demand from climatic changes could reach $3 billion to $6 billion by 2010. Climatic change could add between $33 billion and $73 billion to capital costs in this sector by 2055, depending on GNP growth, according to EPA. (EPA Effects, p. 16-8)

In addition to these effects, many other unanticipated effects could take place. The predictions outlined above cannot be considered immutable; they indicate the adaptation and displacement that may be necessary to cope with significant climate change. In some cases, such as species loss, the damage would be permanent. Other changes, such as agricultural effects, could require a massive restructuring.

Climate change in the range predicted by most models would place the earth's temperature at its highest point since humans appeared on earth. (IPSEP, p. I.1.14-15) The effects on climate-sensitive ecosystems and human activities would be unprecedented.

GOAL ONE: DEVELOP AN INTERNATIONAL AGREEMENT TO PROTECT THE ATMOSPHERE

All nations will be affected by global climate change, and the challenge it poses cannot be met by the United States alone. Indeed, unilateral American efforts to respond to the threat of climate change will be seriously devalued if other countries do not also take action. Projections of population growth, energy use, and land-use indicate that emissions from developing countries are likely to increase rapidly and to overshadow America's emissions in the future. According to EPA predictions, energy consumption in developing nations could increase by a factor of 2.5 to 4 by the year 2025, and by the middle of the next century it could account for the bulk of the carbon dioxide emitted to the atmosphere. At the same time, many developing nations lack the capacity to adapt to climate change and to minimize their contribution to greenhouse gas buildup because they lack the resources and technologies they need for "clean" economic growth. Affluent nations will need to make financial and technological assistance available to developing countries in return for specific commitments to an environmentally sustainable development path. There are several necessary steps:

- The United States must assert its leadership within the international community to negotiate at the earliest possible date an international framework convention that ensures international cooperation to protect the atmosphere.

- Individual protocols or treaties containing specific commitments from all nations on greenhouse gases, energy efficiency, population growth, and other items should be negotiated as soon as possible.

- Agreements to stop deforestation of the earth's tropical belt should be given a high priority.

While forestry programs are promising for the United States' response to global climate change, they are particularly applicable to the developing world. Numerous interrelated social and economic pressures have led to widescale deforestation in Latin American, Africa, and Asia. Population growth has required more land for agriculture and livestock. In debt-strained nations, the valuable agricultural commodities and forest products derived from cleared tropical forests provide much-needed foreign currency. In some countries, the need for fuelwood, often the primary energy source, has required the population to exploit every possible wood source. These pressures have led to widespread clearing of forests in the tropics: each year at least 27.3 million acres are lost, an area roughly the size of Illinois. (EPA, pp. VII-197)

GOAL TWO: UTILIZE COST-EFFECTIVE ENERGY CONSERVATION AND EFFICIENCY MEASURES TO STABILIZE U.S. EMISSIONS OF CARBON DIOXIDE

Meeting the challenge of global climate change will require cooperative action by the states, the federal government, and the private sector. A number of steps that would help minimize the rate and magnitude of global climate change are cost-effective and meritorious regardless of their climate benefits, and should be taken now. These steps include:

- reforming the regulation of electric utilities;
- improving building energy efficiency standards;
- improving appliance efficiency standards;
- improving transportation energy efficiency; and
- expanding state government energy efficiency programs.

Improving energy efficiency is the most effective and immediate step to minimize global climate change. Measures to improve energy efficiency can be put in place over a relatively short period. Benefits can be realized immediately. Moreover, a wealth of opportunities are available for cost-effective energy efficiency improvements in the American economy and worldwide. For efficiency investments that pay for themselves over the life of the equipment through reduced energy costs, the accompanying reduction in carbon dioxide emissions is in essentially a cost-free by-product of a more efficient economy. Efficiency improvements also can reduce emissions of other pollutants, improve economic competitiveness, and enhance U.S. environmental quality, energy independence, national security, and public health.

The energy decisions made in the next decade will have a major bearing on the environmental quality of this nation in the next century and beyond. While the federal government has a critical role to play, states are the primary mechanism for influencing and implementing energy efficiency policy objectives. At the same time, the federal and state partnership in meeting the nation's energy and environmental goals must be strengthened.

More specifically, states and the federal government should pursue energy policy options that are not only prudent, cost-effective, and practical, but which also have the potential for playing a key role in minimizing carbon dioxide emissions.

STRATEGY: PROMOTE UTILITY REGULATORY REFORM

States, through their public utility commissions, have the primary authority to regulate and affect the ability of electric and gas utilities to improve the efficiency of electricity and natural gas use. Several specific tools available to states can encourage improvements in the generation and use of electricity and natural gas, including least-cost planning and rate design reform.

Integrated Resource Planning for Energy

Integrated resource planning (least-cost planning) focuses on meeting a state's future energy needs at the lowest possible cost considering all factors. Using this process, utilities identify and implement all practicable and cost-effective efficiency opportunities that meet energy needs. If utilities need additional supply, they may purchase them at auctions from either independent energy service companies, who may be able to find unexploited energy efficiency opportunities, or from independent power producers offering new electricity generation projects. In a fully developed and integrated competitive bidding system, the environmental benefits and costs of energy efficiency should be explicitly considered in ranking bids for new capacity. New York, Vermont, and several other states are now implementing competitive bidding systems that account for external environmental costs in the evaluation of alternative energy supply systems. Currently, seventeen states have approved utility bidding programs, while eight states are reviewing the option.

Utility energy requirements can be met by a combination of sources, including energy efficiency and demand-side management programs. The Edison Electric Institute estimates that nationwide since 1977 electric utilities have increased the number of energy efficiency and demand-side management programs by nearly tenfold, from more than 130 programs to nearly 1,300 programs today. EEI estimates that these programs have deferred the need for investing more than of $21 billion on new electric generating capacity. The best electric utility demand-side management programs in the country are reducing customer electricity use by 10 to 30 percent (depending on end-use and building type), and are reducing utility peak load growth by up to 5 percent at an estimated cost of less than four cents a kilowatt-hour. (Energy Futures: Balanced Strategy is Key, EEI Background, January 90). The EEI estimates that by the year 2000, savings from such efficiency programs will exceed 45,000 megawatts of capacity and $45 billion in investment.

The importance of using integrated resource management to meet the nation's future electricity needs is underscored by the increasing importance of electricity in America's energy supply mix. Electricity currently accounts for 37 percent of U.S. energy use. Although total U.S. energy use has risen by less than 7 percent since 1972, electricity use has increased by 55 percent, and electric utilities currently account for about one-third of U.S. carbon dioxide emissions. (EEI, op cit). Because a typical power plant converts fossil fuel to electricity with about 33 percent efficiency, an improvement in electricity end-use efficiency will yield a threefold reduction in carbon dioxide. (Energy Technologies for Reducing Emissions of Greenhouse Gases, OECD/IEA, Paris, 1989, p.44)

Another series of promising efficiency improvements increases the efficiency of existing power plants by actions ranging from increased maintenance to "repowering" (i.e. replacing a major portion of an existing plant, such as the boiler, while retaining other portions of the plant, such as the steam generation equipment). A repowered plant using new boiler technology can significantly increase its efficiency.

Rate Design Reform

Utilities traditionally generate revenue by selling energy supplies. To successfully use utility demand-side management and efficiency to meet environmental goals and future load growth, the utility's current disincentive to saving energy must be removed. States can begin to reconcile shareholder and ratepayer interests by giving utilities proper incentives to implement programs that improve the efficient use of energy by all ratepayer classes. This can ensure that it is as profitable for utilities to save energy as it is.

to develop new supplies.

The options include:

- breaking the link between utility sales and profits so that utility profits do not fall in lockstep with conservation and efficiency improvements;

- allowing rate-basing and incentive rates of return for utility investments in customer conservation measures;

- encouraging financial incentives in the form of equipment rebates, low-cost loans, or shared savings arrangements to all classes of customers; and

- offering energy audits and technical assistance to homeowners, businesses, and industries.

STRATEGY: IMPROVE BUILDING ENERGY EFFICIENCY STANDARDS

The residential, commercial and industrial sectors are estimated to contribute more than 35 percent to the nation's carbon dioxide emissions. This figure climbs to 50 percent if electricity use in these sectors is included. Significant potential exists to improve the efficiency of buildings through efficiency measures aimed at lighting, heating, cooling, ventilation and building envelopes. The tools available to states include building codes, loans for conservation investments, and mortgage subsidies for energy efficient buildings.

A number of states have documented significant energy and carbon dioxide savings from building energy efficiency programs. The Illinois Home Energy Loan Program, for example, provided grants and low-interest loans for home energy efficiency improvements, and reduced the average heating bill by 22 percent for participating homes. This program resulted in an average reduction of more than one and one-half tons of CO_2 annually from each home. Vermont offers technical assistance through its Industrial Energy Conservation Advisory Program, and estimates its program has resulted in a 20 percent saving in fossil fuels and a 10 percent saving in electricity use in more than 700 industries visited since 1980. This program has reduced annual carbon dioxide by an estimated 3,600 tons.

One of the more ambitious energy-efficient home programs in the nation is operated in the Pacific Northwest, through the Northwest Power Planning Council, the Bonneville Power Administration, state governments in Washington, Oregon, Idaho, and Montana, and Northwest utilities. The Super Good Cents Program, a private/public partnership between government and utilities, certified more than 6,000 energy-efficient homes last year. The states and utilities have provided training for builders, consumers, lenders, appraisers, and realtors to build the infrastructure necessary to increase energy efficiency throughout the region. Utilities within the Northwest have also paid a portion of the incremental cost of building to the high standards to guarantee that new homes use cost-effective energy efficiency measures.

In 1989 Iowa saved more than $1 million in fuel costs and nearly 40,000 tons of carbon dioxide from state buildings as the result of its building energy management program. The state operates a similar program for schools and institutions. The state of Washington has had a residential building energy efficiency code since 1977, and the latest standards include insulation specifications by fuel type for the state's two climate regions. These standards have reduced annual space heating by approximately 60 percent in homes heated with electricity and 43 percent in homes heated with natural gas. In partnership with the federal government, states should establish an aggressive model building efficiency code and urge its adoption and enforcement in all jurisdictions throughout the country where no such standards currently exist.

STRATEGY: IMPROVE AND ADOPT APPLIANCE EFFICIENCY STANDARDS

Similarly, states and the federal government should pursue the potential for improving the efficiency of appliances, lighting, and electric motors. States and the federal government could act in concert to build on the National Appliance Energy Conservation Act (NAECA) and the U.S. Department of Energy's recent rules on refrigerators and freezers to implement more stringent national standards for fluorescent and incandescent lamps and fixtures.

Lighting accounts for 20 percent of the electricity used in United States - 25 percent if air conditioning and ventilation needed to remove heat from inefficient lights is included. (Renew America, p. 15) Using currently available high-efficiency fluorescent lights could cut the amount of electricity used for lighting by 50 to 92 percent. (ACEEE; Lovins and Sardinsky, 1988) Dramatic improvements also have been made in the efficiency of electric motors, which are estimated to account for more than 60 percent of all electrical consumption in the commercial and industrial sectors. Adopting minimum motor efficiency standards for new and replacement motors could result in significant electricity savings. These efficiency gains also cut carbon emissions significantly by reducing the need for electricity generation.

STRATEGY: IMPROVE TRANSPORTATION EFFICIENCY

The nation's transportation sector contributes nearly one-third of the nation's carbon emissions. Although much of our transportation policy is established at the federal level through the corporate average fuel economy (CAFE) standards and federal excise taxes, states also can improve the efficiency of the transportation sector through such measures as gas guzzler taxes on automobiles, car pool requirements, promotion of alternative automotive fuels, mass transit improvements, and control of traffic patterns. All potential alternative fuels, including ethanol, methanol, compressed natural gas, electricity, and reformulated gasoline, should be fairly considered.

The imperative to improve transportation efficiency is particularly compelling in urban areas. Many such areas are already suffering from the pressures of congestion and air pollution from mobile sources. At current rates of population and GNP growth, the Federal Highway Administration estimates that vehicular miles traveled will increase by 70 to 140 percent by the year 2020. Counteracting this trend, and the automotive emissions associated with it, will be a formidable challenge to policymakers.

To date, efforts to control growth in vehicular miles traveled have resulted in modest reductions in transportation growth rates. Most programs have focused on commuters, who account for 30 percent of all miles. An estimated 20 percent of all commuters car pooled in 1983, resulting in a 4 percent reduction in transportation energy use. Consumer preferences in transportation are strongly motivated by fuel costs and the high value placed on privacy. By making car pooling more appealing through high-occupancy vehicle benefits and other incentives, commuters can be encouraged to reduce both vehicular miles traveled and greenhouse gas emissions associated with transportation.

The task force recommends a multifaceted approach to improve transportation efficiency:

- The federal government should increase the corporate average fuel economy beyond the current 27.5 miles per gallon standard. The technology to improve fuel efficiency has already been developed by both domestic and foreign automakers. Some of these prototypes have achieved efficiencies of more than 100 miles per gallon, without compromising vehicle interior space, comfort, and safety.

- All levels of government should encourage the use of transportation modes that release less carbon dioxide. Depending on their energy source, electric-powered subway and rail systems result in significant carbon dioxide savings while reducing congestion and air pollution. On average, switching from automobiles to subways reduces carbon dioxide emission per mile traveled by about half (see Figure 13).

CARBON DIOXIDE EMISSIONS FOR VARIOUS TRANSPORTATION MODES

MODE	CO_2 RELEASED
Automobile*	1.15 pounds/mile
Air travel	0.9 pounds/mile
Bus, urban	0.7 pounds/mile
Bus, intercity	0.2 pounds/mile
Railway or Subway	0.6 pounds/mile

*Assumes a fleetwide average fuel economy of 19 miles per gallon.
Source: National Audubon Society

- Telecommuting holds great potential or energy savings, by allowing greater work at home via personal computers and modems and reducing travel between home and office. A major pilot program is now underway in the state of Washington, where rapid urban growth in the Puget Sound area has caused substantial traffic congestion. The telecommunications program will document motor fuel savings as well as employer/employee benefits and problems.

- Government should encourage increased utilization of ride sharing and high-occupancy vehicle lanes, especially where public transit is not practical. These programs limit the number of cars on the road and can reduce carbon dioxide emissions as well as pollutants responsible for ozone pollution.

STRATEGY: EXPAND STATE GOVERNMENT ENERGY EFFICIENCY PROGRAMS

States play a critical role in delivering objective energy information, technical assistance, and financial incentives to improve energy efficiency. State energy efficiency programs target all end-users and all fuel forms. State strategies that improve energy efficiency and also reduce air emissions include the following:

- providing financial incentives or rebates to improve the efficiency of appliances and residential furnaces and boilers;

- developing energy rating systems for new housing to provide consumers with objective energy efficiency information;

- implementing energy audit programs for small- and medium-sized commercial and industrial facilities;

- establishing financial incentive programs to provide lower cost financing, through interest breaks or principal reduction, for implementing energy efficiency improvements in commercial, industrial, agricultural, and multifamily housing facilities; and

- stimulating the increased use of state-of-the-art solar designs and renewable resources in home and business design and construction.

States currently operate a range of programs from energy hotlines to energy audits and lower cost financing for implementing identified energy efficiency measures. For example, Georgia operates two programs designed to help agricultural producers save energy. The program aimed at irrigation saves farmers more than $3.5 million annually, while eliminating 50,000 tons of carbon dioxide, at a cost of about one dollar per ton. Georgia also has developed a program for dairy farmers, using the "waste" heat in fresh milk to heat wash water in the dairy. It takes about two years for the average dairy to recoup costs through energy cost savings.

Among other energy programs, Pennsylvania has developed a research project aimed at demonstrating advanced weatherization technologies in the homes of low-income families. The project has demonstrated energy savings averaging 29 million BTU's per household -- or about 34 tons of carbon dioxide per household if operated over twenty years -- at a negative cost of about $40 dollars per ton. The carbon dioxide reduction itself has a negative cost because the energy savings in the home more than pays for the weatherization services at current energy prices.

New York's national award-winning Energy Advisory Service to Industry provides free onsite energy surveys to small- and medium-sized commercial and industrial firms throughout the state. To date, more than 8,500 audits have been performed. They are estimated to have saved more than 4 million gallons of oil, 14.3 million therms of natural gas, and more than 600 million kilowatt-hours of electricity. These savings translate into annual emissions reductions of more than 3,700 tons of sulfur dioxide, 1,400 tons of oxides of nitrogen, and nearly 700,000 tons of carbon dioxide.

In recent years, states have used petroleum overcharge recovery funds to implement the most aggressive energy efficiency programs in this nation's history. Unfortunately, the federal government has not maintained its support for state energy programs. The federal government should encourage state energy efficiency initiatives through increased emphasis and financial support to further tap the vast potential for energy efficiency improvements. Petroleum overcharge funds are diminishing at a time when the environmental dividends of energy efficiency are most needed.

GOAL THREE: STOP PRODUCTION OF AND RECYCLE CHLOROFLUOROCARBONS AND UTILIZE COST-EFFECTIVE MEASURES TO STABILIZE OR REDUCE OTHER GREENHOUSE GASES

Carbon dioxide accounts for about half of all greenhouse gases from human sources, and it has been the focus of a much of the global warming controversy. However, any climate stabilization strategy must consider other climate-altering gases as well. In cases where controlling these other gases is not immediately feasible, further research is crucial. There are several important steps that should be taken as expeditiously as possible.

STRATEGY: PHASE OUT CHLOROFLUOROCARBONS

Chlorofluorocarbons are the strongest greenhouse gases on a per molecule basis and have been linked to stratospheric ozone depletion. With atmospheric life spans of up to hundreds of years, chlorofluorocarbons released to atmosphere today will be trapping heat well into the future. Despite the ban on "nonessential" chlorofluorocarbon uses, U.S. emissions have grown rapidly over the last several years. Efforts to phase out the use of chlorofluorocarbons by the year 2000 or sooner have begun under the auspices of the Montreal protocol. These negotiations mark a milestone in international environmental law and may serve as a model in future international negotiations on other greenhouse gases. The federal government should seek an international agreement phasing out chlorofluorocarbons at the earliest possible date, and requiring the recapture and recycling those currently in use. Improper disposal can have very destructive effects. An auto air conditioner, for example contains the chlorofluorocarbon equivalent of 17,500 pounds of carbon dioxide if released to the atmosphere. The average car emits the equivalent of 2,600 pounds annually through use, leakage, and servicing. (Audubon) In New Jersey, state fleet vehicles are required to recycle their automotive chlorofluorocarbons. Vermont and Hawaii are phasing out all chlorofluorocarbon-based auto air conditioners statewide and are requiring recapture and recycling of existing chlorofluorocarbons.

STRATEGY: RECOVER METHANE FOR ENERGY USE

When organic matter decays in oxygen-deprived conditions, methane is produced. Methane from waste can be captured and used to produce heat and electricity. Methane from landfills accounts for 3 percent of global methane emissions. This share is expected to increase significantly in the future. According to EPA, each ton of municipal solid waste produces between 1000 and 7000 cubic feet of methane. (EPA, p. VII-189) The United States generated approximately 148 million tons of municipal solid waste, enough to produce between 148 and 1,036 billion cubic feet of methane. About 17 percent of all municipal solid waste landfills recover, vent, or flare methane, less than 2 percent of landfills recover the gas for energy use. EPA reports that the methane resource from landfills is equivalent to 1 percent of the nation's annual energy needs. (EPA Options, p. VII-191).

Coal seams are responsible for between 3 and 10 percent of annual methane emissions. (EPA Options, p. II-52) Before the development of methane recovery technology, the gas was usually vented to the surface using high-powered fans. Today, recovery of methane from this source has become an economically viable alternative to atmospheric release. Energy companies are capturing the methane for use as natural gas. The Colorado School of Mines estimates that 95 trillion cubic feet of methane are economically recoverable from this source, more than four times the amount of natural gas consumed annually in the United States. Federal tax credits have encouraged energy companies to capture methane from their coal seams. (Washington Post, "Long Feared, Methane Now Valued," Thomas Lippman, April 12, 1990.)

STRATEGY: EXPAND RESEARCH INTO ANIMAL DIETS THAT REDUCE METHANE

In their digestive process, cows and other ruminants convert plant fiber into usable animal products. This process also accounts for 13 to 20 percent of the methane emitted annually. (EPA Options, II-52) With the cattle population growing at more than 1 percent annually, ruminant animals will continue to be a significant methane source in the future. Increasing the productivity of livestock decreases the amount of methane produced per unit of animal product. Livestock diets also can influence the amount of methane produced per animal.

STRATEGY: IMPROVE THE EFFICIENCY OF FERTILIZER APPLICATION

Measurements of nitrous oxide in the atmosphere suggest that its sources are widely variable; furthermore, they are not all identified. Nitrogenous fertilizer use in agricultural crop production appears to be a major anthropogenic source and probably has the most potential for control. Use of this fertilizer is growing 1.3 percent annually in industrialized countries and 4.1 percent in developing countries. (EPA Options, p. VII-259) In addition to its effects on atmospheric concentrations of nitrous oxide, increased fertilizer usage can degrade water quality. According to EPA, these emissions can be reduced by improving the efficiency of fertilizer application and using advanced fertilizers that inhibit nitrous oxide. These methods derive more fertilization benefits from a smaller amount of fertilizer, while reducing the associated nitrous oxide releases and increasing the farmer's profit margin. Through their departments of agriculture and agriculture extension services, states can encourage more efficient and environmentally sensitive use of fertilizers.

GOAL FOUR: DEVELOP AND COMMERCIALIZE ALTERNATIVE ENERGY SYSTEMS, INCLUDING CLEAN FOSSIL, RENEWABLE ENERGY SOURCES, AND NUCLEAR

Fossil fuels have been crucial in the development of the industrial age. The history of the industrial economies is one of increasingly intense energy use, as power substituted for labor as a factor of production. In recent decades, however, problems associated with the pollution inherent in energy use have become apparent. Cleaner energy for transportation and cleaner electric power generation are especially critical.

The nation is becoming increasingly electrified, and according to DOE, at least 50 gigawatts (GW) of new generating capacity will be needed by the year 2000, in addition to the 70 GW already planned or under construction. (Long Range Energy Projection to 2010) The use of alternative energy technologies can allow the country to meet this demand for electricity while minimizing carbon dioxide emissions. States have powerful tools available to affect the choice of generating technologies, including electric utility regulation, technology incubation and transfer programs, and tax incentives. Alternative sources for electricity generation include:

- cleaner coal and other fossil fuel technologies;
- cogeneration;
- solar energy;
- wind power;
- geothermal energy;

- biomass;
- hydroelectricity; and
- nuclear power;

From a historical perspective, the mix of fossil-fired electric power generation in the United States in 1986 produced an average of 874 metric tons of carbon dioxide per gigawatt hour (GWh), compared to 18 metric tons of carbon dioxide per GWh for renewable energy technologies (solar, geothermal, wind, biomass, and hydropower). Renewable sources, primarily hydroelectricity, contributed about 11 percent of U.S. electric power generation in 1988. According to one DOE study, based on "conservative estimates of future energy use and renewable energy contribution," renewable energy technologies could displace 519 million tons of carbon dioxide (18 percent) in 2010, compared to an equivalent electric output from fossil-fired power facilities. (San Martin, Energy Technologies, OECD/IEA, Vol. I, p. 269).

STRATEGY: UTILIZE CLEANER COAL COMBUSTION TECHNOLOGIES

The United States has extensive coal reserves -- almost 29 percent of the estimated global recoverable reserves -- and cannot forego coal's contribution to the nation's energy supply. The only presently available technological option for removing carbon dioxide from conventional coal plants involves the use of scrubbers, which uses 25 to 50 percent of the plant's output of electricity to remove 90 percent of the carbon dioxide in the tail gas (R. Kane, Energy Technologies, OECD/IEA, volume I, p.46). Moreover, the reuse or disposal of captured carbon dioxide is constrained by inadequate markets and uncertain disposal capacity. These considerations make carbon dioxide recapture infeasible at the present time.

There are several near-term options for the cleaner use of coal in electrical generation, including pressurized fluidized bed combustion and integrated gasification combined cycle technologies. Development of these technologies has been progressing rapidly, and many are on the market today. Because they are more efficient than conventional coal technologies, they use less coal and produce less carbon dioxide for a given electricity output. It is expected that carbon dioxide reductions of 10 to 20 percent are possible, compared to conventional technologies. These systems also control sulfur dioxide, oxides of nitrogen, and other pollutants more effectively.

In the longer run, even more efficient coal use is expected to be available through coal-based fuel cells and magnetohydrodynamics. These technologies will operate with thermal efficiencies of 45 to 60 percent, reducing carbon dioxide emissions 25 percent or more, compared to today's emission levels.

STRATEGY: PROMOTE COGENERATION OF ELECTRICITY AND HEAT

Another way to use fossil energy more effectively is to cogenerate electricity and heat. Most older power plants waste the heat remaining in their steam after it has passed through the turbines. Frequently those who generate steam for process purposes waste the opportunity to produce electricity as well. Cogeneration ties steam and electricity production together. At Iowa State University, for example, the university's central heating plant generates power for the university with a coal-fired steam turbine, then uses the spent "extraction steam" to heat campus buildings, drive steam chillers that produce 22,000 gallons of 40-degree water per minute used for cooling purposes, and compress air for university applications. Because so little heat is wasted, the plant is about 50 percent more efficient than a conventional power plant, and saves the institution some $600,000 annually in fuel costs.

The Public Utilities Regulatory Policies Act (PURPA) encourages cogeneration by requiring utilities to buy power from small producers in order to avoid costs of building new capacity. Of the 62,000 MW that qualified for PURPA benefits from 1980 to 1987, almost three-fourths came from cogeneration. (Robert H. Williams, Expanding Roles for Gas Turbines in Power Generation, December 1988, p. 9)

STRATEGY: UTILIZE SOLAR ENERGY

Solar energy is perhaps the most familiar of the renewable energy resources developed in the 1970s. While virtually any region with normal sun exposure can benefit from solar energy applications, development of this source has been concentrated in the Southwest. No longer limited to simple pool heaters or small consumer electronics, solar energy can now provide baseload electricity to the power grid. It continues to have numerous other applications in everything from rechargeable street lights to Coast Guard buoys. Nationwide, more than 1.2 million buildings employ solar water heaters. In Phoenix, a twenty-four-home subdivision of all-electric homes is powered by a central photovoltaic grid-tied system. The system offsets more than 455 tons of carbon dioxide each year.

Photovoltaic cells are semiconductors that convert the energy of the sun directly into electricity. The task force toured a Sacramento research facility that produces about 20 KW of photovoltaic power. Photovoltaic electricity still costs more than conventional power, but enormous technological advances have been made in recent years and the signs are encouraging that costs may decrease. Even with reductions in federal research support, photovoltaic prices have dropped to one-fortieth of their 1978 level. (Renew America, p. 29) At current prices, photovoltaic electricity is competitive in several niche markets including rural water irrigation, lighting, and communications.

In a solar thermal electric generating system, an array of mirrored solar collectors focus the rays of the sun onto a receiver, which heats a liquid, driving a turbine to produce electricity. The Luz facility uses this technology to produce 200 megawatts of electricity for the Southern California Edison Company at a cost of about eight cents per kilowatt hour, competitive with conventional fossil-fueled power plants. The Department of Energy estimates that solar thermal electricity will become even more competitive by 1995. System costs for solar thermal plants would decline further if Public Utility Regulatory Policies Act (PURPA) regulations did not currently limit qualifying plant size to 80 MW, thus preventing economies of scale. (UCS, p. 33) According to industry representatives, the entire electricity needs of Southern California Edison could be provided on as little as 1 percent of the Mojave desert. The electricity needs of Los Angeles could be provided on 150 square miles of the Mojave, an area about one-third the size of Edwards Air Force Base. (Renew America, p. 26)

In the long term, solar energy also has the potential to be used as a transportation fuel through hydrogen production. Electricity generated from a solar thermal or photovoltaic plant can be used to divide water into hydrogen and oxygen through electrolysis. The hydrogen can then be burned as a transportation fuel. The only by-products of hydrogen combustion are water vapor and a small amount of oxides of nitrogen, which is easily controlled. (WRI, Solar Hydrogen, pp. 1-3) Currently, storage and transport limitations restrict the practicality of solar hydrogen. With continued research into solar power, fuel cells, battery technology, and storage systems, solar hydrogen could provide a substantial portion of transportation fuel while reducing carbon dioxide and air pollutant emissions.

STRATEGY: UTILIZE WIND POWER

Wind turbines have been used for centuries to grind grain and pump water, but it was not until the 1970s that modern wind power came into being. The tax credits available in the late 1970s and early 1980s rushed wind power into the marketplace, sometimes without sufficient testing. In California, the incentives for utilities to use wind power were particularly great; key factors included a 15 percent federal energy tax credit, 10 percent federal investment tax credit, and 50 percent California state energy credit. (American Solar Energy Society, p. 32)

Part of the appeal of wind power is its simplicity; blades are mounted on a tower along a horizontal or vertical axis, which turns a generator to produce electricity. The amount of power produced depends primarily on the efficiency of the generator and the wind speed at the location. The environmental impact of wind energy is minimal; the most serious is sight pollution from large-scale "wind farms." In most cases, wind systems do not preclude other land uses. Prime wind sites in the San Gorgonio Pass, for example, produce between $8,000 and $12,000 of electricity per acre in addition to the income the land earns for cattle grazing. (Renew America) By comparison, prime farmland planted in corn produces about $400 per acre per year. (Renew America, p. 21) Many of the advances that have brought wind power into the modern age have relied on lightweight materials and new designs for rotors. Future research should be directed at harnessing wind from medium- and low-wind sites in order to make more use of this energy source in more regions.

Although the industry has suffered somewhat with the end of the tax credits in 1986, wind power can produce electricity at rates comparable with conventional energy sources. Advanced wind generators are currently producing 2 billion kilowatt hours of electricity at a cost of 7 to 9 cents per kWh. The next generation of wind power is expected to reduce costs even further. This installed wind energy offsets 11 million pounds of air pollutants and 304,000 tons of carbon annually. (Renew America, p. 21) With improvements in engineering and siting, wind turbines have become highly reliable, achieving an average availability of 95 to 98 percent. Operation and maintenance costs average 1.2 cents per kWh compared to 2.2 cents per kWh for coal and 2.0 cents/kWh for nuclear power plants.

As with most renewable energy sources, growth of the wind energy market is limited by the current low costs of fossil fuels. Oregon State University concluded that the Pacific Northwest could produce 19,000 megawatts of energy from wind systems. (Renew America, p. 23) Since the region already has adequate existing power plants, however, wind energy has not been integrated into the region's energy system. With continued improvements in the technology, some studies indicate that wind energy could provide a significant portion of the U.S. energy needs.

STRATEGY: UTILIZE GEOTHERMAL ENERGY

Using the earth's heat, geothermal resources provide an opportunity in some areas to provide very inexpensive power virtually free of air emissions. Moreover, the resource is renewable, at least for several thousand years. In some areas on the West Coast, geothermal electricity is being generated at costs that are actually lower than baseload costs at coal fired power plants. The U.S. Department of Energy has estimated that the United States has about 1.2 million quads of technically recoverable geothermal resources. (DOE, Renewable Energy) Unlike other renewable energy sources, the technology to tap geothermal energy is largely developed and ready to be used. Since 1968, U.S. geothermal power capacity has grown from 78 megawatts to nearly 2,700 megawatts. Geothermal energy does not rely on wind, sunlight, or other unpredictable variables, and has earned a reputation for high reliability. Applications exist to use both high- and medium-temperature geothermal resources. In several areas in the world, geothermal is the largest source of residential heating. (Renew America, p. 30-31)

STRATEGY: DEVELOP BIOMASS FUELS

Biomass -- essentially wood and plant products -- is the oldest and most extensively used form of renewable energy. Before the development of coal and other fossil fuel resources, wood was the energy source of choice in the world. Currently, biomass provides only about 14 percent of all energy consumed in the world, but it is the only source of energy for more than 2 billion people. (EPA Options, p. VII-137) In the United States, biomass supplies 4 percent of all energy, more than any other renewable source. (Renew America, p. 35) Because of its diverse sources and uses, biomass is very promising.

In terms of impact on global climate and other environmental problems, biomass can have a positive effect if managed responsibly. During photosynthesis, plants absorb carbon dioxide from the atmosphere. If these plants are later burned to produce fuel, electricity, or heat, the same amount of carbon is released into the atmosphere. If plant growth exceeds burning and decay, more carbon dioxide is absorbed than created. At least one company has harnessed this process by planting trees to reduce net carbon emissions from fossil-fired power plants.

The sources of biomass for energy production range from agriculture, forestry, and municipal wastes, to liquid fuels made from energy crops, plant oils, and exotic genetically engineered algae. The forestry industry produces 150-300 million dry tons of waste each year that can be used to produce energy. Currently the industry provides much of its own power by consuming 100 million tons of biomass in its own power plants. In some cases, excess capacity is sold to the local power grid. In 1985, for example, the Hawaiian sugar industry supplied 58 percent of the electricity on the island of Kauai and 33 percent on the island of Hawaii. (Renew America, p. 36) Louisiana and Florida use 80 megawatts of power from similar power plants. Numerous technologies could help convert a portion of the 160 million tons of municipal waste into usable energy. While it is currently cheaper for the forestry industry to use these wastes than to dump them, the feasibility of using all of the remaining wastes is uncertain.

STRATEGY: UTILIZE HYDROELECTRICITY

Hydroelectric power has played an important role in U.S. electricity production since the 1880s. Over this 110-year period, hydropower has grown to 2,029 plants and 88,000 megawatts of capacity. These plants range from less than 1 megawatt to the engineering marvel of the 6,180-megawatt Grand Coulee dam in Washington. Hydropower provides more electricity than any other renewable source at low costs and without any carbon dioxide emissions. (Renew America, p. 33)

In the United States, much of the potential for hydropower has already been developed or is protected from further development by environmental regulations. Of the remaining 147,000 megawatts of potential hydropower resources, it is likely that only 37,000 megawatts will be available for actual development. Through upgrades and retrofitting, however, existing power units could produce considerably more power. Of the 67,000 existing U.S. dams, less than 3 percent produce electricity. Originally built for flood control, many of these idle dams could be retrofitted to generate electricity. According to the Department of Energy, 10,000 megawatts of small-scale hydropower could be derived from this source. (Renew America, p. 34)

STRATEGY: DEVELOP A NEW GENERATION OF SAFE NUCLEAR POWER

The United States should not foreclose the option of generating nuclear electricity. Currently, 111 nuclear power plants are licensed for operation in the United States. They produce almost 20 percent of the nation's electricity and, after coal, constitute the second largest source of electricity. Production of concrete used in the construction of nuclear power plants and the nuclear fuel assemblies produces carbon dioxide. The operation of nuclear power plants, however, produces virtually no carbon dioxide. According to industry sources, the 527 billion kilowatt hours of electricity generated by nuclear plants in 1988 reduced American carbon dioxide emissions by about 128 million tons in that year compared to coal-fired generation. (Reducing Airborne Emissions with Nuclear Electricity, Science Concepts Inc., Washington, D.C., 1990, p.7.)

Despite the carbon-free nature of nuclear electricity, the future of nuclear power in the United States is in serious question at this time. No new nuclear generating units have been ordered in the United States since the Three Mile Island accident in 1979, and all those ordered since 1973 have been cancelled. Four nuclear units are currently under construction in the United States. Once those are completed, it is unlikely that there will be additions to nuclear generating capacity for at least ten years, because it takes that long to plan and build a new nuclear plant.

If nuclear power is to play a major role in America's energy future, the federal government must press for the resolution of certain critical issues. It will be necessary to ensure the safety of nuclear technologies, ensure the safe disposal of nuclear waste, and bring the cost of nuclear power down; nuclear plants completed in recent years have cost an average of $2,700 per installed kilowatt of capacity, not including $800 to $900 per kilowatt in real interest costs incurred during construction. This makes electricity generated by these nuclear units almost twice as expensive as new coal-fired units, on average. (Cool Energy, The Renewable Solution to Global Warming, Union of Concerned Scientists, Cambridge, Massachusetts, 1990, p.15.) Priority should be given to the development and evaluation of advanced, passively safe reactor designs; waste management technologies; nuclear fusion research; and plant retrofit and life extension.

GOAL FIVE: DEVELOP FORESTRY PROGRAMS TO REDUCE THE EFFECTS OF GLOBAL CLIMATE CHANGE

The ability of the forests to sequester carbon has raised interest in their use to reduce greenhouse gases. While the exact mechanisms of exchange are unknown, the land biota holds approximately 420 to 660 billion tons of carbon; 90 percent of this amount is held in the woody biomass of the world's forests, while the remaining share resides in crops and grasslands. (IPSEP, p. 1.3-26) Forests are 20 to 100 times more efficient at absorbing carbon dioxide than croplands, depending on the location and plant regimes. (EPA Options, p. VII-195)

By destroying vast areas of carbon rich tropical rain forests, humans have started to eliminate a huge natural sink for carbon. Before human disturbances, forests covered 47 percent of the earth's land area. Today, forests account for about 39 percent of the earth's surface. (IPSEP, p. I.3-33) When these forests are burned, they release the carbon they hold into the atmosphere. Currently, human alteration of forest ecosystems accounts for emissions of carbon dioxide equal to about 10 to 30 percent of total emissions from human sources. (EPA Options, Ibid.).

At current rates of forest carbon uptake, it would require 1.65 billion acres of new plantation forests to absorb the 5.5 gigatons of annual worldwide carbon emissions, or roughly 73 percent of landmass in the United States. A total offset of all carbon emissions is probably not a practical response to global warming, but it is clear that some role for forestry is needed as a part of any global climate strategy. The strategies include:

- encouraging forest offsets for new carbon dioxide emissions;
- improving forest management; and
- planting trees, especially in urban areas.

STRATEGY: DEVELOP FOREST OFFSETS FOR NEW CARBON DIOXIDE EMISSIONS

Several studies have concluded that increased forest cover can be used to offset the increases in carbon emissions expected from future electric capacity expansions. One study projects that by 1996, 22,643 megawatts of coal-fired and 2,580 megawatts of oil-fired new electric generating capacity will come on-line in the United States. This additional capacity will add more than 166 million tons to the annual carbon dioxide emissions in the United States. Using relatively inefficient trees for carbon storage (silver maples, for example) would require more than 11 million acres of new plantings. Using a more efficient tree, such as eucalyptus, could reduce the required acres to under 7.5 million. (EDF, Dudek, p. 8)

Increasing tree planting can be done through numerous existing mechanisms. The Conservation Reserve Program (CRP) of the USDA uses economic incentives to encourage farmers to set aside highly erodible land for conservation purposes. Under current law, land owners enter into a ten-year contract that pays them about $50 an acre plus half the costs of implementing an approved conservation program. The goal of the program is to set aside 40 to 45 million acres, but by February 1989 only 30 million acres (between two-thirds and three-quarters of all eligible acres) were in the program. Of the total acreage set aside in 1988, only a small portion was planted with trees. CRP payments could be increased to encourage greater participation and to encourage planting of trees rather than some other land cover. If payments were doubled for acreage planted in trees, first-year costs for sequestering the carbon dioxide from all new power plants expected to be built by 1996 -- 9.26 million acres of trees, using trees of average carbon dioxide uptake efficiency -- would amount to $1.62 billion, or about 7 percent of the total cost of the new power plants. These figures do not include any of the costs recouped from the forest harvest in future years. (Dudek, pp. 9-10)

Applied Energy Services (AES), an energy company in Virginia, launched a carbon offset project in 1989. The 15 million tons of carbon that will be emitted over the forty-year life span of a new 183 megawatt coal-fired station will be offset by 52 million trees planted in Guatemala. AES contributed $2 million to the project and received further funding through CARE, the Peace Corps, the U.S. Agency for International Development, and the Guatemalan Forestry Service. (The Greenhouse Trap, WRI, 1990, p. 93)

STRATEGY: IMPROVE FOREST MANAGEMENT

Other possibilities for improving the forest absorption of carbon dioxide emissions involve state forestry programs, intensive forest management, and the creation of tree plantations. Modern forestry practices have increased the productivity of Douglas fir and loblolly pine -- and hence increased carbon uptake by 26 percent to 100 percent. However, many experts warn that converting of our varied forests to plantation-style monoculture would have devastating ecological effects. (Dudek, pp. 14-15, EPA pp. VII 220-222) The loss of genetic diversity would lessen the forests resistance to pests and disease, which would increase both the need for pesticides and the strain placed on water resources. In the near term, intensely managed tree plantations are probably uneconomical compared to the crop set-aside approach. According to some studies, converting mature old growth forests, such as those in the Northwest, to tree plantations would lead to an increase in net carbon dioxide emissions. Although old growth forests do not absorb large amounts of carbon, they hold tremendous carbon stores in the woody biomass. The carbon in the trunks, branches, roots, leaves, and soils could take more than 250 years to replace. However, if extremes are avoided, management of existing forests can significantly improve productivity without disturbing the overall health of the forests. Accordingly, forestry strategies in response to global climate change should probably concentrate on marginal lands, reforestation, and a sensible management of existing forests rather than conversions of old growth forests to fast growing tree plantations.

STRATEGY: PLANT TREES, ESPECIALLY IN URBAN AREAS

Trees are valuable in urban areas for numerous environmental and aesthetic reasons. In an urban setting, trees serve the dual role of absorbing CO_2 and controlling energy use. Trees can be used to shade buildings from the sun and reduce the demand for air conditioning. During the winter they both slow evaporative cooling and shelter buildings from wind. According to one study (Akbari, cited in EPA, p. VII-235), three strategically placed trees per house can reduce energy needs by 10 to 50 percent. Moreover, trees break up the urban "heat island," the warming effect caused by absorption of solar energy by city buildings and other structures. Because they reduce the need for energy and break up the urban heat island, an urban tree is about fifteen times more valuable in reducing carbon dioxide emissions than a tree in the wilderness. (EPA, p. VII-235.)

Despite the obvious benefits to be gained from urban trees, their numbers have diminished drastically; on average, only one urban tree is planted for every four removed. Because of these circumstances, the President has recently proposed a program to plant a billion trees a year in rural and urban areas. As part of its centennial celebration, North Dakota has developed an initiative to plant 10 million trees annually, adding 100 million trees by 2000. The project is being voluntarily coordinated through several state agencies.

Another opportunity for tree planting exists through the highway system. In 1985, highways covered 29.5 million acres of land (1.3 percent of the contiguous United States). EPA estimates costs of $777 million for tree plantings on 20 percent of highway corridors. (EPA, pp. 235-236) This option can be used to beautify the nation's roadways while sequestering a considerable amount of carbon. Planting trees on 20 percent of interstate, state, and local highways would offset roughly 20 percent of the carbon from new power plants.

GOAL SIX: PLAN AND ACT NOW FOR ADAPTATION TO A CHANGING CLIMATE

Many scientists believe that some change in our climate is now inevitable due to past emissions of greenhouse gases, even if drastic changes are made to control future emissions. On the other hand, economic infrastructure has been developed on the assumption that the present climate will be stable over the long term. The task force considers it prudent to begin planning now for adaptation to a different climate. It is likely that considerable funds will be needed to adjust the nation's infrastructure to climatic change. This cost must be balanced against the crucial role infrastructure plays in the productivity of the national economy. Three steps are particularly important:

- ensure that coastal development is consistent with the possibility of sea level rise;
- consider changes that may be necessary in water programs in response to different hydrologic conditions; and
- take steps to prepare for agriculture under conditions very different from those most farmers have experienced.

ADAPTING TO SEA LEVEL CHANGES

One of the most probable results of global warming will be an increase in sea level. Global warming causes sea level to rise through thermal expansion of oceans, and by net melting of glaciers and ice sheets. Assuming a global temperature increase of 3 to 10 degrees Fahrenheit, the most recent predictions are that mean global sea level would rise between one and two feet. (Nature, January 1990) Because the oceans have a large thermal inertia, it could take 50 years or more for higher sea levels to follow increased temperatures. Rising sea levels could devastate coastal areas by exacerbating coastal flooding; accelerating the destruction of wetlands; intensifying coastal erosion; inundating lowlands; and increasing the salinity of rivers, bays, and aquifers. As the result of these changes, communities could lose their water supplies as they become too salty to drink. Infrastructure and natural resources could be damaged or destroyed by flooding, erosion, and salt water intrusion.

STRATEGY: STRENGTHEN COASTAL ZONE MANAGEMENT PROGRAMS

In order to adapt to the changing coastal environment, a concerted effort must be made to promote further research, planning, evaluation, and assessment about the effects of rising sea level. Institutions that manage the coastal zone should be strengthened so that they can effectively develop and implement policies that anticipate sea level rise and increased frequency and severity of meteorological events. New Jersey is conducting a comprehensive study of sea level rise and other coastal changes to better understand their effects on the New Jersey shore. Policies will be developed to respond to anticipated changes, in consultation with the public and affected governmental entities.

The impact of future climate change on the levels and ecosystem of the Great Lakes is even less well understood at this time. A significant increase in temperature and drought conditions could result in a substantial lowering of lake levels and an increase in ambient lake water temperatures. A directed effort to determine the economic and environmental impacts of such changes on this major freshwater resource is critical.

STRATEGY: DEVELOP APPROPRIATE LAND-USE PLANS

In planning for less developed areas, incorporating land-use controls and management strategies could substantially reduce the impact of a rising sea level as well as protect the natural environment. Among other things, proper land-use planning can allow wetlands and other natural areas to migrate inland in response to rising sea level, reducing the loss of such natural areas. A substantial portion of the nation's coastal wetlands have already been lost as a result of human activities. According to EPA, a three-foot rise in sea level could destroy 25 percent to 80 percent of the remaining wetland resources. Maine and Texas have recently implemented protective land-use policies requiring all structures located in coastal areas to move inland in response to migrating coastal ecosystems. Not only does this policy protect wetlands, but it is also flexible and cost efficient in that if no rise in sea level occurs then no action need be taken. States also can use their flood insurance systems to encourage the development of land-use plans that account for the possibility of climate change.

STRATEGY: DEVELOP APPROPRIATE PROTECTIVE INFRASTRUCTURE

Erecting bulkheads and levees is one option for protecting low-lying communities and lands. However, such measures generally lead to beach erosion in other nearby coastal areas. Pumping sand onto beaches is another option for protecting beaches against erosion. Not only does this protect the beach, but it also prevents erosion induced by barrier construction.

Since the timing and magnitude of sea level rise is not clear, anticipatory strategies need not be implemented immediately. While it may be appropriate in highly developed areas to delay protective measures until the threat is imminent, it may be more cost effective to gradually incorporate protective structural measures into a community's infrastructure than to wait until the impact of sea level increase occurs.

In many areas, the best option for protecting drinking water supplies and agricultural land from saltwater contamination is to construct barrier dams in canals and estuaries to divert salt water.

ADAPTING TO CHANGES IN AGRICULTURE

Predictions are inconclusive on the effects of global climate change on agriculture. Possible changes include the migration of climate zones northward, changes in plant and animal pests and diseases, and changes in the demand and availability of water. According to the most extensive studies to date, American agricultural production may shift regionally but will still maintain sufficient supplies for domestic demand. (EPA Effects, p. 10-1) Although net output may not change (or may even increase marginally), the disruption of traditional farming patterns could cause significant problems for regional economies. Adaptive strategies developed in the near term can ease the possible transitions necessary and provide benefits to producers today.

STRATEGY: STRENGTHEN AGRICULTURAL RESEARCH AND PLANNING

Substantially increased research efforts are needed with regard to global climate change and agriculture. Priority should be given to identifying the most vulnerable regions and farming types given anticipated changes in climate; establishing the efficacy of various adaptation and mitigation measures; identifying response strategies for new diseases and pests; establishing more tolerant crop varieties; and modifying or improving traditional farming practices.

Land use plans can also be altered to account for potential changes in agricultural suitability in the future. Long-term development plans should be made to reflect the possibility of a northward shift in climate regimes. Water use planning should incorporate the possibility of increased demand for irrigation (due to low rainfall in some areas and higher evaporation everywhere) and strained water supplies. More careful long-term planning also benefits water quality and quantity.

Under most climate change scenarios, the range and abundance of agricultural pests increases. The ability of surveillance and pest control programs to detect and respond to the introduction of new pests should be assessed and strengthened. Land grant universities and extension services can play a critical role in these efforts.

Research into drought-resistant species of crops and livestock could ease the transition to a climate with higher temperatures and lower soil moisture. Results from this research could lessen the need for northward migration of the agricultural belt. Advances in biotechnology have the potential to make agricultural products more climate resistant.

STRATEGY: IMPROVE CONSERVATION OF SOIL AND WATER

The relationship between excess soil erosion and diminished yields is well established. Excessive loss of top soil and inefficient use of water will exacerbate farm yield reductions that may be caused by increased heat waves and drought. Conversely, improved conservation will better protect our farms and give farmers more options. In Oregon, the Governor's Task Force on Global Warming has recognized that water availability is likely to be the most important factor in determining future crop patterns, and the state Water Resources Commission is developing a water conservation plan focusing on irrigation efficiencies and reducing waste.

Increased use of conservation tillage and crop rotation improves the sustainability of soils and may lessen the need for pesticides. These practices also improve the resilience of crops to extreme weather events (e.g., droughts, floods, storms) that may occur with greater frequency due to climate change. The states' cooperative extension programs can be used to promote the adoption of these methods by farmers.

STRATEGY: ENCOURAGE GREATER DIVERSITY AND FLEXIBILITY IN FARMING SYSTEMS

The resilience of agriculture to changes in climate can be increased substantially by encouraging greater diversity in farming systems, such as through the development of new crops and more mixed-crop systems. In addition, the agricultural infrastructure, such as irrigation systems, can be made more flexible to allow adjustment to a range of future conditions. Finally, efforts to maintain genetic diversity and propagate heat- and drought-tolerant crop and livestock varieties will allow greater adjustment to future climate changes.

ADAPTING TO CHANGES IN WATER SUPPLY AND DEMAND

A number of studies suggest that global climate change will increase the frequency and severity of drought, particularly in mid-continental areas such as the American Midwest. Moreover, higher temperatures can increase the evaporation of soil moisture, exacerbating the effect of drought. These conditions result in both increased demand for and reduced supply of water. For some regions, severe water shortages are anticipated. In other areas, water tables may rise, necessitating different policy responses.

STRATEGY: IMPROVE THE EFFICIENCY AND FLEXIBILITY OF WATER USE

Improving the efficiency of water use provides a cushion against drought. There are numerous ways to conserve water. More efficient irrigation systems can improve the efficiency of water use dramatically. Pricing water at its replacement cost would discourage waste. Water managers can examine the use of market mechanisms to transfer water rights.

If new reservoirs or dams are constructed, planners should evaluate the marginal cost of adding capacity that could be used to respond to changing conditions in the future. Although it may not make sense to undertake large investments now in anticipation of future needs, it may be much less expensive to add marginal capacity to water systems while the reservoir is being built rather than later.

It may also make sense to protect options for future water supply development through a number of means, such as protective easements or land-use restrictions protecting potential reservoir sites. Water resource managers should also explore issues surrounding the transfer of water during periods of drought or excess supply.

STRATEGY: PROTECT WATER QUALITY

The quality of water directly affects its availability for certain uses. By assuring that all water bodies are clean, more water can be made available for use in times of shortage. Cleaner waters will also reduce the impact on aquatic ecosystems during low stream flow conditions. States manage programs to control point source and non-point source water pollution; these programs can be used to address potential climate-related water quality threats. Meeting state and federal water quality standards is essential.

GOAL SEVEN: PURSUE AN AGGRESSIVE SCIENTIFIC RESEARCH PROGRAM TO REDUCE KEY UNCERTAINTIES IN CLIMATE CHANGE

National and international efforts have already begun to address the uncertainties surrounding the science of global warming. Internationally, the United Nations and the World Meteorological Organization have organized the Intergovernmental Panel on Climate Change. This group will release a report on the state of the art in global climate science, predicted effects of climate change, and strategies for reducing global warming. Its work will then be reflected in the process for developing an international framework convention on the atmosphere.

In the United States, multidisciplinary research is being coordinated by the U.S. Global Change Research Program. The President's fiscal 1991 budget calls for more than $1 billion to fund this program, a 57 percent increase over fiscal 1990. (President's Budget for FY91, p. 130). As a joint effort of seven agencies and departments within the executive branch, this research program will be directed to improving the scientific basis for national and international policy formulation.

As a worldwide leader in basic and applied scientific research, the United States must aggressively pursue a research program to improve understanding of the planet's climate, including its effects on the environment and its socio-economic impacts. The Governors strongly support efforts to improve the state of scientific knowledge surrounding the climate change issue at both the national and international levels.

CONCLUSION

During the last several decades, the world has become more deeply aware of the relationship between people and the environment. New insights have reaffirmed that we are a part of nature rather than master over it. Potential catastrophies such as global climate change reinforce the need to consider the long-term effects of human actions. The balance between the necessities of economy and environment must be struck rationally and with full consideration of all the risks involved. Continued human prosperity can only occur in a healthy and habitable environment.

Global warming is at once one of the most threatening and the most misunderstood challenges humanity has ever faced. There is irrefutable evidence that human activities are changing the composition of the atmosphere. Physical laws indicate that a buildup of greenhouse gases should lead to a warmer climate. But the conjecture involved in predicting the actual effects of increased greenhouse gas concentrations make policy choices particularly complicated. With the scientific knowledge currently available, the choice is between waiting for more proof or ensuring against the possibility of a future disaster. Waiting may either prevent further unnecessary waste of resources, or vastly exacerbate the predicted effects. Taking steps now could significantly reduce climate change in the future and avert disaster, or squander valuable resources and effort. Avoiding the negative impact of either extreme is at the center of the dilemma faced by policymakers at all levels.

The task force reviewed the extensive literature produced in the last several years on climate change and consulted representatives from the scientific, government, business, and environmental communities. Each of these groups has devoted serious and extensive consideration to global climate issues. It remains for representatives in government at state, federal, and international levels to make the weighty decisions -- decisions that will be felt for generations. Ideally, these choices would be based on irrefutable evidence. In reality, they must be based on existing data.

The most important finding for the task force is that some steps should be taken now that can reduce the risk of future climate alteration while yielding other benefits in the short term. Many of these activities are already being undertaken by states, both as precautions against global warming and for the good economic, environmental, and social sense they make. The task force believes that these measures, many of which are described in this report, will not give us cause to regret our commitment to them. They are the most sensible steps to take now to achieve our goals.

Climate studies have deservedly received increased research priority and funding from the federal government. Depending on the results of these studies and others from around the world, our response may have to be adjusted to account for new understanding. The measures outlined above will provide the necessary flexibility to adjust to these developments. Great strides have been made toward understanding the planet; it is imperative that human actions continue to progress commensurate with available knowledge.

GLOSSARY

biomass energy - There are numerous forms of biomass energy. In its most familiar form, wood is burned to heat buildings or provide cooking heat. Wood or almost any form of plant fiber can also be burned to run a generator and produce electricity. Plant fiber can also be chemically altered to produce methanol and ethanol to be used as automotive fuels.

British Thermal Unit (Btu) - basic unit of energy consumption in English system. One Btu is roughly equivalent to the energy of one blue-tip kitchen match.

clean coal technology - This technology removes a significant proportion of the pollution-forming impurities in coal. Some of these technologies raise the efficiency of coal-fired power plants, and thereby reduces CO2 emissions by requiring less coal to produce the same amount of electricity.

cogeneration - Cogeneration technology makes use of the heat generated through industrial processes to produce electricity. Many production plants use steam for heat or to make their products. Cogeneration takes advantage of the some the heat to make electricity.

exajoule (EJ) - a unit of energy equal to 10^{18} joules. The United States consumes about 84 EJ of energy annually.

geothermal energy - Geothermal energy relies on the natural heat of the earth to produce electricity. There are several different forms of geothermal energy in various stages of development, ranging from hydrothermal -- the most common form used today -- to systems that rely on molten rocks in volcanic areas.

hydroelectric power. A hydroelectric system relies on falling water to turn a turbine, which generates electricity.

joule - basic unit of energy consumption; it is the energy required to lift a one kilogram weight about 10 centimeters.

kilowatt (1,000 watts) megawatt (MW, 1 million watts) gigawatt (GW, 10^9 watts) - generally used to measure generating capacity.

kilowatt-hour - used to measure the amount of electric energy produced. In a conventional steam-turbine plant, about 10.9 megajoules (10^6 joules) of primary energy are required to produce one kilowatt-hour of electricity. One barrel of crude oil equals approximately 1,700 kilowatt-hours of electricity consumed.

quad - an abbreviation for quadrillion Btu (British Thermal Units). The United States consumes about 80 quads of energy annually. One quad is a little more than one EJ.

solar thermal electric energy - A solar thermal system uses mirrors to direct the sun's rays onto a receiving surface. A heating liquid is pumped through the element, which in turn produces steam that drives a turbine to produce electricity.

solar photovoltaic electricity - photovoltaics are semiconductors which convert sunlight directly into DC electricity.

watt - Watts are units of power; 1 Watt is equal to 1/746 of a horsepower.

wind power - Wind power converts the power contained in moving air into electricity using a wind mill.

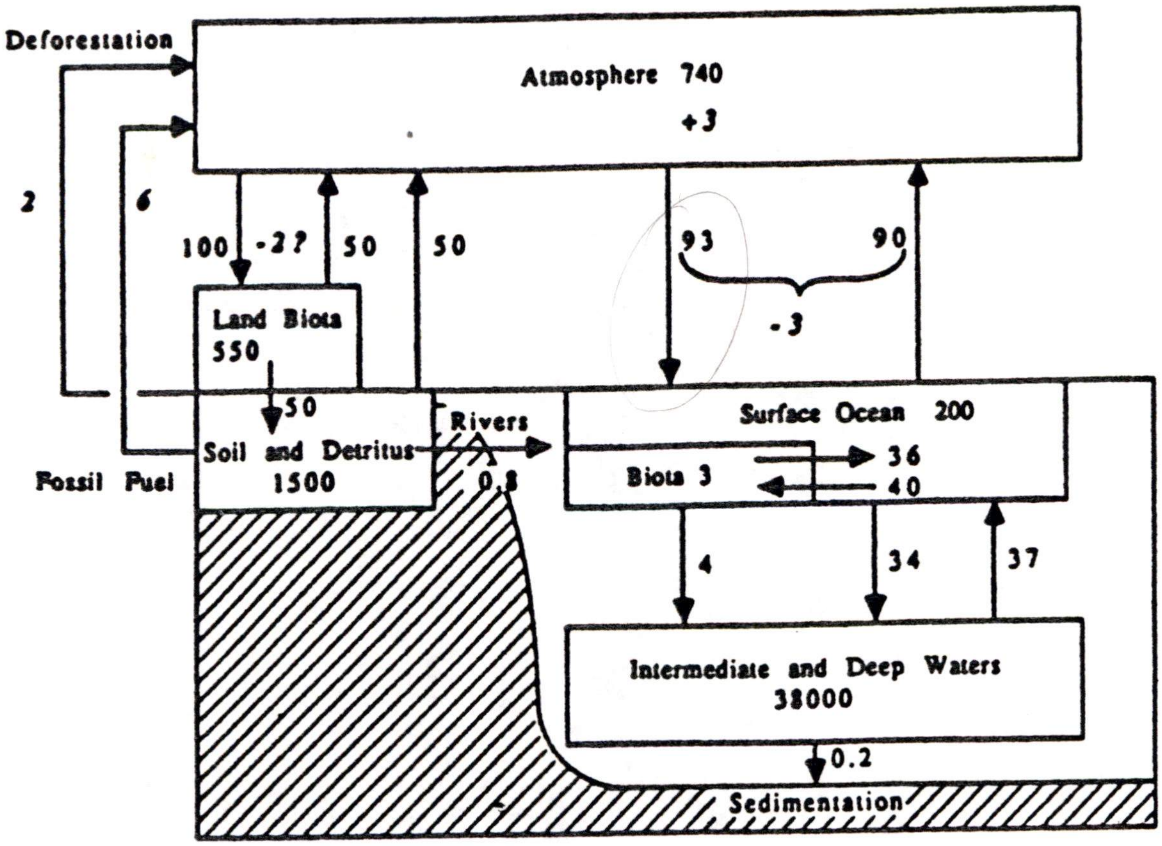


Figure 1: Global carbon reservoirs and fluxes. The numbers apply for the present-day situation and represent typical literature values. Fluxes, e.g. between atmosphere and surface ocean, are gross annual exchanges. Numbers in bold-face italics indicate net annual perturbation fluxes to the atmosphere and annual atmospheric CO_2 increase due to human action. Units are gigatons of carbon (GtC; 1Gt = 10^9 metric tons = 10^{12}kg) for reservoir sizes and GtC yr^{-1} for fluxes. More details and discussions are found in several reviews (Sundquist, 1985; Trabalka, 1985; Bolin, 1986; Siegenthaler, 1986).

6

WILLIAM D. NORDHAUS

Global Warming: Slowing the Greenhouse Express

POLICYMAKERS WHO yearn for the familiar will undoubtedly have the opportunity to struggle with perennial problems such as recessions, inflation, and government deficits. As if traditional ills are not enough, in the late 1980s governments were confronted with yet another issue: the deterioration of the global environment. Recent studies have identified four major global environmental concerns: widespread damage from acid rain; the appearance of the Antarctic "ozone hole," interpreted by some as the harbinger of global ozone depletion that threatens to remove the shield from harmful ultraviolet radiation; deforestation, especially in the tropical rain forests, which may upset the global ecological balance and deplete genetic resources; and the "greenhouse effect," which threatens global warming and major climatic changes in the decades to come.

Although all four issues concern policymakers, this chapter concentrates on global warming, both because it is likely to have the most important economic impact and because it has been the source of the greatest controversy. The discussion covers the scientific theory and evidence of global warming; the economic effects of climatic change; the kinds of policy responses that might be available; and policy recommendations for the near term.

Scientific Theory and Evidence of Global Warming

For almost two centuries scientists have suspected that climate could be affected by changes in the chemical composition of the earth's atmosphere. The first analysis of this idea was carried out in 1896 by S. A. Arrhenius, who estimated that a doubling of the atmospheric con-

Helpful comments were provided by Jesse Ausubel, Garry Brewer, Clark Bullard, Robert Chen, William Clark, John Perry, Thomas Schelling, and Aaron Wildavsky.

TABLE 6-1. Estimated Atmospheric Concentrations of Important Greenhouse Gases, Selected Years, 1850–2100

	Level (parts per billion)			*Growth (percent per year)*	
Greenhouse gas	*1850*	*1986*	*2100*[a]	*1850–1986*	*1986–2100*
Carbon dioxide	290,000	348,000	630,000	0.16	0.52
Methane	880,000	1,675,000	3,100,000	0.56	0.54
Nitrogen oxides	285,000	340,000	380,000	0.15	0.10
Chlorofluorocarbons[b]	0	0.62	2.90	...	1.37

SOURCES: Donald J. Wuebbels and Jae Edwards, *A Primer on Greenhouse Gases*, prepared for Department of Energy, DOE/NBB0083, March 1988; and Environmental Protection Agency, *Policy Options for Stabilizing Global Climate* (February 1989), vol. 1: chaps. 1–6.
a. Projected from EPA, *Policy Options.*
b. Includes only major sources, CFC-11 and CFC-12.

centration of carbon dioxide (CO_2) would increase global mean temperature by 4° to 6° centigrade (C).[1] What causes the greenhouse effect? The atmosphere is composed of a number of "radiatively active" gases that absorb radiation at different points of the spectrum. Those known as the "greenhouse gases" (GHGs) are transparent to incoming solar radiation but absorb significant amounts of outgoing radiation. The net result is an increase in the earth's temperature of about 33°C (59°F). The greenhouse effect helps explain the hot temperatures on Venus along with the frigid conditions of Mars.

Human activities are raising atmospheric concentrations of greenhouse gases significantly and thus pose a threat to the climate. GHGs of greatest concern are carbon dioxide, methane, nitrogen oxides, and chlorofluorocarbons (CFCs). Scientific monitoring has firmly established that these GHG concentrations are increasing (see table 6-1).

Not all greenhouse gases are created equal. GHGs have different radiative properties and different lifetimes. Table 6-2 shows the important greenhouse gases, their "instantaneous" and "total" contribution to global warming, and the industries in which the emissions originate.[2]

1. A short history of scientific concerns about the greenhouse effect can be found in Jesse H. Ausubel, "Historical Note," in National Research Council, *Changing Climate: Report of the Carbon Dioxide Assessment Committee* (Washington: National Academy Press, 1983), pp. 488–91.

2. Traditionally, the relative effect of greenhouse gases is measured by their *instantaneous* contribution to global warming (in °C). The problem with this method is that GHGs differ in their lifetimes and chemical transformations. In order to calculate the *total* contribution of each GHG, I have estimated the sum of the instantaneous contributions over the indefinite future (in ° C-years).

TABLE 6-2. Estimated Contribution of Different Greenhouse Gases to Global Warming for Concentration Changes, 1985–2100

	Relative contribution (percent)		
Greenhouse gas	*Instantaneous*[a]	*Total*[b]	*Source of emission*
Sources by chemical compound			
CO_2	76.1	94.7	Largely from combustion of fossil fuels
Methane	9.6	0.8	Poorly understood; from a wide variety of biological and agricultural activities
CFCs	11.6	3.3	Wholly industrial, including solvents and refrigerants
Nitrous oxides	2.7	1.2	From fertilizers and energy use
Sources by economic activity			
Energy	62.8	76.2	CO_2 emissions, nitrous oxides, methane[c]
Agriculture	20.6	19.8	CO_2, methane, nitrous oxides[c]
Industry	0.7	0.1	Methane[c]
Natural	4.3	0.7	Methane, nitrous oxides[c]
Other	11.6	3.3	Chlorofluorocarbons

SOURCES: For chemical compounds, see William D. Nordhaus, "Contribution of Different Greenhouse Gases to Global Warming: A New Technique for Measuring Impact," Yale University, Department of Economics, February 1990; for economic activity, see William D. Nordhaus, "To Slow or Not to Slow: The Economics of the Greenhouse Effect," paper prepared for the 1990 annual meeting of the American Association for the Advancement of Science. Estimates of emission sources are from EPA, *Policy Options*, vol. 1, chap. 2.
a. The effect of concentration change at the instant of release.
b. The relative contribution to global warming over indefinite future.
c. Sources highly uncertain for methane and nitrous oxides.

CO_2 is the principal contributor to global warming, and most of it comes from the combustion of fossil fuels. Of the fossil fuels, natural gas emits 58 percent as much CO_2 per unit of energy as coal, and petroleum 81 percent as much. Next in importance are the chlorofluorocarbons (CFCs), which are small in volume but have a warming potential almost 20,000 times as powerful as CO_2 per unit of volume.

One difficulty in estimating the economic and environmental damage from climatic change and the costs of slowing it is to find an index that can apply to both. In this discussion, I use the "CO_2 equivalent" of GHG emissions, which can provide a unit of measurement for the cost effectiveness of policies in different sectors.

Climate Models and Forecasted Climatic Change

No one disputes the buildup of greenhouse gases. The question is, how can one predict the climatic changes this buildup will cause many years into the future? Today, mathematical models are used to trace the effect of changes in the radiative balance on climatic variables such as temperature, humidity, winds, soil moisture, and sea ice. Because these changes are unprecedented in recorded history, the models cannot rely on historical experience, but must extrapolate beyond current observations.

Large general-circulation models (GCMs) simulate changes in the weather over a century or more. The largest models take average conditions in 500-kilometer-square grids through several layers of the atmosphere. Such models are extremely expensive to run, and a single CO_2 scenario might take a supercomputer up to a calendar year to calculate.

Interestingly, the basic estimates of the effect of a CO_2-equivalent doubling on *equilibrium* appear to have changed little since the earliest calculations. A National Academy of Sciences panel concluded in 1983: "When it is assumed that the CO_2 content of the atmosphere is doubled and statistical thermal equilibrium is achieved, all models predict a global surface warming. . . . [GCMs] indicate global warming [from CO_2 doubling] to be in the range between about 1.5 and 4.5° C."[3] Even with improvements in models and faster computers, there has been no significant narrowing of this estimate since 1983. The current range of scientific opinion is shown in table 6-3. Most experts believe that mean temperature will rise and that precipitation and runoff will increase as a result of the warmer climate. Some models predict hotter and drier climates in midcontinental regions, such as the U.S. Midwest. Few modelers expect to be able to forecast regional climatic changes over smaller areas, and not many modelers expect to do so with any degree of accuracy in the foreseeable future.

Temperature Records

There are several possible ways to test the climate models, but they can only be fully validated when and if global temperatures actually begin to rise. According to available historical records, which have very inadequate coverage for much of the globe, global mean temperature has increased about 0.5° C since the 1880s. Whether the increases observed in the temperature record are consistent with the predictions of climate models is a hotly debated question. Some authors have used statistical techniques to test for the presence of a "greenhouse signal" in this upward trend over the past century. The statistical hypothesis that the global mean temperature follows a trendless process can be rejected at a high level of confidence.

Still, a great deal of evidence suggests that climatic variables fluctuate over periods of a century or more. Unfortunately, there is not enough known about the background trends and cycles to determine whether the warming in recent years is a normal fluctuation or something new and different.[4] Although statistical analysis of the historical record has lagged far behind the construction of new and more refined GCMs, this record is an important, independent source of evidence about the pace of global warming.

3. Carbon Dioxide Assessment Committee, "Synthesis," in NRC, *Changing Climate,* p. 28.

TABLE 6-3. Range of Estimates from Climate Models: Equilibrium Effect of Doubling of CO_2 Equivalent on Main Variables

Variable	Projection of probable global average change	Distribution of regional change	Confidence in prediction[a]: Global average	Regional average
Temperature	+2 to +5° C	−3 to +10° C	High	Medium
Sea level	+10 to +100 cm	. . .[b]	High	. . .[b]
Precipitation	+7 to +15 percent	−20 to +20 percent	High	Low
Soil moisture	???[c]	−50 to +50 percent	???[c]	Medium
Runoff	Increase	−50 to +50 percent	Medium	Low
Severe storms	???[c]	???[c]	???[c]	???[c]

SOURCE: Adopted from L. Mearns, P. H. Gleick, and S. H. Schneider, "Prospects for Climate Change," in Paul Waggoner, ed., *Climate Change and U.S. Water Resources* (Wiley, 1990).

a. The "confidence in prediction" is a subjective estimate of experts of their confidence that the range of estimates provided is accurate. These estimates are based on formal models, historical analogy, and other experience.

b. Increases in sea level are the average of the global rate. Sea-level rise in particular locations will be higher or lower than this figure, depending on local geological conditions.

c. No basis for forecast of this variable.

4. The eminent climatologist James Hansen has stated that he is "99 percent" confident that the warming of the 1980s was associated with the greenhouse effect. See James Hansen, testimony before the Senate Energy Committee, June 23, 1988. According to other respected scientists, however, "No conclusion about the magnitude of the greenhouse effect in the next century can be drawn from the 0.5° C warming that has occurred in the last 100 years." See George C. Marshall Institute, *Scientific Perspectives on the Greenhouse Problem* (Washington, 1989), p. 29.

Uncertainties about Future Climatic Change

A particularly nettlesome aspect of this subject is the chain of uncertainties about the magnitude, timing, and effects of climatic change. Uncertainties include the rate of economic growth over the next century and the rate of emission of GHGs per unit of economic activity, not to mention the rate of atmospheric retention of different GHGs, the equilibrium relationship between increased concentrations in GHGs and climate change, the speed with which actual climate will move to the new equilibrium, and the extent to which climate would change were humans influences absent.

A rational response to climatic change must take these uncertainties into account. I have combined estimates of uncertainty about future climate change from a number of sources.[5] The assumed effect of rising GHGs follows the consensus of modelers that a doubling of CO_2 would in equilibrium raise global temperatures by 3° C (with a standard deviation of 1° C). I have derived an estimate of the lag of actual temperature behind the equilibrium temperature using evidence from GCMs and the historical record.

Figure 6-1 presents my estimated range of greenhouse warming over the period from 1850 to 2000 and an index of actual mean surface temperature over the past century.[6] The median estimate of realized warming from 1800 to 1990 is about 0.7° C, and about 0.6° C from the beginning of the temperature record in 1880. This estimate approximates reasonably well the actual temperature increase of 0.5° C shown by the highly volatile series in figure 6-1.

Figure 6-2 shows the estimated range of greenhouse warming over the next century. My projection of the most likely global temperature rise is 1.8° C from 1800 to 2050 and 3.3° C from 1800 to 2100. According to this calculation, the chances are one in four that the

5. Estimates of the distribution of emissions of some GHGs are derived from William D. Nordhaus and Gary W. Yohe, "Future Carbon Dioxide Emissions from Fossil Fuels," in NRC, *Changing Climate*, pp. 87–153. Estimates of emissions and concentrations of CFCs, methane, and other GHGs are from Environmental Protection Agency, *Policy Options for Stabilizing Global Climate* (February 1989), vol. 1: chaps. 1–6.

6. A description of the procedure for calculating the uncertainties is outlined in William D. Nordhaus, "Uncertainty about Future Climate Change: Estimates of Probable Likely Paths," Yale University, Department of Economics, January 1990.

FIGURE 6-1. Actual Global Mean Surface Temperature and Estimated Distribution of Greenhouse Warming, 1850–2000[a]

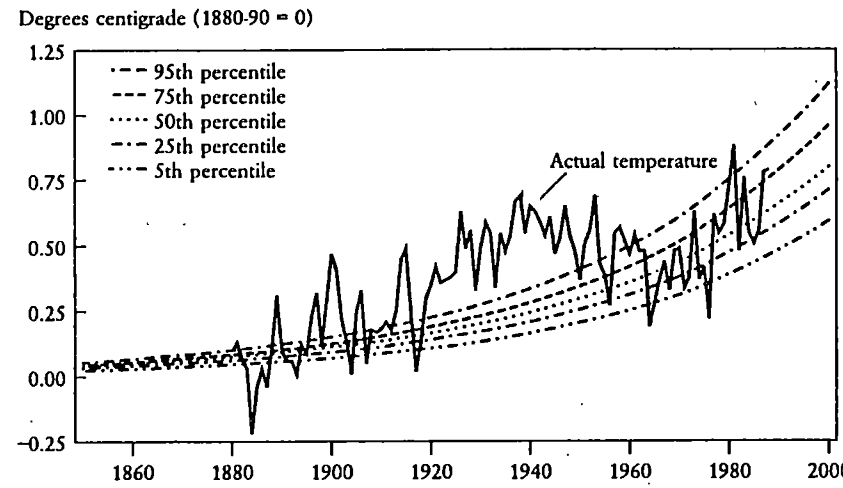
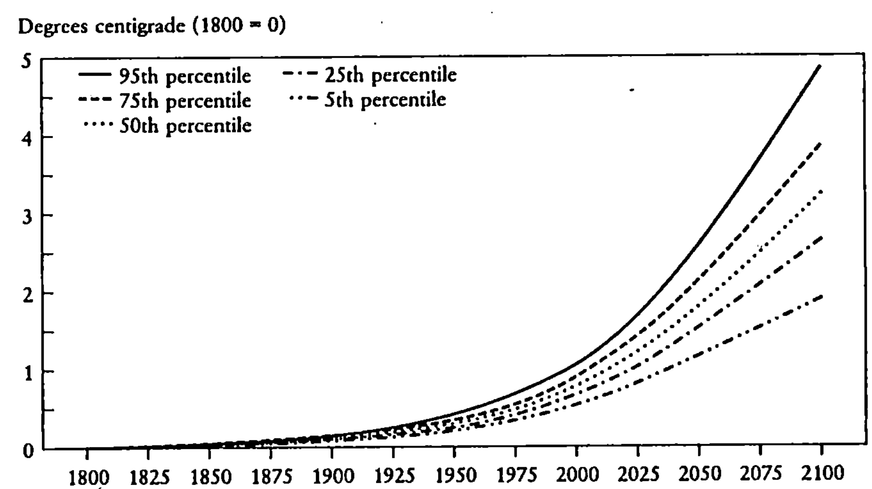


FIGURE 6-2. Calculated Change in Temperature, 1800–2100[a]



a. Percentiles represent distribution of estimated future greenhouse warming. The range spanned by 25th and 75th percentiles represents a range of temperature increases in which warming has a one-in-two chance of lying.

temperature change from 1800 to 2050 will be less than 1.5° C or greater than 2.2° C.

Another important question to ask is when the canonical 3° warming, used in many economic studies, will occur. I estimate that the average temperature will rise 3° from 1800 by 2090; there is a one-in-four chance that this much warming could occur by 2075, but a less than a one-in-twenty chance that it will occur before 2050. On the optimistic side, these calculations suggest that there is almost one chance in two that global mean temperature will rise less than 3° C between 1800 and 2100.

It should be emphasized that projecting climatic change is hazardous at best. But these estimates suggest that a 3° C warming is most likely to occur about a century from now and is quite unlikely to occur before the middle of the next century.

Social and Economic Effects of Climatic Change

Technological change has made it possible for human societies to thrive in a wide variety of climatic zones, with the result that variables such as temperature or humidity have little effect on economic activity in advanced countries. Indeed, since the development of air conditioning, migration patterns in the United States have favored warmer regions.

At the same time, globally averaged surface temperature is not the most important variable to consider when estimating effects. Precipitation or water levels and extremes like droughts or freezes are likely to be more significant. Mean temperature is chosen because it is a useful *index* of climatic change that tends to be associated with most other important changes. Another point to note is that the degree of projected climatic changes is quite small in comparison with the changes normally experienced from day to day. The change in temperature normally experienced between 8:00 and 9:00 A.M. on an April morning is likely to be far greater than the expected change from 1990 to 2090. Few people are likely to notice the CO_2 signal amidst the pandemonium of their daily lives.

Economic Effects in the United States

Climatic change is likely to have different effects on different sectors of the economy.[7] In general, those sectors that interact with unmanaged ecosystems—in other words, that are heavily dependent on naturally-occurring rainfall, runoff, or temperatures—may be hit the hardest. Agriculture, forestry, and coastal activities fall into this category. Most parts of the U.S. economy have little *direct* interaction with climate, and the effects of climatic change are likely to be very small in these sectors. For example, climatic change is not likely to pose a direct threat to activities performed in a carefully controlled environment, such as cardiovascular surgery or the manufacture of microprocessors.

Table 6-4 presents a breakdown of U.S. national income, organized by the sensitivity of the sector to greenhouse warming.[8] Approximately 3 percent of U.S. national output originates in climate-sensitive sectors and another 10 percent in sectors modestly sensitive to climatic change. About 87 percent of national output comes from sectors that are negligibly affected by climatic change. These measures of output may understate the impact of climatic change on well-being because they omit important nonmarket activities—especially leisure activities—that may be more sensitive to climatic change than measured output.

Information from recent studies can be used to speculate on the likely economic effects of climatic change. Of the sectors for which numerical estimates are available, agriculture is the most climate-sensitive. Some studies suggest that greenhouse warming will reduce the yields of many crops, but the higher CO_2 concentrations will have a fertilization effect and will tend to raise yields. A National Academy of Sciences panel concluded that "we do not regard the hypothesized CO_2-induced climate changes as a major direct threat to *American* agriculture *over the next few decades*."[9] The Environmental Protection Agency (EPA) has estimated that a CO_2 doubling may lead to a rise or fall in the value of U.S. agricultural output by as much as $10 billion annually, depending on the magnitude of the climate change.[10] The forest products industry may also benefit from CO_2 fertilization.[11] Water systems (such as runoff in

7. I concentrate on the United States because the most careful studies of the impact of greenhouse warming have been conducted for this country. See Environmental Protection Agency, *The Potential Effects of Global Climate Change on the United States* (December 1989). Although the studies reviewed here use different assumptions, one should envisage the estimated effects as occurring in the second half of the next century.

8. "National income" is total national output measured at factor costs. It equals GNP less indirect business taxes and depreciation.

9. Carbon Dioxide Assessment Committee, "Synthesis," in NRC, *Changing Climate*, p. 45 (emphasis in original).

10. EPA, *Potential Effects of Global Climate Change on the United States*, p. 45.

11. Clark S. Binkley, "A Case Study of the Effects of CO_2-Induced Climatic Warming on Forest Growth and the Forest Sector: B. Economic Effects on the World's Forest

TABLE 6-4. Breakdown of Economic Activity by Vulnerability to Climatic Change, 1981

Sector	National income	
	Value (billions of dollars)	Percentage of total
Total national income	2,414.1	100.0
Potentially severe effect	74.8	3.1
Farms	67.1	2.8
Forestry, fisheries, other	7.7	0.3
Moderate potential effect	243.6	10.1
Construction	109.1	4.5
Water transportation	6.3	0.3
Energy and utilities[a]		
Energy (electric, gas, oil)	45.9	1.9
Water and sanitary	5.7	0.2
Real estate		
Land-rent component[b]	51.2	2.1
Hotels, lodging, recreation	25.4	1.1
Negligible effect	2,095.7	86.8
Mining	45.1	1.9
Manufacturing	581.3	24.1
Other transportation and communication	132.6	5.5
Finance, insurance, and balance real estate	274.8	11.4
Trade	349.4	14.5
Other services	325.2	13.5
Government services	337.0	14.0
Rest of world	50.3	2.1

SOURCE: Based on U.S. National Accounts, *Survey of Current Business*, July 1984, pp. 70–71.
a. National income in electric, gas, sanitary industry is subdivided on the basis of consumption of major components.
b. Estimate of land-rent component is drawn from two sources: national balance sheet data on values of land and structures and surveys of housing prices. Estimate assumes that 25 percent of nonlabor income in real estate industry is from land rents.

rivers or the length of ice-free periods in lakes and rivers) may be affected, but the costs are likely to be determined more by the rate of climatic change than by the new equilibrium climate. Construction in temperate climates will be favorably affected because of a longer period of warm weather.

The effect on recreation and water transportation will be mixed,

Sector," in M. L. Parry, T. R. Carter, and N. T. Konijn, eds., *The Impact of Climatic Variations on Agriculture*, vol. 1 (Dordrecht, Netherlands: Kluwer Academic Publishers, 1988), pp. 197–218.

depending on the initial climate. Cold regions may gain while hot regions may lose; investments in water skiing will appreciate, whereas those in snow skiing will depreciate. But for the much of the economy—manufacturing, mining, utilities, finance, trade, and most service industries—it is difficult to estimate the direct effects of the projected climatic changes over the next fifty to seventy-five years.

Most studies indicate a gradual rise in average sea level over the next century. The consensus until recently was that sea level might rise 70 centimeters in the next century, but recent evidence has cut this estimate sharply. Using the estimate of 70 centimeters, the EPA projects the costs of sea-level rise to be about 6,000 square miles in land lost; a total capital outlay on the order of $100 billion for the protection of high-value property (by levies and dikes); and costs of protecting open coasts.[12] Total costs are approximately 0.1 percent of cumulative gross private domestic investment over the period 1985–2050.

Greenhouse warming will also increase the demand for space cooling and decrease the demand for space heating. The net impact of CO_2 doubling on energy use is estimated to be less than $1 billion at 1981 levels of national income.

The fact that many valuable goods and services are not captured in the net of the national income accounts might affect the calculations. The most notable ones are human health, biological diversity, amenity values of everyday life and leisure, and environmental quality. Some people will place a high moral, aesthetic, or environmental value on preventing climate change, but I know of no comprehensive estimates of what people are willing to pay to stop greenhouse warming.[13] I am aware of no studies that point to major nonmarket costs, but further analysis will be required to determine whether these omitted sectors will affect the overall assessment of the cost of greenhouse warming.

In sum, the climatic changes induced by a doubling of CO_2 concentrations are likely to have only a small effect on the U.S. economy. The best guess today is that the impact, in terms of those variables that have been quantified, is likely to be around one-fourth of 1 percent of national income. However, current studies omit a number of potentially important effects, so this estimate has a large margin of error.

12. But see National Research Council, *International Perspectives on the Study of Climate and Society: Report of the International Workshop on Climate Issues* (Washington: National Academy Press, 1978).
13. EPA, *Potential Effects of Global Climate Change on the United States.*

Economic Effects outside the United States

Only a few preliminary studies have been completed for other countries, so no general conclusions can be drawn at this time.[14] Existing evidence suggests that other advanced industrial countries are likely to experience modest effects, similar to those in the United States. Detailed studies for the Netherlands and a less comprehensive study for six large regions (the United States, Europe, Brazil, China, Australia, and the Soviet Union) found that the overall impact of a CO_2-equivalent doubling will be small and probably difficult to detect over the next half-century or more.[15]

Small countries that are heavily dependent on coastal activities or that experience a significant climatic change may be severely affected. It has been suggested that low-lying areas in Bangladesh may be inundated and that the Maldives may eventually disappear, but the timing of these impacts is conjectural. Particular concerns arise where people or activities cannot easily migrate in response to climate change. Such situations include natural reserves (like Yosemite) or populations limited to small areas (like South Sea islanders).

Developing countries are probably more vulnerable to greenhouse warming than are industrialized countries, particularly those poor countries with few resources to divert to problems connected with climatic change. However, most of these countries depend on agriculture, and the benefits of CO_2 fertilization might offset the damages.

In summary, I conclude that CO_2-induced climatic change is likely to produce a combination of gains and losses of uncertain magnitude and distribution with no strong presumption of substantial net economic damages. This conclusion applies especially to large, wealthy, and geographically diverse countries, with many unanswered questions about small, poor countries. This statement should not be interpreted as being a brief *in favor of* climatic change. Rather, it suggests that those who paint a bleak picture of desert Earth devoid of fruitful economic activity may be exaggerating the injuries and neglecting the benefits of climatic change.

14. Remember that the studies referred to here represent "best-guess" scenarios of climatic change. They omit uncertainties and possible nonlinearities, which are covered later in the chapter.

15. See National Oceanic and Atmospheric Administration, National Climate Program Office, *Climate Impact Response Functions: Report of a Workshop Held at Coolfont, West Virginia* (GPO, 1989).

Possible Responses to the Threat

A wide variety of responses have been suggested to deal with the threat of global warming (see figure 6-3). The option that has received the greatest public attention is to slow or prevent the warming itself. Most policy discussion of this option has focused on reducing energy consumption, switching to nonfossil fuels, and undertaking reforestation to remove CO_2 from the atmosphere. Whatever the final choice, the policy should be structured to obtain the maximum reduction in harmful climatic change for a given level of expenditure.

Second, greenhouse warming could be offset through climatic engineering, for example, by shooting particulate matter into the stratosphere to cool the earth or changing cultivation patterns in agriculture. Although these proposals have not been fully investigated, many environmentalists are opposed to them because "you shouldn't fool with Mother Nature."

Third, an effort could be made to adapt to the warmer climate. As the climate changes and the oceans rise, adaptation can take place gradually on a decentralized basis through the automatic response of people and institutions or through markets. In addition, governments can prevent harmful effects by introducing land-use regulations or investing in research on living in a warmer climate.

Preventive Measures

The most important question policymakers face at present, however, is whether major steps should be taken in the near term to prevent global warming. The answer depends on the costs of reducing GHG emissions relative to the damage that they would cause if they continued unchecked.

The little work that has been done on estimating the costs of slowing greenhouse warming has concentrated on reduction of emissions and atmospheric concentrations of greenhouse gases (the first strategy in figure 6-3). These examples—reducing CFC emissions, reducing CO_2 emissions, and reforestation—are not the only options, but they have been studied most intensively.

In my calculations, I measured the cost of preventive measures in tons of CO_2 equivalent. Measures that cost up to \$5 per ton of CO_2 equivalent are considered inexpensive; at this cost, global warming could be stopped dead in its tracks at a total cost of less than \$40 billion per year (about 0.2 percent of global income). Costs approaching \$10 to \$50 per ton CO_2 equivalent are expensive but manageable (costing ½ to 2½ percent

FIGURE 6-3. Alternative Responses to the Threat of Greenhouse Warming

Slow or prevent greenhouse warming: reduce emissions and concentrations of greenhouse gases
Reduce energy consumption
Reduce GHG emissions per unit of energy consumption or GNP
  Shift to no-CO_2 or low-CO_2
  Divert CO_2 from entering atmosphere
  Shift to substitutes for CFCs
Remove greenhouse gases from atmosphere
  Grow and "pickle" trees

Offset climatic effects
Climatic engineering
  Put particles into stratosphere
  Species selection and cultivation patterns

Adapt to warmer climate
Decentralized/market adaptations
  Population and capital move to new temperate zones
  Corn belt migrates toward Canada and Siberia
Central/governmental policies
  Build dikes to prevent ocean's invasion
  Regulate land use
  Conduct research on drought-tolerant crops

of global income). Measures costing more than $100 per ton of CO_2 are extremely expensive.

Reducing CFC emissions. Reducing emissions of chlorofluorocarbons into the atmosphere should probably be the first strategy to consider because they are extremely powerful greenhouse gases. Scientists believe that new chemical substitutes for the two most important CFCs can be found that will significantly reduce greenhouse warming. A rough estimate is that these substitutes can reduce warming at a cost of less than $5 per ton of CO_2 equivalent. This approach would bring a significant reduction in warming at a modest cost.

Reducing CO_2 emissions. More than 95 percent of CO_2 emissions come from the energy sector and deforestation. These emissions can be reduced by increasing energy efficiency, decreasing final energy services, substituting less GHG-intensive fossil fuels for more GHG-intensive fossil fuels, substituting nonfossil fuels for fossil fuels, and developing new techniques of production along with new products and services.

Because energy interacts with the economy in so many ways, complex models of the energy system are required to estimate the costs of reducing CO_2 emissions. These models must take into account the behavior of

both producers and consumers as well as possible future technological changes. A number of studies have employed such models to provide estimates of the long-run costs of reducing CO_2 emissions.[16] The results point to two main conclusions.

First, small reductions incur low costs. Reductions of up to 10 percent of CO_2 emissions from the energy sector can be attained over the long run at an average cost of less than $10 per ton of CO_2 reduced. At the current global level of emissions (about 6.5 billion tons of CO_2 a year), a 10 percent reduction would cost around $6 billion a year.

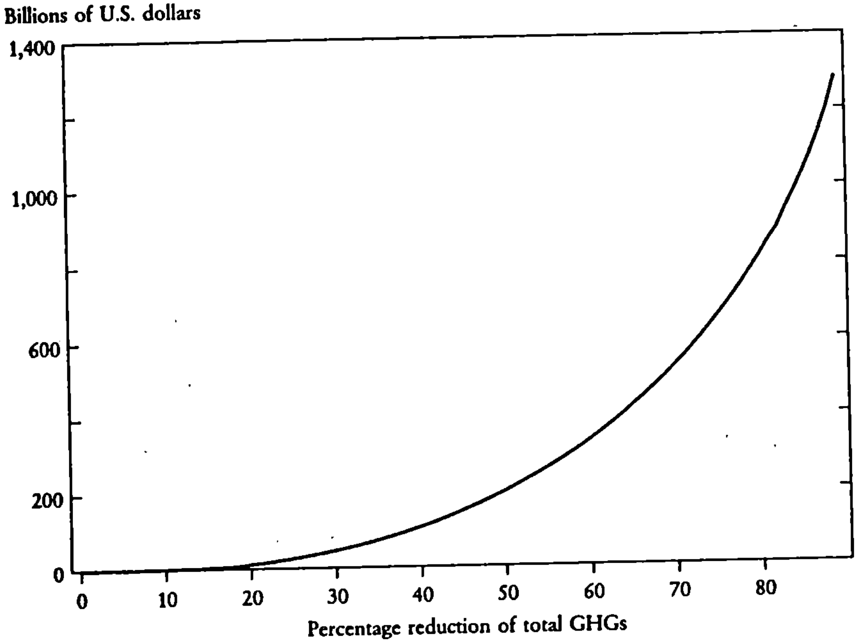
Second, the cost of reducing CO_2 emissions increases rapidly and becomes extreme when the reductions are substantial. I estimate that in the long run, but with today's energy technologies, the marginal cost of a 50 percent reduction in CO_2 emissions is approximately $130 per ton of CO_2. In other words, to induce producers and consumers to reduce their CO_2 emissions by one-half, policymakers would have to impose a carbon tax (or the regulatory equivalent thereof) of $130 per ton of CO_2, which would generate tax revenues totaling about $400 billion a year. The *total* resource cost of a 50 percent reduction in CO_2 emissions is about $180 billion a year, which is slightly less than 1 percent of world output at current price and output levels.

The incremental costs of reducing CO_2 emissions rise rapidly because no substitutes currently exist for many uses of fossil fuels. For example, transportation uses could achieve a large reduction in CO_2 emissions only if people traveled less or fewer goods were transported. Both of these solutions would be quite costly.

Forestry options. Several studies have proposed using trees to remove carbon from the atmosphere. Four interesting suggestions are to slow the deforestation of tropical forests; reforest open land, and thereby increase the amount of carbon locked into the biosphere; introduce a "tree bounty" to subsidize the sequestration of wood in durable products; and store trees indefinitely, in a "tree pickling" program.

16. The studies reviewed for this discussion included estimates based on specific technologies (such as CO_2 scrubbing and substitution of methane for oil and coal); econometric or elasticity analysis (often using highly aggregated models); and mathematical programming or optimization approaches (which often use activity-analysis specifications of energy technologies). For all three of these approaches, one can estimate the cost of reducing CO_2 emissions as a function of the *penalty* or *tax* imposed on those who emit CO_2. Note that all these estimates refer to the long-run cost—that is, the cost after the capital stock has fully adjusted. Attempts to reduce CO_2 emissions in the short run would be much more expensive. These costs do not include any adjustments for unmeasured or external environmental, health, or economic effects.

FIGURE 6-4. Total Global Cost of Greenhouse Gas Reduction[a]



a. The calculations assume 1989 levels of world output and prices and 1989 levels of GHG emissions per unit output. Details of the calculations are provided in William D. Nordhaus, "Uncertainty about Future Climate Change: Estimates of Probable Likely Paths," Yale University, Department of Economics, January 1990.

It has been estimated that deforestation in tropical forests adds 0.5 billion to 3 billion tons of carbon per year to CO_2 emissions (this amounts to 5 to 30 percent of total GHG emissions). Much deforestation is uneconomic in tropical regions even without the greenhouse effect. Therefore, if uneconomical deforestation was stopped, greenhouse warming could probably be slowed down significantly at little cost. The other three options would entail modest costs, but would only be marginally successful in reducing atmospheric concentrations of carbon.

Overall costs of prevention. It appears that a significant fraction of GHG emissions—perhaps one-sixth—can be eliminated at relatively low cost (figure 6-4). The most cost-effective way to slow greenhouse warming would be to curb CFC production and prevent uneconomic deforestation. Putting all the low-cost options together, I estimate that about one-sixth of CO_2-equivalent emissions can be reduced at an average cost of $4 per ton of CO_2 equivalent, for a total cost of about $6 billion a year.

To achieve further reductions in GHG emissions after the low-cost

options have been exhausted, it will be necessary to curb CO_2 emissions, say, through taxes or regulations on the carbon content of fuels. But a sharp reduction of GHGs quickly hits diminishing returns: a 50 percent reduction in GHG emissions in the long run will cost about $200 billion a year, which is about 1 percent of global output; attempts to restrict GHG emissions severely in the short run would be even more expensive.

It will be useful to compare these costs with historical events or regulatory programs. A low-cost program for slowing global warming (say one associated with the low-tax proposal in table 6-5 below) would impose a burden equivalent to a major U.S. regulation, such as those on drinking water, noise, or surface mining.[17]

The more stringent program to cut GHG emissions by half (associated with the high-tax scenario in table 6-5) would impose annual costs of around 1 percent of world output. This can be compared with the costs of *all* environmental, health, and safety regulations in the United States, which were estimated to cost 1 to 3 percent of GNP.[18] Another parallel is with the impact of the energy price increases of the 1970s. Dale Jorgenson estimates that the energy price increase lowered U.S. output growth by 0.2 percent a year, or a total of about 3 percent, between 1974 and 1980.[19] Charles Schultze found similar estimates for the effect of the first oil shock.[20]

Adaptive Measures

Faced with the prospect of a changing climate, societies may decide to adapt. The key adaptions are by private agents—such as consumers and businesses. Decentralized adaptations—population migration, capital relocation, land reclamation, and technological change—will occur more or less automatically in response to changing relative incomes, prices, and environmental conditions.

Governments can also play an important role by ensuring that the legal and economic structure is conducive to adaptation. In particular, they can make sure that the environmental or climatic changes are reliably translated into the price and income signals that will induce

17. See Robert E. Litan and William D. Nordhaus, *Reforming Federal Regulation* (Yale University Press, 1983), chap. 2.
18. Litan and Nordhaus, *Reforming Federal Regulation.*
19. Verbal communication from Dale Jorgenson.
20. Edward R. Fried and Charles L. Schultze, eds., *Higher Oil Prices and the World Economy: The Adjustment Problem* (Brookings, 1975).

private adaptation. This may be difficult to do because markets do not set appropriate prices on most of the effects of climatic change. For example, greenhouse warming may alter the runoff patterns of major rivers, but water is allocated in such an archaic way that there is no guarantee of efficient allocation when water availability changes.[21] Governments can improve adaptation by introducing general allocational devices (such as water auctions) that will channel resources to their highest-value uses. Similar issues will arise over the use of land near sea coasts and in floodplains.

Although adaptation and prevention are often treated as though they were the same solutions, they differ in one crucial respect: whereas preventive policies must generally precede global warming, adaptive policies will be taken as warming occurs. This point is crucial since cause precedes effect by a half-century or more. Immediate action is necessary to stabilize climate, while adaptations can wait for decades.

Although many people recognize that climate changes slowly, they often make the mistake of thinking about future climatic changes in the framework of today's world and ignore the inevitable social and economic evolution that will also take place in the coming decades.[22] If, as suggested earlier, it takes eighty years or more for CO_2 to double, adaptations will be spread over a similar period. Yet social and economic structures will change enormously over that time. Think of how much the world has changed since 1910. That was the age of empires, when the Ottoman, Austrian, and Czarist regimes ruled much of Eurasia. The map of Europe has been redrawn three times since 1910 and is being restructured again. The power density of the United States was about 1½ horsepower per capita as opposed to 130 horsepower per capita today; one-sixth of the horsepower was produced by the 21 million horses in use, which were the leading polluters of the time. Air conditioning, nuclear power, electronics, and computers were unheard of.

Consequently, it would be foolish to prescribe adaptive steps *now* to smooth the transition to climatic changes over the next century. The time scale of most adaptations is much shorter than the time scale of climatic change. CO_2 doubling will take place over the next century, whereas financial markets adjust in minutes, product prices in weeks,

21. See Roger R. Ravelle and Paul E. Waggoner, "Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States," in NRC, *Changing Climate*, pp. 419–32.

22. These issues are discussed at length by Thomas C. Schelling, in "Climatic Change: Implications for Welfare and Policy," in NRC, *Changing Climate*, pp. 449–82.

labor markets in a few years, and the economic "long run" is usually reckoned at no more than two decades. To adapt now would be akin to building a Maginot Line in 1935 to cope with the military threats of the 1990s.

When adaptation is viewed in this light, it seems unwise to undertake costly adaptive policies unless (a) they have such long lead times that they must be undertaken now to be effective; (b) they would clearly be economical even in the absence of climatic change; or (c) the penalty for delay is extremely high. By these criteria, the only effective adaptive measures that surely can be taken now are to promote a healthy economy, strive to internalize most external effects to ensure an appropriate response to changing climatic signals, and raise the national saving rate to provide the investments needed for changing infrastructure.

Policies to Slow Global Warming

The discussion up to now suggests that it is difficult to find large economic costs of climatic change. Even so, the prospect of a catastrophic change might justify taking steps to slow global warming. What should the United States do now to respond to the threat of global warming over the next century?

A Cost-Benefit Approach

On economic grounds alone, any policies that promise incremental benefits worth more than their incremental costs are worth undertaking.[23] As I mentioned earlier, it is useful to define policies as carbon taxes that penalize emissions of greenhouse gases in proportion to their global warming potential. These "taxes" are in a sense a metaphor for explicit steps the government might take to reduce GHG emissions through energy or gasoline taxes, CFC bans or regulatory limits, prohibitions on tree cutting, taxes on carbon emissions, or energy-efficiency standards.

Using the damage estimates outlined above and assuming a low

23. The analysis that follows ignores any relationship or "tie-in" between policies to slow global warming and policies to correct other economic or environmental problems. In fact, these relationships are often quite significant. For example, reducing CFCs is aimed primarily at countering ozone depletion, reducing oil consumption will improve the trade balance, and reducing coal consumption will reduce acid precipitation and other kinds of air pollution. These reinforcing effects are omitted here because the analysis examines appropriate policies to combat global warming; any further effects should be analyzed separately and added to or subtracted from the appropriate policies discussed here.

TABLE 6-5. Measures of Effects of Different Carbon Taxes[a]

Dollars unless otherwise specified

Sector of effect	Level of stringency of GHG reductions: Low tax	High tax
Tax effect		
Tax on CO_2 equivalent (per metric ton carbon)	5.00	100
Effect on fossil-fuel prices (1989 prices)		
Coal price		
Per metric ton	3.50	70
Percentage increase	10	205
Oil price		
Per barrel	0.58	11.65
Percentage increase	2.8	55
Gasoline price		
Per gallon	0.014	0.28
Percentage increase	1.2	23.3
Overall effects		
Estimated percentage reduction of GHG emissions (CO_2 equivalent)	13	45
Total tax revenues, U.S. (billions)	10	196
Estimated global net economic benefits (+) or costs (−), billions of dollars per year, 1989 global economy[b]	12	−96

SOURCE: Nordhaus, "To Slow or Not to Slow."

a. Figures do not take into account the reduction in GHG emissions in response to carbon tax; that is, they are "without feedback."

b. Assumes a discount rate equal to 1 percent in excess of the growth of output and damages from a CO_2 doubling equal to 1 percent of global output.

discount rate on future damages from climatic change, I calculate that an efficient policy would impose a penalty on GHG emissions of about $5 per ton of CO_2 equivalent.[24] This tax or penalty would lead to a total reduction in GHG emissions of about 13 percent, which would include a large reduction in CFCs and a small reduction in CO_2 emissions. Such a tax would amount to $3.50 on a ton of coal, 58 cents on a barrel on oil, and 1.4 cents on a gallon of gasoline (table 6-5). U.S. revenues from a carbon tax of $5 per ton would amount to about $10 billion annually. I also show the impact of a more severe restraint—$100 per ton of CO_2—which would be close to the tax required to reduce CO_2

24. The estimate of the "efficient" policy or tax is obtained by combining the estimated costs of reducing GHG emissions and the estimated damages from climate change. The best policy is a tax or restraint on GHGs beyond which the incremental costs of further restraints exceed the incremental benefits of reducing damages from climate change.

emissions by one-half. The high-tax strategy would clearly have a major impact on the U.S. and global economies.[25]

Realistic Complications

A simple economic cost-benefit analysis is a useful way to start assessing possible actions, but it overlooks two practical questions that complicate policy enormously: how to discount future costs and how to allow for uncertainty.

Discounting future climate damages. The question of how to discount the costs of future climatic change in making current decisions is a particularly thorny one because the atmospheric residence time of CO_2 is hundreds of years. In part, discounting involves an ethical question about the relative valuation of the well-being of current and future generations. But a discount rate on climatic change cannot be chosen arbitrarily and without regard to other decisions. A rate close to the return on capital in most countries—say, 8 percent a year or more—would imply that one should forget about climatic change for a few decades.

In contrast, a low discount rate—say, 4 percent a year or less—would give considerable weight today to climate changes in the late twenty-first century. But such a low discount rate implies that other investment opportunities have been exhausted—hardly an attractive assumption in a capital-starved world. A low discount rate on climatic change along with a high return on capital is simply inconsistent. Faced with the dilemma of a low social discount rate and a high return on capital, the efficient policy would be to invest heavily in high-return capital now and then use the fruits of those investments to slow climate change in the future.

Uncertainty. Clearly, the debate on global warming is rife with uncertainty—about future emissions paths, about the GHG-climate linkage, about the timing of climatic change, about the impact on flora and fauna, about the costs of reducing emissions, and even about the

25. See William D. Nordhaus, "To Slow or Not to Slow: The Economics of the Greenhouse Effect," paper prepared for the 1990 annual meeting of the American Association for the Advancement of Science. This analysis assumes that the discount rate on goods and services exceeds the growth rate of the economy by 1 percent a year. If the damage from a doubling of CO_2 is ¼ percent of total output, then the efficient CO_2 tax is $3.20 per ton of CO_2 equivalent; if the damage is 1 percent of output, the efficient tax is $12.70 per ton. I choose $5 as an illustrative intermediate figure.

speed with which the uncertainties can be reduced. How should decisionmakers proceed in the face of such uncertainty: like generals or environmentalists who assume the worst case, or like cigarette manufacturers who assert that unproved is untrue?

One answer would be to take a "certainty equivalent" or "best guess" approach, ignore uncertainty and the costs of decisionmaking, and plunge ahead. The cost-benefit analysis performed above represents this approach. It is appropriate as long as the risks are symmetrical and the uncertainties are unlikely to be resolved in the foreseeable future. Unfortunately, neither of these conditions is likely to be satisfied for the greenhouse effect.

Risk asymmetry. Virtually all observers agree that the uncertainties of climatic change are asymmetrical; people are likely to be increasingly averse to climatic change the larger the change. To go from a 2° to a 4° warming is much more alarming than to move from a 0° to a 2° warming. The greater the warming, the further the climate moves from its current state and the greater the potential for unforeseen events. Moreover, it is the extreme events—droughts and hurricanes, heat waves and freezes, river flooding and lake freezing—that produce serious economic losses. As probability distributions shift, the frequency of extreme events increases (or decreases) proportionately more than the change in the mean. Whether the increases in unpleasant extremes (like droughts in the corn belt) will be greater or less than the increases in pleasant extremes (like frost-free winters in the citrus belt) is, like most questions about climatic change, unanswered.

In addition, most climatologists think that the chance of unpleasant surprises rises as the magnitude and pace of climatic change increases. One must go back 5 million to 15 million years to find a climate equivalent to what is likely to occur over the next one hundred years; the concentrations of GHGs in the next century will exceed levels previously observed. Climate systems are complex, and it is not known whether they have multiple locally stable equilibria. It is sobering to remember that the Antarctic "ozone hole" was a complete surprise.

Among the kinds of physical effects that have been suggested and cannot be ruled out by scientists today are extensive shifts of glaciers and a subsequent rise in sea level of twenty feet or more in a few centuries; drastic changes in ocean currents, such as the displacement of the Gulf Stream, that would alter the climates of Atlantic coastal communities; and large-scale desertification of the grain belts of the world. Climatic changes might also upset the delicate balance of bugs, viruses, and humans as the tropical climates that are so hospitable to spawning and spreading new diseases move poleward. No one has demonstrated that these effects *will* occur. Rather, it seems likely that unexpected and unwelcome phenomena, like the Antarctic ozone hole, will occur more frequently under conditions of more rapid climatic change.

Learning. The threat of an unforeseen calamity argues for more aggressive action than a plain-vanilla cost-benefit analysis would suggest. However, the possibility that uncertainties about climatic change might soon be resolved argues for postponing action until knowledge is more sound. Most scientists believe that research can improve understanding of the timing, extent, and impact of climatic change and thus sharpen the ability to identify appropriate policies. The best investment today may be in *learning* about climatic change rather than in *preventing* it.

In attempting to prevent climatic change, decisionmakers could easily make some serious mistakes. Imagine that a massive nuclear power program had been mandated for twenty years, only to find that the technology was expensive and unacceptable. Learning to cope with the threat of climatic change includes not only improving the estimates of its consequences, but also performing research to develop inexpensive and reliable ways of slowing climatic change.

A Framework for Policy

In designing policies to slow global warming, government must first recognize that this is a *global* issue. Efficient policies cannot be devised unless all countries take steps to restrict GHG emissions. In order to induce international cooperation, the United States and other high-income nations may need to subsidize the actions of poor nations (say, to slow deforestation or to phase out CFC use). Unilateral action may be better than nothing, but concerted action is better still.

In view of the costs of global warming that have been identified, the world would be well advised to take three modest steps to slow the process and at the same time avoid any precipitous and ill-designed actions that it may later regret. First, a concerted effort should be made to improve understanding of the climate by better monitoring of the global environment; analyzing past climatic records, as well as the environmental and economic effects of past and future climatic change; and evaluating the steps that might be taken to slow climatic change. Great strides have already been made in this direction in the past two decades, but further research is required to sharpen pencils for the tough decisions that will have to be made in the future.

Second, the United States should support research and development (R&D) efforts aimed at finding new technologies to slow climatic change—particularly energy technologies that have low-GHG emissions per unit of output. Very little is invested in such work at present because of a "double externality": private returns are less than social returns, both because the fruits of R&D are available to those who spend nothing on research and because the benefits of GHG reductions are currently worth nothing in the marketplace. More government support should also go toward developing replacements for fossil fuels. Inherently safe nuclear power, solar energy, genetic engineering, and breeding of better biofuels, as well as energy conservation, are particularly promising areas of research.

Third, policymakers should try to identify and accelerate the myriad sensible measures that would tend to slow global warming, often at little or no economic cost. For example, they could strengthen international agreements that severely restrict CFCs, take steps to slow or curb uneconomic deforestation, and try to slow the growth of the uneconomic use of fossil fuels, say, through higher taxes on gasoline, on hydrocarbons, or on all fossil fuels.

These three steps would suffice for today, but should it be desirable to press further, one more step might be worth taking. Global environmental taxes could be imposed on the CO_2-equivalent emissions of greenhouse gases, particularly on CO_2 emissions from the combustion of fossil fuels. A GHG tax on the order of $5 per ton of CO_2 equivalent would be a reasonable response to the future costs of climatic change. A carbon tax would be preferable to regulatory interventions because taxes provide incentives to minimize the costs of attaining a given level of GHG reduction, whereas regulations often do not. To reap the maximum advantage, a carbon tax should be part of an international agreement implementing a tax or restraint in all the major countries of the world.

Some would argue that carbon taxes in particular would be a sensible economic policy. The consumption of fossil fuels has many negative spillovers beside the greenhouse effect, such as local pollution, traffic congestion, wear and tear on roads, and accidents. In addition to slowing global warming, carbon taxes would discourage the consumption of fossil fuels, encourage R&D on nonfossil fuels, favor fuel switching to low-GHG fuels like methane, lower oil imports, reduce the trade and

budget deficits, and raise the national saving rate. Indeed, in the tax kingdom, a carbon tax is the rara avis that increases rather than reduces economic efficiency.

Although the arguments for a carbon tax are persuasive, I hesitate to recommend it at the present time. Negotiating a global carbon tax would be a daunting task even for a president who likes taxes. Reducing the risks of climatic change is a worthwhile objective, but humanity faces many other risks and worthy goals. In providing for the future, in allocating investment resources, there is a long list of important targets—factories and equipment, training and education, health and hospitals, transportation and communications, research and development, housing and environmental protection, population control, and curing drug dependency. Reducing GHG emissions is yet another investment, the goal of which is to prevent the damages from climatic change. Given the numerous urgent economic problems around the world today, it is difficult to justify devoting a much larger share of investment to this area than the amount proposed above.

Current Policy Initiatives

How does this framework for policy compare with the approach taken by the Bush administration? The current political concern about greenhouse warming can be traced in part to the unusual heat wave of the summer of 1988, which coincided with a growing scientific consensus that greenhouse warming indeed posed a serious threat. Candidate George Bush promised to move ahead vigorously on environmental issues and endorsed action to slow global warming. Other heads of government joined President Bush at the Paris summit in July 1989 in recognizing the need for international cooperation to solve global environmental problems.

The administration's policy on global warming was finally unveiled in February 1990.[26] In terms of the four sets of policy measures discussed above, the policies are as follows:

1. Expand knowledge. The administration proposes a large expansion in its funding of studies of "global climate change." The programs it

26. The central political statement is found in President Bush's speech to the Intergovernmental Panel on Climate Change at Georgetown University on February 5, 1990. The 1990 *Economic Report of the President* contains an extensive discussion of the scientific, economic, and policy issues. The details of the budget changes are contained in the budget for fiscal 1991.

TABLE 6-6. Energy Research and Development Funds in Fiscal Year 1991 Budget, Budget Authority

Budget category	Amount (millions of dollars)		Percentage change
	Fiscal 1990	Fiscal 1991	
Total Department of Energy budget	16,423	17,480	6.4
Total, civilian applied research and development	1,298	1,057	−18.6
R&D on technologies with low-GHG emissions	415	436	5.2
Conservation	194	183	−5.9
Solar, renewables, geothermal, other	138	175	27.3
Nuclear (reactor programs only)	83	79	−5.6
R&D on technologies with high-GHG emissions	883	621	−29.7
Coal	829	566	−31.7
"Clean coal"	554	456	−17.7
Other coal	275	110	−59.9
Oil and gas	54	54	0.5
Basic research	2,399	2,680	11.7
Basic physics	872	952	9.2
Superconducting super collider	219	318	45.4
Biological and environmental	418	436	4.4
Basic energy sciences			
Magnetic fusion	320	325	1.6
Other	570	649	13.8
National Science Foundation, basic research	1,651	1,853	12.2

SOURCE: *Department of Energy Posture Statement and Fiscal Year 1991 Budget Overview*, January 1990; and *Budget of the United States Government, Fiscal Year 1991*.

recommends are largely scientific and, at $1.03 billion for fiscal 1991, they represent a 57 percent increase in outlays over the prior year.

2. Reorient energy research and development. Table 6-6 shows a breakdown of the administration's energy R&D budget for fiscal 1991. Although the overall budget of the Department of Energy is designated for a modest increase, civilian R&D programs will decline sharply; there will also be a large cut in fossil energy programs, but little change in low-GHG technologies after correcting for inflation. The reduction in conservation is puzzling given the importance of increasing energy efficiency.

3. Phase out the most powerful CFCs. The U.S. government has taken the lead in this important initiative, which is contained in the Montreal

Protocol of 1987 that commits signatories to cut production in half by 1998. (Note that the decision to phase out CFCs was made in order to prevent ozone depletion; the impact on global warming is a welcome but serendipitous side effect.) Even with the Montreal Protocol in place, however, the climatic impact of CFC emissions is expected to rise over the next century.

4. Plant trees. The Bush administration also proposes a "plant-a-tree" program, with proposed outlays of $175 million annually, to plant a billion trees each year. I estimate this program will reduce annual global emissions of GHGs by about 0.01 percent.

On the whole, the government's policy to date represents a reasonable response to the threat of global warming. The Bush administration has recommended a cautious approach and avoided measures that would set the economy on a path that could not respond flexibly to new information or emerging technologies. If only all national priorities were addressed this well!

Final Thoughts

The United States and other large industrial countries would be well served by continuing to pursue the first three goals outlined above—improving knowledge, investing in R&D in new technologies, and tilting away from greenhouse gases. This approach would prepare the world for whatever developments might unfold in the future—for a tightening of the screws if the threat of global warming accelerates or for a relaxation of policy if science or technology alleviates concerns.

But above all, I would leave policymakers with the following advice: The threat of climate change is uncertain. It may be large, and might conceivably be devastating. But we face many threats. And don't forget that humans have the capacity to do great harm through ill-designed schemes, as the communist experiment clearly shows. Gather information, move cautiously, and fashion policies efficiently and flexibly so that you can respond quickly as new information becomes available on the gravity of greenhouse warming.

Welcome Aboard

MILITARY AIRLIFT COMMAND

UNITED STATES AIR FORCE

FLIGHT INFORMATION

From LENINGRAD To LONDON

Distance 1425 Statute Miles

Flight Time 3 Hours 5 Minutes

Flight Altitude 31,000

Please Set Your Watches Back ~~Ahead~~ 3 HOURS For

A 12:15 ~~AM~~ PM Arrival.

Our Route Will Be Over USSR- FINLAND

The Enroute Flight Conditions Will Be GOOD

DESTINATION WEATHER FORECAST

Temperature 75 °F Precipitation NONE

Wind SW 8MPH Clouds SCATTERED

Other

89TH MILITARY AIRLIFT WING

FRANK PELUSO

Aircraft Commander

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THE WHITE HOUSE

WASHINGTON

June 14, 1990

MEMORANDUM FOR JOHN H. SUNUNU

FROM: D. ALLAN BROMLEY

SUBJECT: SEA LEVEL CHANGE AND ENVIRONMENTAL MATTERS

Like all else in the global warming arena the calculation of sea level change is much more complicated than it appears. First some general comments:

1. Assuming for the moment a rise in atmospheric temperature there are two determining constants at work. First is that at the atmosphere-ocean interface, i.e., how much thermal energy is transferred to the water and at what rate? Second is that of the internal ocean transport mechanisms that carry this thermal energy into the bulk ocean.

2. Considering the Atlantic, as an example, thermal energy transferred to the Gulf Stream is carried northward and in the Greenland-Iceland region it splits with something like 90 percent remaining on the surface and continuing its clockwise surface circulation. This involves the upper 100-200 meters at most. The remainder (about 10%) is carried downward and flows again southward at much greater depth. What this means is that the thermal expansion of the ocean from the bulk of the ocean--depths greater than 100-200 meters-- is delayed by something between 50 and 100 years as compared to that of this 100-200 meter surface layer.

3. It is important to note that for salinity greater than 24.7 permil, the density of sea water increases with decreasing temperature all the way to the freezing point, i.e., there is no maximum in the liquid density vs temperature plot as is the case with fresh water. Also counterintuitively, the coefficient of thermal expansion of sea water increases with increasing pressure i.e., depth.

4. The simple minded expansion calculation--in zeroth order follows from the hydrostatic equation

$p = \rho g h$ where p = pressure, ρ = density
g = acceleration due to gravity
h = depth

and $a = -\frac{1}{\rho}\frac{d\rho}{dT}$ where T is the temperature and
a is the thermal expansion coefficient

5. As water expands the sea levels rises but $\partial p = 0$

$$\partial p = \partial \rho g h + \rho g \partial h = 0 \text{ so}$$
$$a \rho h \partial T = \rho \partial h \text{ and } \partial h / \partial T = a h$$

Here in the zeroth order we simply take an average depth <h> ~3800 m on the assumption (wrong!) of complete thermal equilibrium and set

a (T, p, s) ~ (10 to 20) $\times 10^{-5}/°C$ where s is the salinity, and so find

$$\partial h / \partial T \sim 60 cm/°C$$

6. From this we see that a 0.10C rise in temperature corresponds to 6 cm sea level rise as indeed would a 0.4 C rise in the top 1000m and no temperature change in the lower levels. But this is a <u>very</u> crude model.

7. In the IPCC WG 1 report that predicts an effective CO2 doubling by 2030, the predicted sea level rise is 18cm. This is composed of the following contributions

(a) Thermal expansion--10 cm. The report discusses in some detail an up-to-date box diffusion model that does take into account the variations of salinity and of temperature. The authors of this particular section of the report are publishing a book later this year on their calculation and perhaps reflecting that, their discussions in the IPCC report are not as clear as they might be in places. Indeed one could (as I did) read the policymaker's summary as suggesting that the 10 cm figure came from a linear extrapolation of historical data on sea levels to the 2030 temperature predicted by the GCM models. I find however that the more complex box model calculations were actually used.

(b) Melting of land based glacier ice--7 cm. Here I am quite confident that this number results from simple linear extrapolation of the recent historical data on the retreat of mountain glaciers.

> Note: Such extrapolations are on shaky grounds. The association of past historical behavior with the atmospheric temperature--on a single parameter basis--has very little justification. Similarly, there is little justification for linear extrapolations. The global circulation models give static, point-in-time predictions but no insight into the path from one of these states to the next. The historical record suggests substantial fluctuations about any average. Finally, my earlier memo on the carbon cycle raises its own questions regarding the assumption of effective doubling in 2030.

(c) Melting of the Greenland ice cap--2 cm. All GCM's predict that polar regions will experience greater greenhouse warming than equatorial ones in any warming scenario.

(d) Sequestering of water in Antarctica--(-1) cm. Because of its much greater area and predicated increased snowfall it is anticipated that Antarctica will actually

sequester water in a warming scenario. It bears noting that melting of 0.1% of the Antarctic ice corresponds roughly to a 1 meter change in global sea level.

Adding up all these contributions then leads to the quoted 18 cm prediction for sea level rise in 2030.

What we really need is a solid scientific look at this entire question, recognizing that it is difficult and that many of our input data are fuzzy. I am hoping to interest NOAA and NSF in doing such a study. We can do better!

I share your concern, and Dick Darman's, that by focussing on the anthropogenic greenhouse gas sources and sinks in the policymaker's summary--and the executive summary--and by omitting much mention of the 20 times greater natural fluxes, the authors end up with a distorted perspective even though both anthropogenic and natural fluxes are treated quite well in the body of the main report--which relatively few people will ever read!

I am also concerned that if we appear to accept IPCC WG 1 as ultimate truth then to some extent we have been effectively coopted into accepting the recommendations of the IPCC WG 2 and 3 which may well be substantially different from what we had in mind.

Let me turn then to a different topic.

The June 8 UNEP and RSWG (IPCC WG 3) meetings in Geneva, in my opinion, were particularly important in demonstrating that we are increasingly seen as occupying a centrist position with the EC (Netherlands, FRG, etc.) as the extremists. It will be important for us to continue fostering this view as more and more nations begin to recognize that they were overly hasty and even emotional in their willingness to sign up for targets and timetables last November in Noordwijk. Sanity is returning slowly to this field!

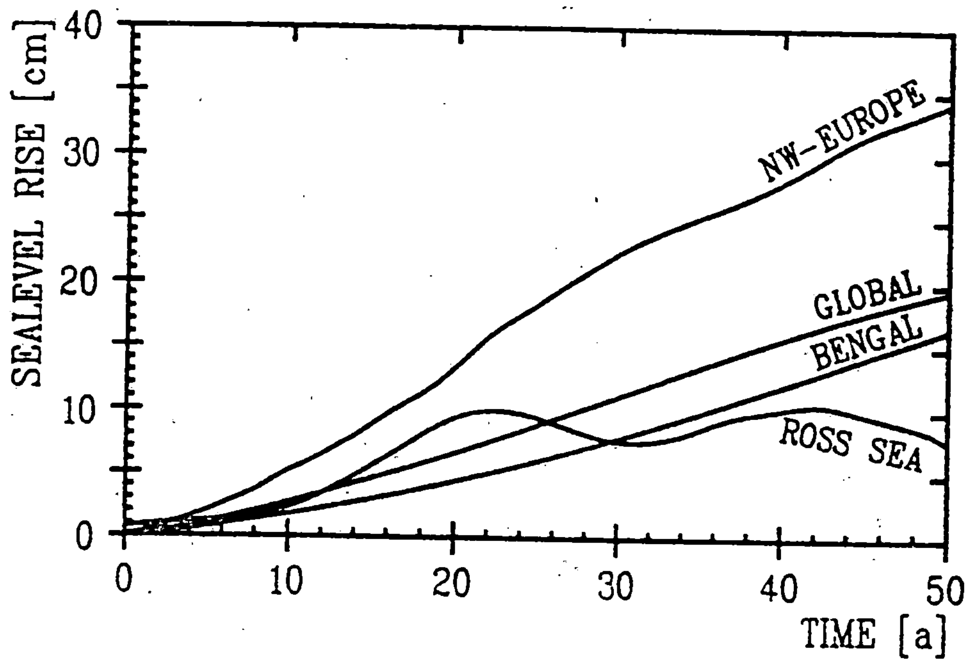
I believe that the President's leadership in this entire global change area is increasingly being recognized--albeit reluctantly in some communities--and that by injecting economics directly into the discussions at the White House Conference we have achieved much more than the international press was prepared to admit at the time.

It will be very important for us to develop our positions in the entire global change and environmental areas as soon as possible because in the face of the rather ridiculous number of conferences, workshops, ministerials, etc., upcoming, in the absence of such firm and generally agreed upon positions, we tend to get ratcheted toward positions that are not in our best interests.

Your suggestions and comments would be most welcome.

Max-Planck-Institut für Meteorologie

REPORT No. 49



OCEAN RESPONSE TO GREENHOUSE WARMING

by

U. MIKOLAJEWICZ • B. SANTER • E. MAIER-REIMER

HAMBURG, MARCH 1990

Ocean Response to Greenhouse Warming

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Abstract

An ocean general circulation model is used to simulate the sea level change resulting from a rapid greenhouse warming. The changes in sea level and sea surface temperature are regionally strongly variable. The projected global mean sea level rise due to thermal expansion alone is 19 cm in 50 years. However, regional values can vary between 40 cm and even a decrease in sea level due to changes in ocean circulation. The simulated oceanic change patterns are compared with measurements.

1 Introduction

An increase in sea level is likely to be a first order impact of greenhouse-gas-induced climate change. Even moderate changes in sea level (less than 50 cm) can have tremendous societal and economic impacts, particularly in heavily-populated regions of the world which are close to sea level. Projecting regional changes in sea level is therefore extremely important.

Several recent studies have considered the transient response of coupled ocean-atmosphere models to time-dependent CO_2 and greenhouse-gas forcing (1,2,3), but have not discussed sea level changes. Virtually all studies which have examined the sea level response have used simple 1-D pure diffusive or upwelling-diffusive models (4,5) in which only thermal expansion is treated. These investigations cannot simulate the regional distribution of sea level change. The only study which has attempted to do this, including both thermal expansion and extremely simplified ocean dynamics, yielded spatially homogenous sea level changes (6). Here we consider both thermal effects and the full dynamic effects associated with changes in oceanic general circulation.

In the present study we isolate the purely oceanic response to a 'pseudo-transient' atmospheric forcing consisting of monthly mean surface air temperature anomalies ($2xCO_2$ minus $1xCO_2$) derived from atmospheric general circulation model (AGCM) equilibrium response experiments. We examine the robustness of certain features of the coupled models' oceanic response (such as inter-hemispheric asymmetry in the sea surface temperature (SST) changes) in a simpler uncou-

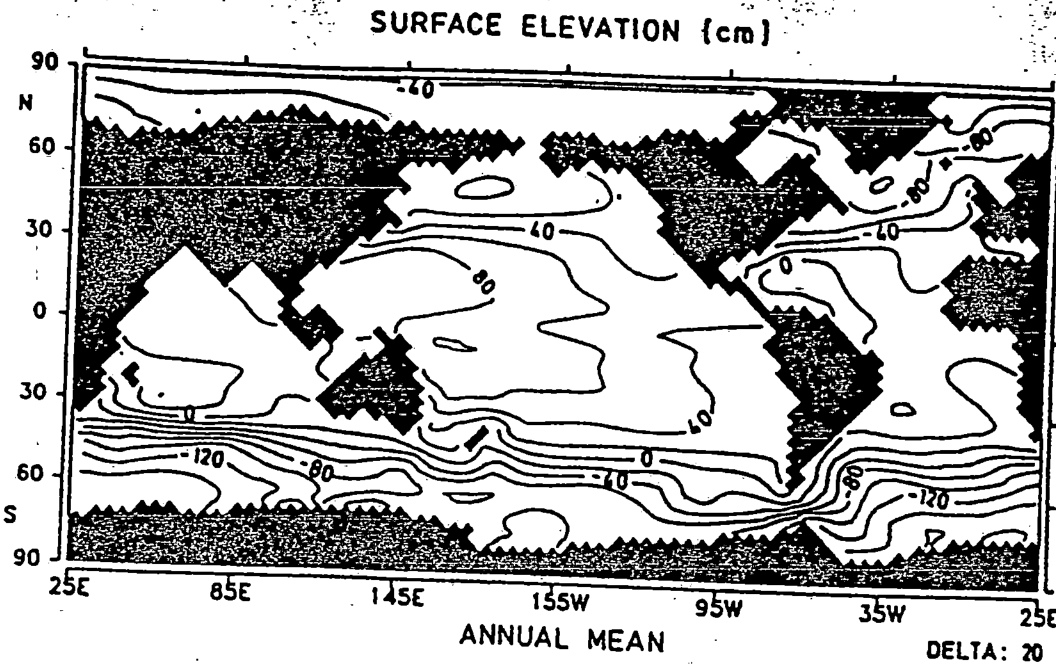

Figure 1a: Annual mean distribution of sea surface elevation of the control experiment.

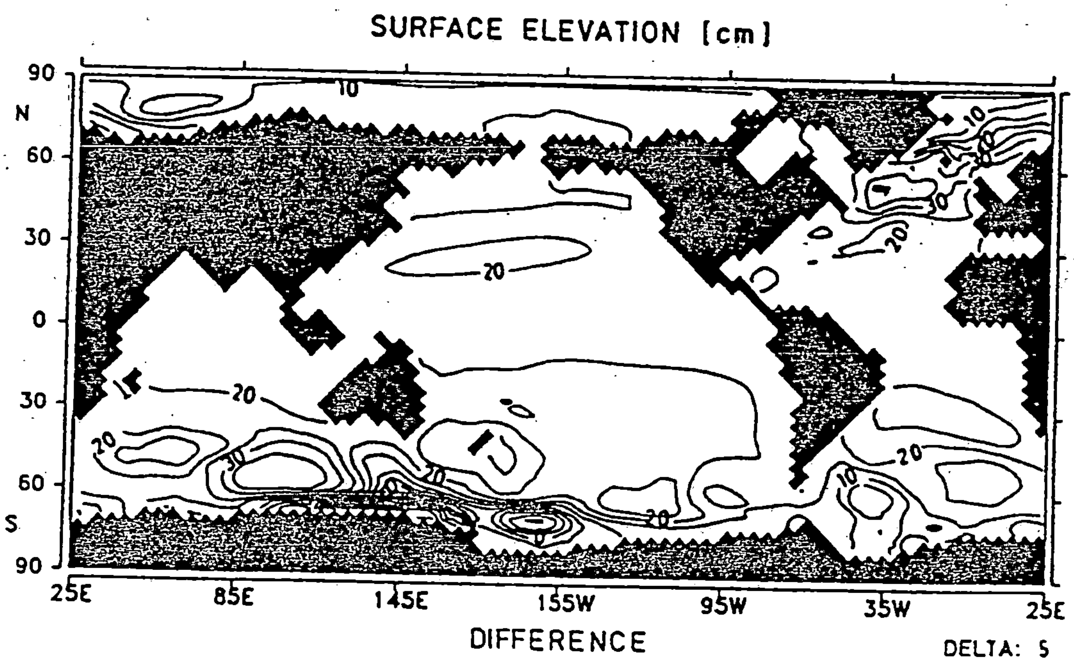

Figure 1b: Pattern of changes in sea surface elevation for year 50 relative to the control experiment. Note that changes in the Ross Sea area are negative.

pled experiment using an ocean general circulation model (OGCM) with realistic thermohaline circulation.

2 The model

We use the Hamburg large-scale-geostrophic OGCM (7). The model is based on the conservation laws for heat, salt and momentum (the latter in a linearized form) and uses the hydrostatic assumption. The flow field is divided into a vertically-averaged barotropic component and the residual baroclinic components. The model has a dynamically active sea surface elevation. Changes in the surface elevation are due to divergence of flow, thermal expansion and fresh water fluxes. The formulation of the model is fully implicit, so that a time step of 30 days can be used, as compared with a few hours typical for explicit integration schemes. A one-layer thermodynamic sea ice model with advection is included.

The horizontal resolution is 3.5 x 3.5 degrees on an E-type grid (8). The model has 11 vertical layers (centered at 25, 75, 150, 250, 450, 700, 1000, 2000, 3000, 4000 and 5000 m).

The model was spun up from an initially homogeneous state and integrated for 10000 years to steady state with climatological forcing (monthly mean wind stress (9) and air temperature (10) and annual mean climatological surface salinity (11)) coupled to the top layer with Newtonian time constants of approximately 2 months. During the last 500 years of spin up the fresh water fluxes required to restore the salinity to climatology were stored and used as forcing in a control run, for which the surface salinity was no longer prescribed but computed from the fresh water fluxes. Initially the model showed a slight drift with this type of forcing, but after a further 4000 years of integration the model again reached a steady state which was very close to the state attained before switching to fresh water flux forcing.

The model exhibits a realistic mean thermohaline circulation (12) with a flow of 17 Sverdrup (10 tons/sec) of North Atlantic deep water (NADW) leaving the Atlantic at 30°S to the Southern Ocean. At 24°N the strength of the meridional overturning is 20 Sverdrup compared to 17 Sverdrup derived from observations (13). The strength of the Antarctic Circumpolar current (ACC) is 122 Sverdrup, compared to 123 Sverdrup ±10 from pressure gauge measurements (14). The annual mean sea surface elevation of the control run is displayed in figure 1a, showing the well-known subtropical gyres and the ACC. The equilibrium circulation fields attained after this procedure were used as initial conditions for the following experiment.

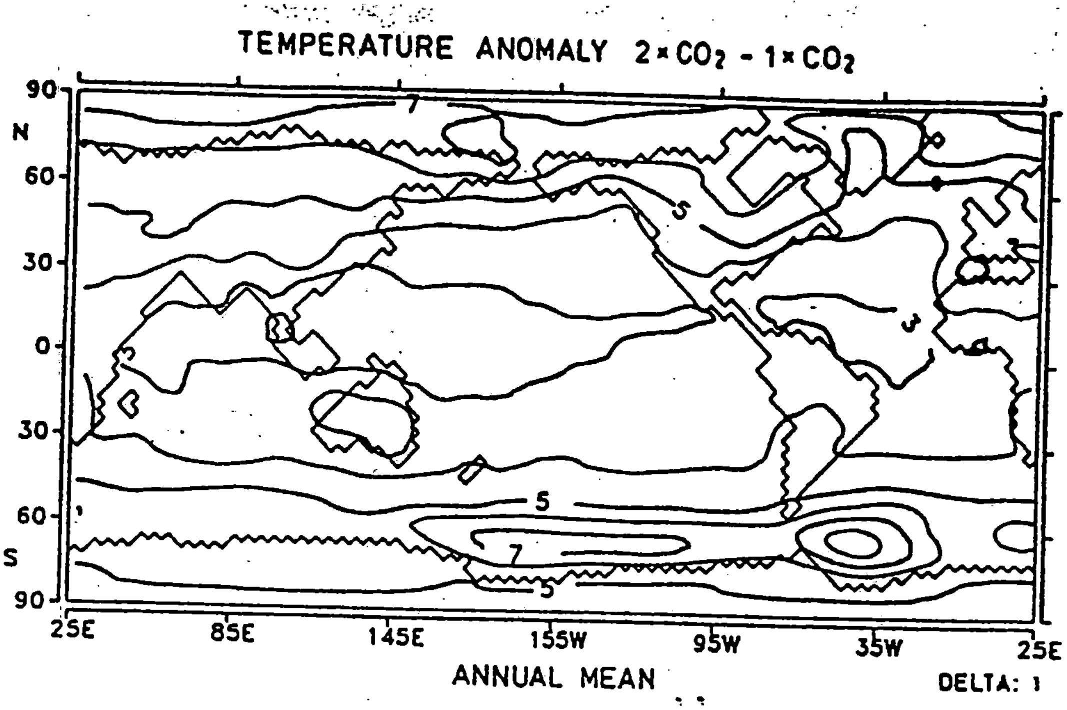

Figure 2a: Pattern of annual mean "model average" surface air temperature anomaly used as forcing for the simulation. The global mean of this temperature anomaly is 4°C (computed over ocean points only). For sources of model data see text.

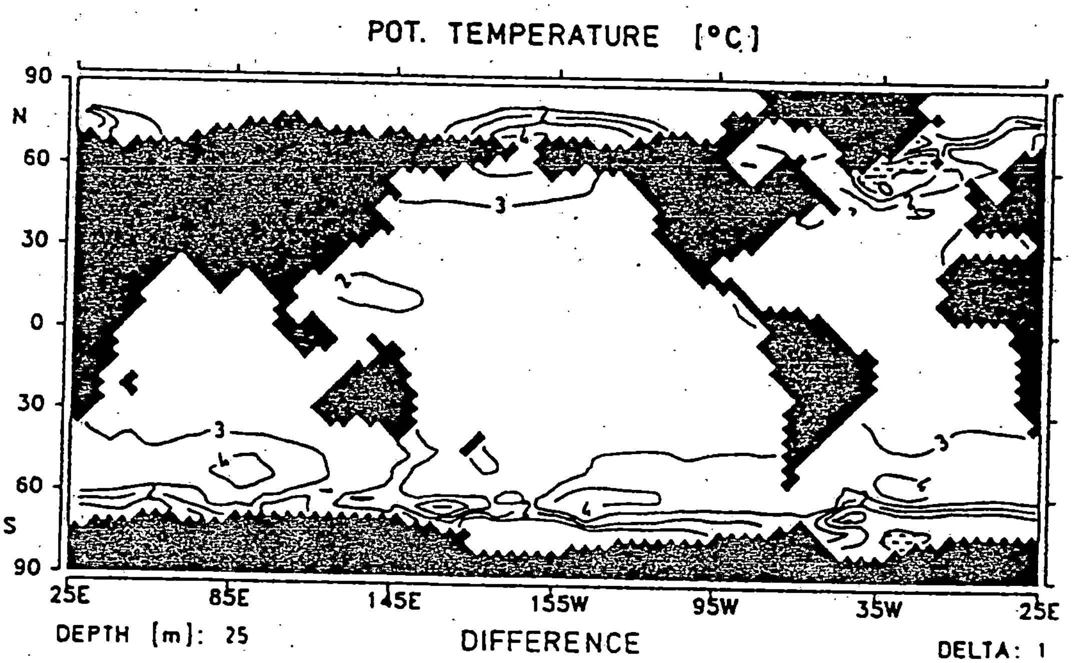

Figure 2b: Geographical distribution of changes in SST in year 50 relative to the control experiment. Shading indicates negative values.

3 The experiment

The ocean model was driven by monthly mean surface air temperature anomalies ($2xCO_2$ minus $1xCO_2$) derived from four equilibrium response experiments conducted with the Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), Oregon State University (OSU) and United Kingdom Meteorological Office (UKMO) AGCMs (15,16,17,18). All AGCMs were coupled with mixed-layer oceans. Rather than using results from a single model only, surface air temperature changes for the four models were interpolated to the OGCM grid and averaged. The resulting model average anomaly fields, defined as an annual cycle over 12 months, utilize all published equilibrium response results from models with comparable levels of atmosphere-ocean interaction, except for results from the National Center for Atmospheric Research (NCAR; 19), which were not available.

The patterns of $2xCO_2$ minus $1xCO_2$ surface temperature changes were very similar for the four models, with poleward amplification of the temperature change in the winter hemisphere due to ice-albedo feedback effects. The major inter-model differences were in the amplitudes of the surface temperature changes. Thus our averaging procedure should not significantly smooth the response patterns while being less biased by individual model sensitivities. The averaged monthly mean anomaly fields were positive everywhere with a mean warming of 4°C over the oceans. The annual mean spatial pattern of the applied temperature anomaly is shown in figure 2a.

We assumed that the model-average patterns are time-invariant, only the amplitude varying during the transition from $1xCO_2$ to $2xCO_2$. To simulate the expected transient temperature increase in response to time-dependent greenhouse-gas forcing, the amplitude evolution was described by the linear exponential function $f(t) = 1 - e^{-(t-t_0)/a}$ with a time constant a = 40 years. The initial time t_0 was set to January 1st for year 0. The time evolution of the mean forcing temperature changes over the oceans is shown in figure 3a; by the year 50 the projected warming is 2.9°C. The forcing due to possible changes in the wind stress and fresh water fluxes relative to the control run was not considered.

The neglect of atmospheric feedback, anomalous wind stress and fresh water flux forcing, and the assumption of time-invariant patterns of the surface temperature change in the forcing fields clearly represent major idealizations in our experimental design. Recent evidence from the few GCM experiments which have been performed with time-dependent greenhouse-gas forcing suggests in fact that important differences may exist between the equilibrium and transient response patterns (1,3,20). We stress that the experiment performed here must be regarded only as a zeroth order test of the sensitivity of the ocean circulation to a specified forcing, and not a prediction. However, we feel that such a test can give valuable insight into typical sea level response properties which may not have been generally appreciated and which would also apply to a more realistic coupled ocean-atmosphere

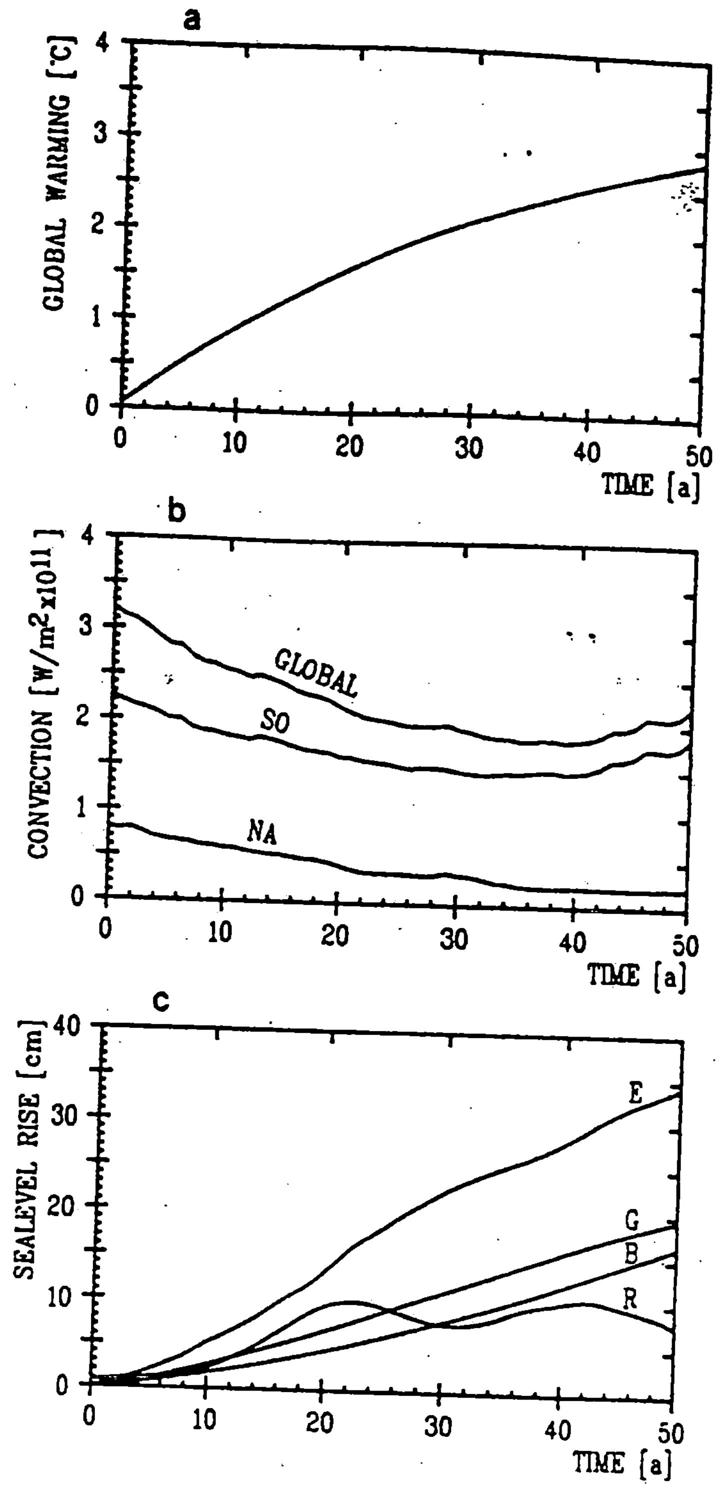

Figure 3a: Time evolution of annual mean globally averaged surface air temperature anomaly imposed on the OGCM.

Figure 3b: Time evolution of global, North Atlantic (NA) and Southern Ocean (SO) deep water formation, measured as rate of loss of potential energy due to convection.

Figure 3c: Sea level rise as a function of time: global mean (G), North West Europe (E), Ross Sea (R) and Bay of Bengal (B).

simulation.

4 Results

The time evolution of the deep water production (measured as the rate of loss of potential energy by convection) is shown in figure 3b. The global deep water production decreases initially and attains a minimum in year 40 (approximately 2/3 of its original value). The fractional reduction is stronger in the North Atlantic than in the Southern Ocean. After the year 40, the global deep water formation increases again. This can be attributed exclusively to increased formation of Antarctic Bottom water (AABW). Generally there is a trend in the deep water formation to a higher fraction of AABW compared to NADW.

Figure 2b displays the changes in SST for the year 50 relative to the control. Although the average surface air temperature anomalies are consistently positive throughout, for all space and time, with the largest values in the winter hemisphere at ice margins (see figure 2a), negative SST anomalies appear in the vicinity of the Irminger Sea and in the Weddell Sea. This pattern of local SST decrease (or much weaker increase than the rest of the ocean) is persistent throughout the entire experiment, with the largest decreases occurring in the Irminger Sea. This is the region in which the model produces most of its NADW in the control run. The result can be attributed to the suppressed production of deep water, and to a resultant reduction of the large convective heat flux from lower layers to the surface, which in the control run was responsible for the relatively warm temperatures in this region. The cooling process is accompanied by a freshening of surface waters in the North Atlantic and higher surface salinities at lower latitudes (figure 4).

A section through the western Atlantic (figure 5) shows the penetration of the warming signal into the deep ocean for the year 50. Except for polar regions, where the suppression of the upward deep convective heat flux is an efficient mechanism for warming the deep ocean, the warming is confined to the upper 1000 m. In the deep Atlantic, a cooling is seen. This is due to changes in the relative contribution of the different deep water sources, with an increased ratio in the production of cold, fresh AABW to warm, salty NADW.

The time evolution of the global mean sea level rise caused by thermal expansion is shown in figure 3c. In year 50 the global mean sea level rise is 19 cm. This is almost completely due to effects above the thermocline. The steady state sea level rise after 2000 years of integration is 51 cm. Whereas the prescribed atmospheric warming in year 50 has reached 72% of the equilibrium value, the response in global mean sea level is only 38.4%. Eighty years were required for the sea level to reach 50% of its equilibrium level, and 210 years to reach 75%. This clearly demonstrates the long time scales involved in the downward penetration of the

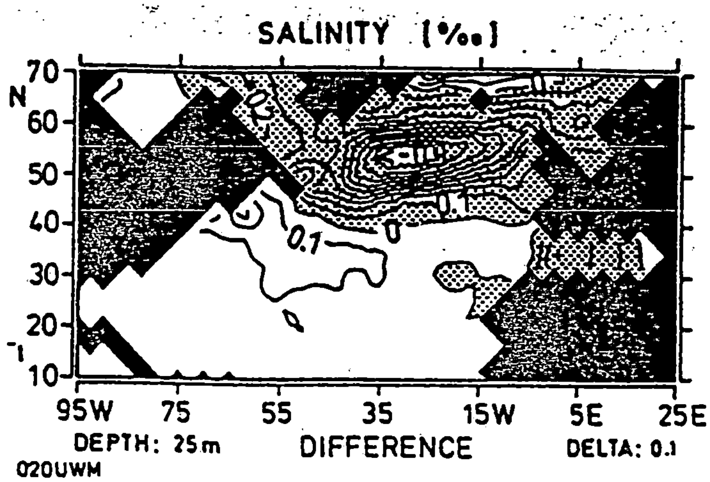

Figure 4: Geographical distribution of changes in the surface salinity in the North Atlantic in year 20 relative to the control experiment. Shading indicates negative values.

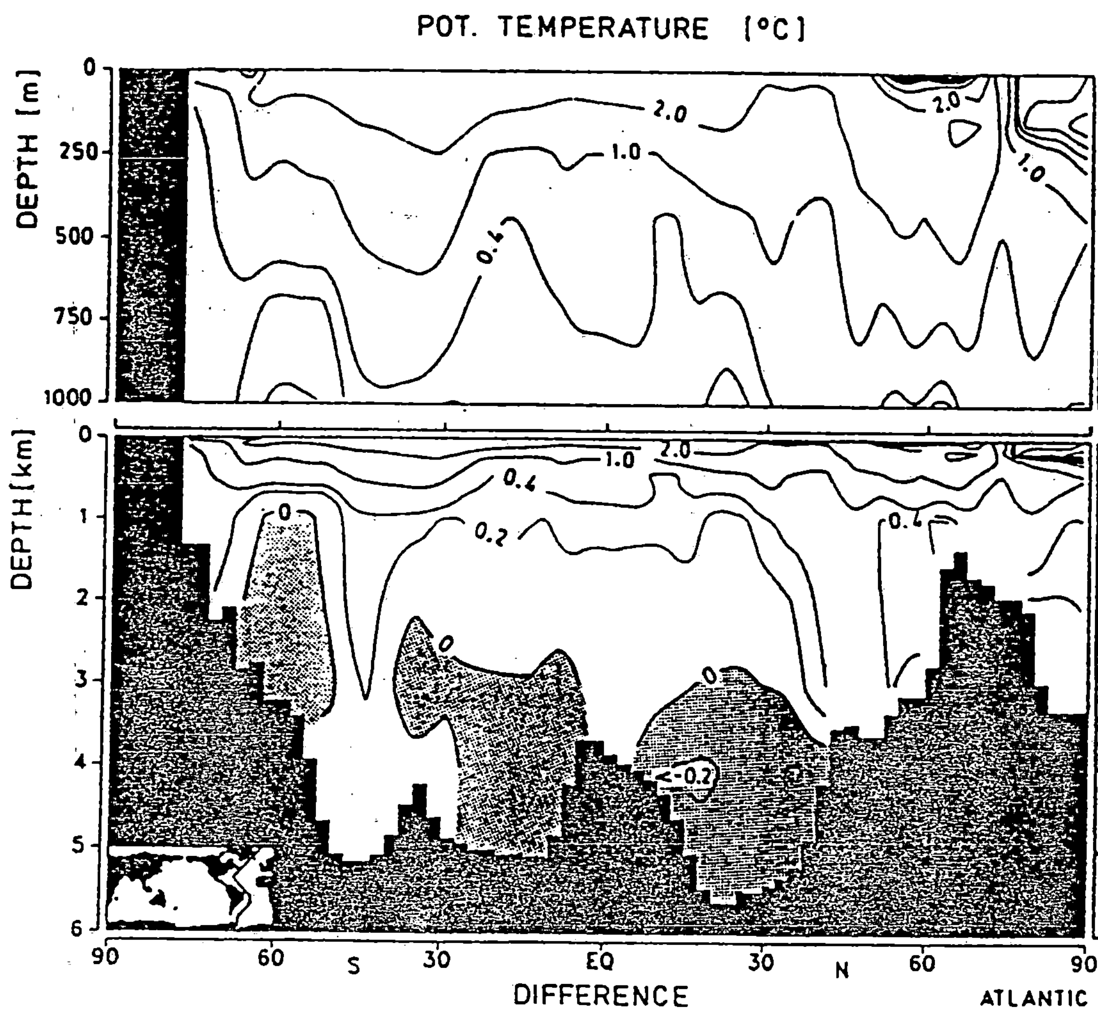

Figure 5: Pattern of change of potential temperature on a meridional section through the Atlantic in year 50 relative to the control experiment. The location of the section is shown in the insert. Shading indicates negative values.

warming signal.

The curves for selected locations differ considerably (figure 3c). The sea level increase of 35 cm in North-West Europe is almost twice as large as the global mean sea level change, while for example the increase in the Ross Sea is much smaller than the global mean. In general, the local sea level changes due to changes in the ocean circulation pattern are of the same magnitude as the changes due to the local thermal expansion, and both vary regionally.

The horizontal distribution of the sea level change for the year 50 is shown in figure 1b. The largest increases in sea level occur in the North Atlantic, as a result of the reduced NADW formation and reduced surface density, and on the northern edge of the ACC, through the southward displacement of the ACC. The increased gradient of sea level across the ACC is due to the larger fraction of bottom water produced at this location, as expressed by the increased vertical homogeneity of water mass properties.

5 Discussion

Coupled ocean-atmosphere models have not been used to investigate the sea level response to greenhouse-gas forcing (1,2,3). We are therefore restricted to comparing our sea level changes with results from simpler models.

Wigley and Raper (21) used an upwelling diffusive energy balance model to estimate the global sea level rise due to thermal expansion alone. For a comparable climate sensitivity ($\Delta T_{2x} = 4.5°C$) to that used here and "best guess" model parameters, they obtained an estimated global sea-level rise of 23 cm from 1985 to 2050. This is in good agreement with the global mean value obtained here (19 cm after 50 years).

With a simple model based on linear concepts of ventilation of the thermocline and Sverdrup balance, Godfrey et al.(6) arrived at a global sea level rise due to thermal expansion of between 13 and 30 cm after 60 years for an assumed global warming of 3°C in the first 40 years. This model also provides information on the spatial patterns of projected changes in sea-level. The authors obtain an almost uniform increase, with slightly weaker values around Antarctica. The disagreement with our results can be attributed to their neglect of changes in the deep water formation and the associated changes in the convective heat flux, which was found to be the most important effect in our experiment.

The circulation changes obtained here can be compared with those obtained in recent experiments with coupled ocean-atmosphere GCMs. A characteristic feature of our experiment, the cooling or reduced warming of SST in zones where deep water is produced, has been found also in a GFDL coupled AGCM-OGCM simulation with sector geography (1). The model's equilibrium response to CO_2-

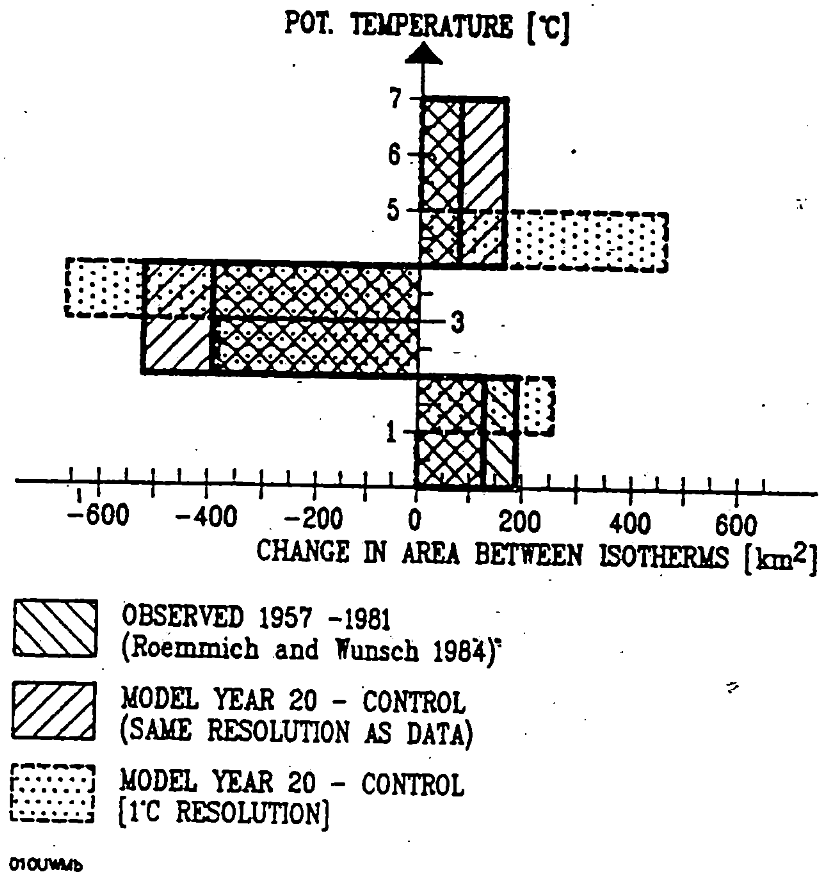

Figure 6: Observed vs. simulated relative changes in area between isotherms for a zonal Atlantic section at 24°N. In order to normalize the curves to the same bottom water temperature, 1°C has been subtracted from the model data. For the model results, two different resolutions have been plotted.

doubling yielded a cooling around Antarctica, with maxima located at the positions of strongest deep water formation in the control experiment. Due to an almost complete lack of NADW formation in this simulation, however, there was no equivalent cooling in the Northern Hemisphere.

The recent GFDL coupled AGCM-OGCM (3) simulation with a transient CO_2 increase of 1%/year (compound) shows similar results to those obtained in the present simulation. After 60 years of integration, the production of AABW is increased relative to NADW and in the zonal average a cooling is found in the deep ocean centered at 30° N (c.f. our figure 5). There is a relatively weak (compared to the zonal average) warming in the North Atlantic and a cooling around Antarctica. This pattern of SST changes generally corresponds to that obtained here, except for a discrepancy between our strong North Atlantic cooling and the weaker warming in the GFDL experiment. This discrepancy may be related to differences in the production of NADW, which is considerably weaker in the control run of the GFDL experiment than in our control run. The surface freshening which we obtain in the North Atlantic is also present in the GFDL simulation. The authors attribute this to a regional increase in runoff and precipitation minus evaporation, an explanation which cannot apply in our case.

The reduced production of NADW and the related cooling offers a possible explanation for the observed trend of decreasing marine air temperatures in the North Atlantic during the last 20 years, in contrast to the increase in Northern Hemisphere and Southern Hemisphere annually-averaged surface air temperature (22). Support for this conjecture is found in the observation of a strong negative salinity anomaly in the North Atlantic during the seventies. This anomaly was accompanied by suppression of convection and surface cooling (23). During this period the surface salinity further south (at ca. 40°N) was increased relative to the late fifties (24). A similar feature is found in the model response (figure 2b).

The simulated cooling in the deep Atlantic is consistent with the trend inferred from a comparison of temperature data taken in 1957 and 1981 for two transatlantic sections at 24°N and 36°N (25). Figure 6 shows the changes in areal coverage for observed (1981 minus 1957) and simulated (year 20 minus Control) isotherms for the section at 24°N. As the simulated deep water is roughly one degree warmer than the observations, the simulated curve has been reduced to the observed potential temperature in the bottom water by subtracting one degree from the simulated temperatures. The similarity between the two curves is striking.

However, although there are some striking similarities between the observed changes from the late fifties to the seventies and early eighties and the pattern which the model produces in response to the imposed warming, we stress that the observed anomalies could well be generated by other effects - for example, anomalous atmospheric circulation patterns (26). In the eighties the surface salinity in the North Atlantic was returning to its former values (23) and the relative cooling trend abated.

6 Conclusions

Significant changes are induced in the ocean circulation in response to an imposed forcing in surface air temperature corresponding to GCM equilibrium response results for a CO_2 doubling. In regions where deep water formation was formerly active, the projected increase in SST is small or even decreases relative to the zonal average. The formation of NADW is more strongly suppressed than the formation of AABW. The subsequent changes in deep water temperatures and salinities result in an effective cooling of the deep Atlantic. This signal may be useful in the detection of CO_2-induced climate change, although signal-to-noise problems are even more serious in the deep ocean than for surface data due to the sparseness of observations. Recently, the measurement of acoustic travel times has been proposed as a technique for monitoring deep ocean temperature changes associated with a CO_2 warming (27). The present experiment stresses the need for reliable ocean circulation response studies to compute the magnitude (and even sign!) of the expected temperature changes.

The projected atmospheric warming of ca. 3°C by the year 50 leads to a global sea level rise of 19 cm due to thermal expansion effects alone. Thermal expansion, however, is only one component of the simulated sea level response. Regionally-specific changes in the dynamic topography of the sea surface are of the same magnitude, with the strongest increases predicted in the North Atlantic, and the weakest increases (or even a decrease) predicted for the Ross Sea. Simpler models without a dynamic ocean cannot treat such effects in a realistic way. This shows the need for using an OGCM with realistic ocean circulation (particularly for the deep ocean) to simulate the regional sea-level changes in response to greenhouse-gas forcing.

The decrease in global deep water formation rates must be expected to have a strong impact on the atmospheric CO_2 content. At present, a significant fraction of the emitted CO_2 is transported with the newly-formed deep water to the deep ocean, thus limiting the increase in atmospheric pCO_2 (7). If the efficiency of this marine transport and storage mechanism is reduced, the increase in atmospheric pCO_2 will be amplified. This positive feedback can have important consequences for the evolution of future atmospheric pCO_2 concentrations.

Acknowledgements

Discussions with Klaus Hasselmann, Tom Wigley and Syd Levitus helped to improve this paper substantially. We gratefully acknowledge the assistance of Marion Grunert in preparing the diagrams.

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NATIONAL ACADEMY OF SCIENCES

2101 CONSTITUTION AVENUE, NW WASHINGTON, D. C. 20418

OFFICE OF THE PRESIDENT

May 22, 1990

The Honorable John H. Sununu
Chief of Staff
The White House
Washington, D.C. 20500

Dear John:

I enjoyed our conversation yesterday -- much substance on important matters. Enclosed is the charge to the Evans panel and some additional information about it. Bob White and I are following the deliberations closely.

Recalling our discussion about the annual carbon cycle, you are correct in that the natural cycle involves quantities of C going in and out of the atmosphere that dwarfs the annual anthropogenic contributions. However, the equilibrium between the atmosphere and the reservoirs is so well balanced that the anthropogenic contribution is not noise on top of large quantities but a clear signal that can be monitored riding through the residual seasonal oscillation. The famous graphs which show this and which you are undoubtedly familiar with are enclosed.

Call on us (NRC/NAS/NAE/IOM) if we can be of help.

Yours sincerely,

Frank

Frank Press
President

Enclosure

Need data through 1989

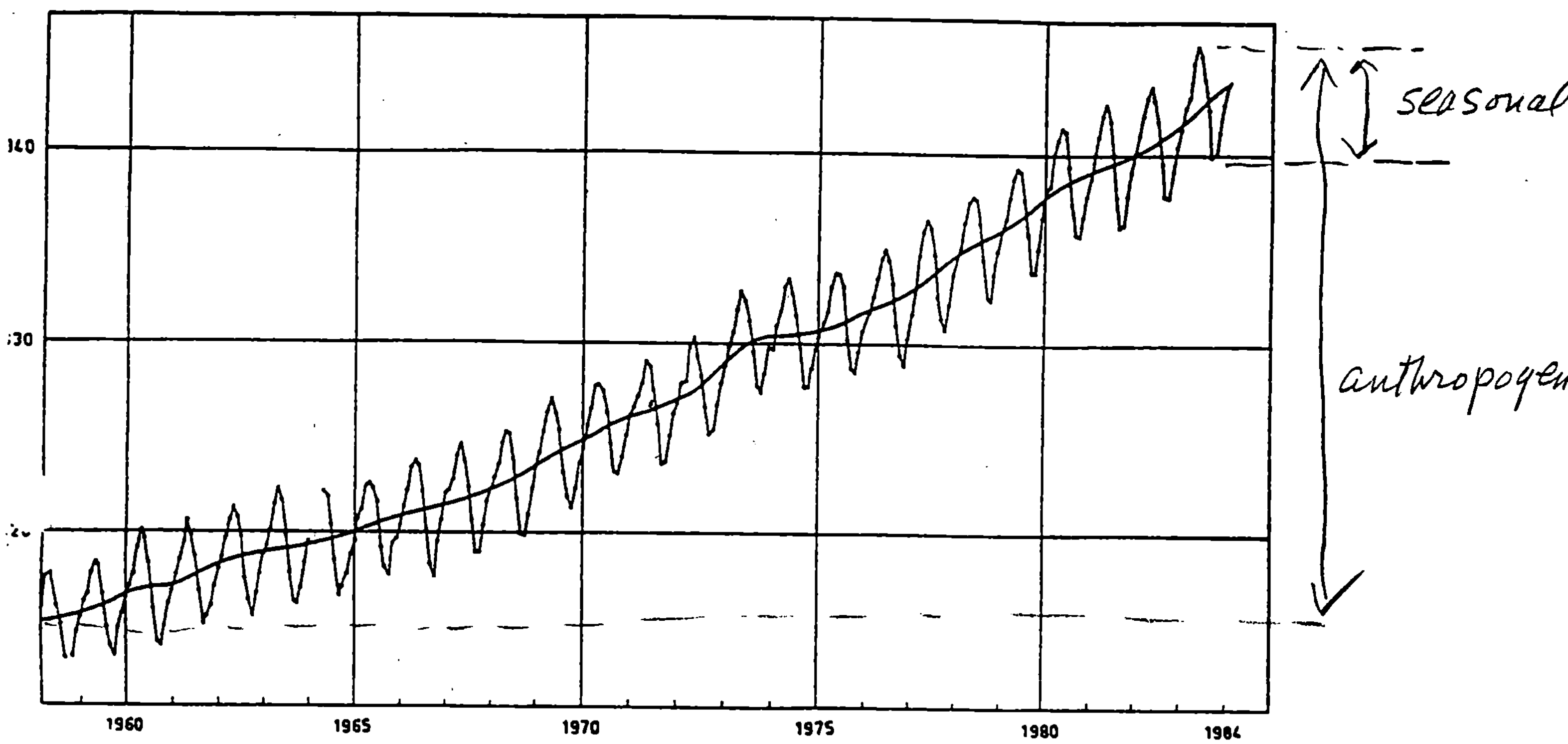

Figure 1 Concentration of atmospheric CO_2 at Mauna Loa Observatory, Hawaii. Dots indicate monthly averages determined from continuous measurements. Based on data reported by Bacastow and Keeling (1981). supplemented by data from recent years supplied by personal communication

Figure 1.1

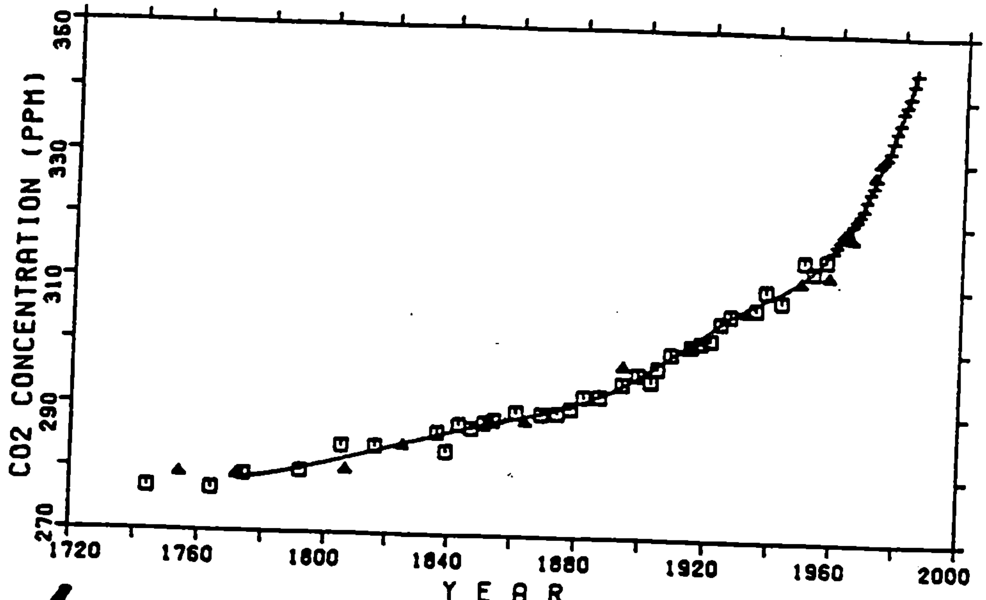

Fig. 2 Atmospheric CO_2 increase in the past 200 years as indicated by measurements on air trapped in old ice from Siple Station, Antarctica, measured by infra-red laser spectroscopy (full triangles; Neftel et al., 1985) and by gas chromatography (open squares; Friedli et al., 1986), and by the annual mean values from Mauna Loa Observatory (crosses; C. D. Keeling, personal communication). The full line is a spline fit through all data.

Fig 1.2

COSEPUP Panel on Policy Implications of Greenhouse Warming

PROJECT MILEPOSTS

Task	Function	Apx. Date
PHASE ONE - START-UP		
1. Initialize project	Establish cost center #	May 89
2. Hire staff		May-Aug 89
3. Name chair		June 89
4. Name panel		July 89
5. Prepare 1st meeting materials, develop work plan	Meet with chair, prepare	July-Aug 89
6. Name subpanels chairs	(after initial meeting)	Aug-Sept 89
7. Name subpanels	(after initial meeting)	Aug-Sept 89
PHASE TWO - ANALYSIS AND WRITING		
8. 1ST PANEL MEETING work plan, assignments	Bias statements, scope,	Sept 89
9. Prepare subpanels	Prepare materials, develop work plans	Sept-Oct 89
10. 1st EFFECTS SUB-PANEL MEETING	Bias statements, scope, work plan, assignments	Nov-Dec 89
11. 1st MITIGATION SUBPANEL MEETING	Bias statements, scope, work plan, assignments	Nov-Dec 89
12. 1st ADAPTATION SUB-PANEL MEETING	Bias statements, scope, work plan, assignments	Nov-Dec 89
13. 2ND PANEL MEETING	Discuss political challenges, anticipated audience, & study approach	Jan 90
14. Circulate draft from impact sub-panel	Summary of discussion from subpanel discussion	Jan 90

COSEPUP Panel on Policy Implications of Greenhouse Warming

PROJECT MILEPOSTS

Task	Function	Apx. Date
15. 2nd EFFECTS SUB-PANEL MEETING	Review draft materials, develop positions, draft conclusions	Feb 90
16. 2nd MITIGATION PANEL MEETING	Review materials, select policies, set evaluation criteria, determine assignments	Feb 90
17. 2nd ADAPTATION SUB-PANEL MEETING	Review materials, review assessments, formulate conclusions, draft report	March 90
18. 3RD PANEL MEETING	Review subpanel progress, discuss report approach, outline, & conclusions	March 90
19. 3rd EFFECTS SUB-PANEL MEETING	Review materials, review assessments, formulate conclusions, draft report	April 90
20. 3RD ADAPTATION SUBPANEL MEETING	Review materials, review assessments, formulate conclusions, draft report	April 90
21. 4TH PANEL MEETING	Review subpanel reports, determine findings and conclusions, draft report	July 90
22. Rough editing of Support Document		July-Aug 90
23. 4th MITIGATION SUBPANEL MEETING	Review response of Synthesis panel (sign-off on review draft)	August 90
24. 4th ADAPTATION SUBPANEL MEETING	Review response of Synthesis panel (sign-off on review draft)	August 90
25. Rough editing of Synthesis Report		Aug-Sep 90
26. Sign-off on review draft		Sept 90

COSEPUP Panel on Policy Implications of Greenhouse Warming

PROJECT MILEPOSTS

Task	Function	Apx. Date
of Support Document		
27. 5TH PANEL MEETING	Approve report for review	Sept 90
28. Informal Briefings	By Evans (to US delegation to 2nd World Climate Conference?)	Oct 90
29. 2nd World Climate Conference		Oct/Nov 90
30. 6TH PANEL MEETING	Review results of 2nd WCC, adjust report if necessary	Nov 90
31. Sign-off on review draft of Synthesis Report		Dec 90

PHASE THREE - REVIEW AND SIGN-OFF

32. Name Review Monitor		April 90
33. Name review panels		April 90
34. Support Document to review panel(s)	(response in 4 wks)	Aug-Sept 90
35. Synthesis Report to review panel	(panel response in 4 wks)	Sept-Oct 90
36. Redraft Support Document	Staff, in conjunction with chairs	Oct 90-Jan 91
37. Substantive editing of Support Document		Oct 90-Jan 91
38. Redraft Synthesis Report	Staff, in conjunction with chair	Nov 90
39. Substantive editing of Synthesis Report		Nov-Dec 90
40. Adjustment of Synthesis Report if necessary	Staff, in conjunction with chair	Dec 90

COSEPUP Panel on Policy Implications of Greenhouse Warming

PROJECT MILEPOSTS

Task	Function	Apx. Date
41. Resubmission of Synthesis Report to review, if necessary		Dec 90
42. Report sign-off for Synthesis Report		Dec 90
43. Report sign-off for Support Document		Jan 91

PHASE FOUR - PUBLICATION AND RELEASE

44. Initial contact with NAP	graphic art	April 90
45. Launch meeting with NAP	market analysis, production planning	July 90
46. Plan release events	with ONPI	Dec 90
47. NAP processing of Synthesis Report	apx. 3 wks (editing, indexing, proofing)	Jan-Feb 91
48. NAP processing of back-up documents	apx. 8 wks (editing, indexing, proofing)	Jan-Feb 91
49. Release of Synthesis Report	(eg. dinner, press conference, seminar)	Feb 91
50. Release of back-up documents		Feb 91

(or octet) rule because there are only eight valence electrons around carbon, their geometries cannot be explained in terms of the tetrahedral sp^3 hybrid orbitals shown in figure *a*. The distances between the gold atoms in the complex are much longer than those in the parent metal and so these compounds cannot be dismissed simply as interstitial metal carbides.

Grohmann *et al.*[1] now demonstrate that the same gold–phosphine unit can also create unusual coordination environments for nitrogen. The ammonium ion, NH_4^+, is isoelectronic with CH_4 and is also tetrahedral, but the corresponding ions NH_5^{2+} and NH_6^{3+} are unknown. The authors find that the isolobal gold compound $[N(AuPPh_3)_5]^{2+}$ has a trigonal bipyramidal geometry (similar to that in *b*) and briefly mention that another German group have made $[N(AuPPh_3)_6]^{3+}$ which is analogous to structure *c*.

The compound $[C(AuPPh_3)_6]^{2+}$ is very closely related to $[Au(P(tol)_3)_6]^{2+}$ (tol = para-tolyl, 4–Me–C_6H_4), which was formulated as an octahedral cluster without an interstitial carbon atom in 1973[4]. But molecular orbital calculations on this cluster[5] indicated that such a formulation was unlikely because it violated the octet rule. In $[Au_6(P(tol)_3)_6]^{2+}$ there are only four valence electrons involved in bonding because each $AuP(tol)_3$ fragment contributes one electron and the cluster carries a total charge of 2+. I proposed in 1976 that if this compound were reformulated as $[C(Au(P(tol)_3)_6]^{2+}$ the additional four electrons donated by the carbon would make it conform with the requirements of the octet rule. The work of Schmidbaur's group has realized this theoretical prediction and confirmed that $[Au_6(P(tol)_3)_6]^{2+}$ is more correctly formulated as $[C(AuP(tol)_3)_6]^{2+}$. So, although these compounds do not conform to the rigid principle that all carbon atoms must have four tetrahedral bonds, their formulae can easily be predicted within a more delocalized description of the bonding derived from molecular orbital theory. New theoretical calculations[6] have defined the closed shell requirements of analogous compounds with two carbon atoms at their centre. It will be interesting to see whether these predictions turn out to be as accurate as the previous ones. □

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MARINE ECOLOGY

Taking a cool look at iron

Anthony G. Davies

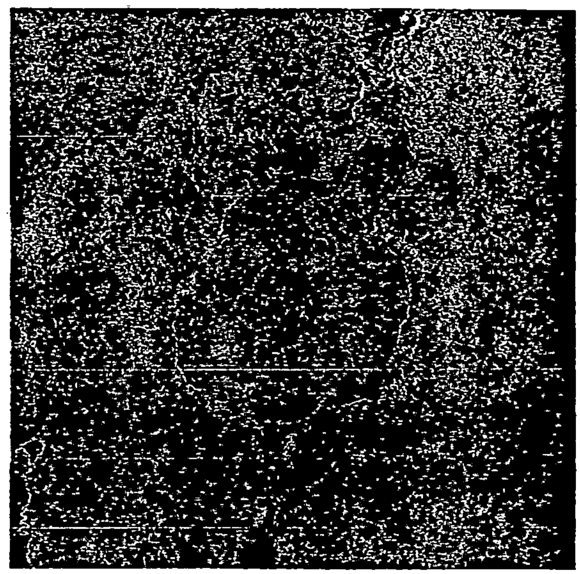
THE rate of photosynthetic carbon fixation by marine phytoplankton is normally controlled by light, temperature and the 'fertilizers' nitrate, phosphate and (for diatoms) silicate. But results of a study by Martin *et al.*, reported on page 156 of this issue[1], suggest that in the open Antarctic Ocean photosynthesis is restricted by a shortage of iron. Iron is a particularly important micronutrient because it is instrumental in the biosynthesis of chlorophyll, and is a main component of ferredoxin which facilitates the intracellular transfer and storage of photosynthetically incorporated energy. Martin *et al.* speculate that, in glacial periods of the Earth's history, iron transported to the Antarctic in wind-borne dust from other continents may have alleviated the iron deficiency. This, they argue, could have stimulated phytoplankton growth thereby increasing the amount of carbon dioxide drawn into the ocean from the atmosphere and contributing to global cooling.

The Antarctic Ocean is unusually rich in nutrients. Concentrations of nitrate, phosphate and silicate are 15–30, 1–2 and 40–90 μmol per kg sea water, respectively[2] (up to three times the corresponding maximum concentrations in the Atlantic water entering the English Channel). On the other hand, chlorophyll *a* concentrations (measures of the phytoplankton biomass) are low (0.1– 1 μg per kg sea water[3]): with a conservative estimate of 1 g chlorophyll *a* per g atom nitrogen in phytoplankton[4], consumption of the nitrate in a bloom would be expected to produce at least 15 μg chlorophyll *a* per kg sea water. Similarly, carbon fixation — typically 0.1 g carbon $m^{-2} d^{-1}$ (ref. 3) — is as slow as that in severely nutrient-depleted oligotrophic regions of the Earth's oceans.

It was suggested as long ago as 1942 that the high productivity of the coastal areas relative to the open Antarctic Ocean is due to the presence of iron or manganese derived from the land[5]. Most of the subsequent attempts to demonstrate that a shortage of trace elements limits phytoplankton productivity have been inconclusive, mainly because of problems in obtaining uncontaminated samples of sea water. When anticontamination techniques have been used, some metal concentrations in the oceans have been shown to be less than previously believed[6]. In particular, for the Gulf of Alaska, another nutrient-rich region, iron concentrations are low enough to limit phytoplankton growth[7,8]. With their new study, Martin *et al.* now extend these results to the Antarctic Ocean.

Iron in sea water is present mainly in colloidal-sized particles of aged hydrous ferric oxide, essentially finely dispersed rust. On the basis of its solubility, the concentration of iron in true solution should be less than 0.1 nmol per kg sea water[9]. Martin *et al.* find that 'dissolved iron' concentrations for the Gulf of Alaska[8] and the open Antarctic Ocean[1] are mostly higher, especially in the deep water. Here the authors use the term 'dissolved' to describe the fraction of iron that passes through 0.4-μm pores of a polycarbonate membrane filter. Whether this iron is truly in solution is central to the debate because there is uncertainty over whether phytoplankton can assimilate iron directly from particles. Although some species produce siderophores — chelating substances with high affinities for iron — to mobilize iron from particles[10] adhering to cell surfaces, it is believed that phytoplankton incorporate only soluble iron produced by the dissolution of the particulate form[11].

Martin *et al.* give no information on total particulate iron in the Antarctic Ocean. In the Gulf of Alaska, concentrations of iron up to 2.4 nmol per kg sea water were present in the top 100 m (ref. 8). Most of this was refractory (unleachable even by 25 per cent acetic acid), so it is not a large source of iron for phytoplankton. The atmosphere therefore



Science Photo Library

False colour satellite image of Antarctic Ocean's summer phytoplankton distribution (red, most dense; blue, least dense).

probably supplies the iron necessary for maintaining the little growth actually occurring[7,8]. It is not clear, though, why the biological availability of aeolian iron settling on the ocean should be any greater than that already in it. In any case, the remoteness of the Antarctic Ocean from the continents results in very low deposition rates, unless, as postulated for the glacial periods, unusual weather conditions prevail[7].

Martin *et al.* hint at the possibility of counteracting global warming by using iron fertilization of the Antarctic Ocean to stimulate phytoplankton growth and thus increase the removal of carbon dioxide from the atmosphere. Assuming (1) that the volume of illuminated nutrient-rich water in the Antarctic Ocean is 3.2 million km^3, (2) that the nitrate concentration is 25 µmol per kg sea water, and (3) the Redfield value of 6.6 for the carbon to nitrogen atomic ratio in phytoplankton, use of all the nitrate should draw down 6.4×10^9 tonnes of carbon (as carbon dioxide) from the atmosphere. This is roughly the same as the annual input of carbon to the atmosphere as a result of fossil-fuel consumption and deforestation[12]. Much of the fixed carbon would initially be carried down into deeper water in moribund phytoplankton and zooplankton faeces. There, decomposition of the organic matter and movement of the deep Antarctic water northwards to warmer areas would eventually return the carbon dioxide to the atmosphere. The effectiveness of such a project would clearly depend on the time-scales of these processes — not to mention a method for uniformly dispersing at least a million tonnes of iron in a usable form. □

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ASTROPHYSICS

Astronomical jet engines

Philip Hughes

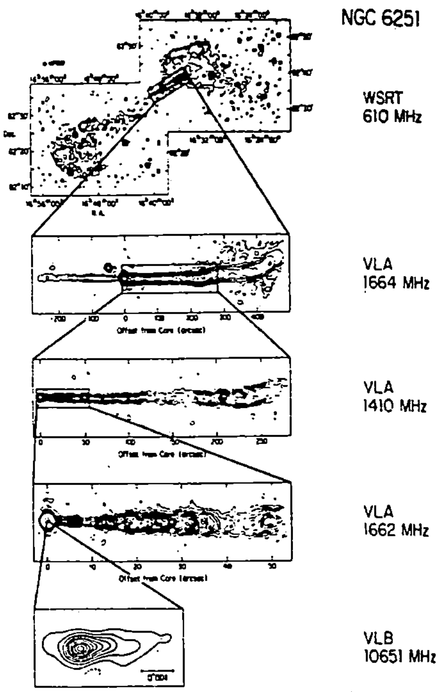

FIG. 1 Maps of the galaxy NGC6251 showing contours of radio brightness at a range of linear scales[1]. The structure in the top panel spans several million light years — much larger than the associated optical galaxy; (whereas the lowest panel covers only a few light years). The 'jet' may be traced continuously from intergalactic to nuclear scales. (Courtesy of A.H. Bridle[1].)

OBSERVATIONS made over the past two decades have shown that a remarkable number of astronomical objects display jets — apparently well-collimated (beam-like) outflows of mass and energy[1-3]. Such flows are associated with active galaxies (and perhaps our own Galaxy), young stars and stellar remnants such as neutron stars. They present the theorist with many challenges, not least of which is to explain their initial collimation. The great majority of current models invoke a disk or torus, tied gravitationally to some massive body, and the collimation is a consequence of a 'funnelling' of material along the system's rotation axis — either by the disk material, or an associated magnetic field. In a novel approach to this problem described on page 136 of this issue, Bell[4] suggests that collimation might be achieved by the anisotropic propagation of radiation through the environment of a 'central engine'.

In early models[5], jets resulted from the formation of bubbles of hot plasma, each with a radius of tens of light years, breaking out of an active galactic nucleus along 'the path of least resistance', namely, the rotation axis of the system. But at that time radio interferometers such as the Very Large Array (VLA) and the Multi-Element Radio-Linked Interferometer Network (MERLIN) had yet to provide the astronomical community with the images (see Fig. 1) that now form the observational core of the field, and intercontinental baseline interferometry had yet to reveal a direct link between intergalactic-scale jets and their associated galactic nuclei. With these advances came the realization that extragalactic jets must originate on scales much smaller than previously imagined.

It has long been realized that the accretion of matter by any object must involve the formation of an accretion disk or torus. Infalling material will possess significant angular momentum, which must be transported away from the inflow by viscous or magnetic stresses in the disk. Although many models assume that the disks are geometrically thin, general arguments suggest that they will become 'bloated'[6]; if the mass accretion rate is low, the disk density will be low, and the disk might not be able to radiate away the energy released by the stresses that enable the transport of angular momentum. The result is a high internal ion pressure which gives rise to an 'ion-pressure-supported torus'. But the survival of such a structure depends critically on whether or not some plasma process can couple the ions and electrons despite the low density — if coupling occurs, the ions' energy can be transferred to the electrons, radiated away, and the disk will not inflate. If the mass-accretion rate is high, the disk density will be high, and the disk will radiate strongly. But in this case, the radiation pressure will cause a bloating of the structure and so a 'radiation-pressure-supported torus' will form. It has become clear that such tori may be unstable[7] and it is quite possible that the same will be true for ion-pressure-supported tori.

To compensate for the uncertainty over the stability of different structures, theorists have constructed models for the generation and collimation of energy for *all* of the recognized classes of disk structure. For geometrically thin disks, collimation can be achieved through the action of a large-scale magnetic field threading the disk, or through the influence of a wind from the upper and lower surfaces of the structure. Particles trapped in the 'funnel' of a radiation-pressure-supported torus are accelerated by the outwardly directed radiation pressure (although the effectiveness of this process seems to be severely limited). In contrast, the inner edge of an ion-pressure-supported torus can sustain electric currents whose associated magnetic field can thread the event horizon of the putative central black hole of an active galaxy and extract its rotational energy (see Fig. 2).

Disks (thick or thin) are natural candidates for the energy-generating and colli-

Duc/Return

sian region would have encountered the prominent Arnhem Land escarpment on moving inland. Malakunanja II occupies a strategic location along its base and may have been brought into use within a few thousand years of first landfall. Any delay is probably accommodated within the estimates of uncertainty about the TL dates. The absence of artefacts in deposits older than 60 kyr at this key site suggests an upper limit on the time of arrival of modern humans in Australia. □

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Iron in Antarctic waters

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WE are testing the hypothesis that Antarctic phytoplankton suffer from iron deficiency[1-3] which prevents them from blooming and using up the luxuriant supplies of major nutrients found in vast areas of the southern ocean. Here we report that highly productive[4] (~3 g C m^{-2} day^{-1}), neritic Gerlache Strait waters have an abundance of Fe (7.4 nmol kg^{-1}) which facilitates phytoplankton blooming and major nutrient removal, while in low-productivity[4] (~0.1 g C m^{-2} day^{-1}), offshore Drake Passage waters, the dissolved Fe levels are so low (0.16 nmol kg^{-1}) that the phytoplankton are able to use less than 10% of the major nutrients available to them. The verification of present-day Fe deficiency is of interest as iron-stimulated phytoplankton growth may have contributed to the drawing down of atmospheric CO_2 during glacial maxima[2,3]; it is also important because oceanic iron fertilization aimed at the enhancement of phytoplankton production may turn out to be the most feasible method of stimulating the active removal of greenhouse gas CO_2 from the atmosphere, if the need arises (J.H.M., manuscript in preparation).

Seawater samples were collected using Teflon-coated, 30-litre Go-Flo bottles suspended on Kevlar line. After filtering through 0.4 μm Nucleopore filters, metals were pre-concentrated from the water by organic extraction[5] or, in the case of Mn, Chelex-100 ion exchange[6]. Small chunks of floating ice were gathered and placed in acid-cleaned plastic bags. After allowing the outer surfaces to melt away, the remaining ice was rinsed with Milli-Q water; meltwater was then collected in bottles and acidified with 4 ml of 6M HCl l^{-1}. As the ice samples were not filtered, the values reported here represent the metals dissolved in the melted water plus the metals that dissolved from particulates when the acid was added and pH lowered to ≈1.9–2.0. Analyses were performed by graphite furnace atomic absorption spectrophotometry. All procedures were carried out using stringent anti-contamination techniques[7].

In the offshore waters of the Drake Passage (Station 2), Fe concentrations in 10 samples ranged from 0.16 nmol kg^{-1} near the surface to 1.55 nmol kg^{-1} at 1,850 m (Table 1). However, when the Fe data were plotted against depth, a 'saw-toothed' profile was observed. It was subsequently determined that in spite of rigorous cleaning, all samples taken from Go-Flo bottle No. 1 had an extra half nmol or so of Fe as well as excess Mn and Co. Nevertheless, the five remaining 'clean' Drake Passage samples are sufficient for initial comparisons of concentrations with those from other offshore waters with an excess of major nutrients, such as the Gulf of Alaska, as well as comparisons with Antarctic neritic waters, such as those from the Gerlache Strait.

Very similar Fe depth distributions were observed in the Drake Passage and the Gulf of Alaska (Ocean Station 'PAPA'; 50° N; 145° W), that is, very low (≈0.10–0.16 nmol kg^{-1}) surface values and increasing concentrations with depth (Fig. 1). As was the case with the Alaska data, increasing Fe values in Drake Passage more or less go along with increasing major nutrient concentrations and decreasing oxygen levels (Table 1); there are not enough data for meaningful regression analysis, however.

Surface Co concentrations (≈25 pmol kg^{-1}) were about the same in both regions; however, the subsurface maximum found in Alaska was not observed here. The Mn maximum commonly found in association with northeast Pacific oxygen minima was also missing (Fig. 1), as would be expected, as subsurface Drake Passage oxygen concentrations do not fall below 180 μmol kg^{-1}. The surface Mn concentration, 0.08 nmol kg^{-1}, is markedly lower than that observed at 'PAPA' (0.52 nmol Mn kg^{-1}). Depth profiles of other elements such as Cu, Cd and Zn (Table 1) were similar to those observed in the northeast Pacific.

Neritic Gerlache Strait concentrations of Fe and Mn were 50–60 times higher than those measured in the open-ocean waters of the Drake Passage (Table 1, Fig. 2). Assuming that the Fe requirement of phytoplankton in relation to nitrogen is about 5000N:1Fe (ref. 2), the 7.4 nmol Fe kg^{-1} is more than enough to support the removal of the ≈24 μmol NO_3 kg^{-1} occurring in the Gerlache. Clearly, there is no Fe limitation, a fact that we believe helps to explain the very high productivity rates reported here (3 g C m^{-2} day^{-1}) (ref. 4) and in other shallow southern ocean coastal regions that should be equally rich in Fe (for example, South Georgia[8] and Deception Island[4]).

In contrast to Fe-rich, shallow, inshore waters, it is apparent that very little Fe is available in offshore Drake Passage waters. For example, if we use an upwelling rate of 0.25 m day^{-1} (ref. 9), the NO_3 upwelling to the surface each day (25 mmol NO_3 m^{-3} × 0.25 m day^{-1} = 6.25 mmol m^{-2} day^{-1}) would be enough to support rates of new phytoplankton productivity of the order of 40 mmol C m^{-2} day^{-1} (6.25 mmol NO_3 × C:N Redfield ratio of 6.6). With the same upwelling rate, and assuming a phytoplankton C:Fe demand ratio of 33,000:1 (ref. 2), the ≈0.10 μmol Fe m^{-3} upwelling with the NO_3 would support only about 1 mmol C m^{-2} day^{-1}. Even using the highest C:Fe ratio[10] for iron-starved phytoplankton (100,000:1) would result in little more than 3 mmol C m^{-2} day^{-1}; that is, less than 10% of the carbon that could be fixed with the upwelled nitrogen.

Clearly, insufficient Fe is introduced by upwelling; and as this station is well offshore (230 km from the Antartic Peninsula), the Fe necessary for phytoplankton growth would have to come from an alternative source such as fallout of atmospheric dust. But, this region is known for having the lowest atmospheric dust loads in the world: Prospero[11] reports only 0.5 ng Fe for the South Pole in comparison to 9 and 90 ng Fe m^{-3} for offshore islands such as Oahu and Bermuda.

The low rates of atmospheric dust input are exemplified by the surface Mn concentration observed at this station,

TABLE 1 Hydrographic, nutrient and trace metal data from the March/April 1989 *Polar Duke* cruise

Depth (m)	Potential temperature (°C)	Salinity (‰)	$\sigma\theta$ ($g\,l^{-1}$)	O_2	NO_3	PO_4	SiO_3	Fe	Mn	Co	Cu	Cd	Zn
Station 1, 56°38'S; 65°20'W, 27 March 1989, North Drake Passage													
50	6.54	34.035	26.72	274	23.0	1.60	2.0	0.16	0.26	27.1	0.71	0.26	0.24
Station 2, 60°46'S; 63°26'W, 28 March 1989, South Drake Passage													
30	2.97	33.798	26.93	314	24.8	1.78	8.8	0.16	0.08	25.4	0.97	0.28	0.63
60	2.96	33.802	26.93	315	25.5	1.76	12.3	(0.52)	(0.20)	(43.3)	1.05	0.28	0.30
110	−0.34	33.928	27.26	341	29.3	2.12	25.7	0.10	0.21	25.8	1.12	0.56	1.49
200	1.51	34.250	27.41	300*	33.9	2.39	51.7	(0.85)	(0.45)	(56.3)	1.46	0.75	3.86
300	1.89	34.399	27.50	225*	35.1	2.54	64.7	0.26	0.25	28.6	1.52	0.81	4.74
400	2.05	34.491	27.56	200*	35.5	2.56	70.2	(0.88)	(0.48)	(47.8)	1.71	0.80	5.10
550	2.11	34.588	27.63	180*	35.4	2.55	89.8	0.40	0.29	27.4	1.68	0.77	5.25
1000	1.92	34.703	27.74	180*	33.3	2.42	96.0	(0.88)	(0.49)	(40.1)	1.90	0.70	5.46
1420	1.56	34.723	27.78	185*	30.3	2.28	101.0	0.76	0.31	21.1	2.07	0.66	5.67
1850	0.80*	34.713*	27.86*	205*	31.6	2.40	108.0	(1.55)	(0.77)	(63.8)	2.38	0.66	6.34
Station 3, 64°55'S; 63°19'W, 1 April 1989, Gerlache Strait													
15	0.92	33.641	26.95	317	23.8	2.19	74.3	7.40	5.05	82.0	2.24	0.56	4.90
50	1.05	33.865	27.13	310	22.9	2.29	81.5	4.70	4.19	58.7	2.09	0.60	5.10
200	0.31	34.389	27.60	272	30.7	2.65	94.0	6.85	3.86	82.0	2.16	0.70	5.90
ice	—	—	—	—	—	—	—	25.9†	—	56.6	0.02	0.02	—

Values for O_2, NO_3, PO_4, SiO_3 are given in $\mu mol\,kg^{-1}$, Fe, Mn, Cu, Cd, Zn in $nmol\,kg^{-1}$, Co in $pmol\,kg^{-1}$.
* Data estimated from GEOSECS Station 78, 61°3'S; 62°58'W, 3 January 1973 (ref. 20). † Total dissolvable Fe. ( ) Contaminated; all taken from Go-Flo No. 1. $\sigma\theta$ is the density of sea water in $g\,l^{-1}$ based on salinity and potential temperature.

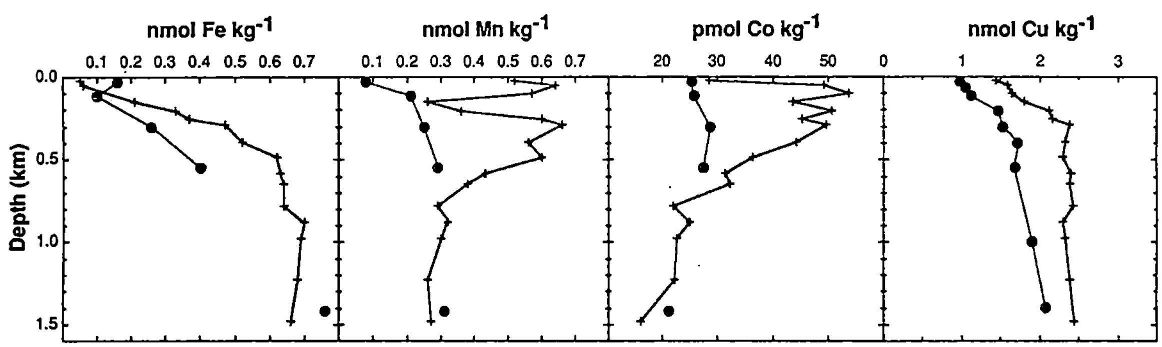

FIG. 1 Drake Passage (Station 2) dissolved Fe, Mn, Co and Cu concentrations (●) compared with those from the Gulf of Alaska (+) Station 'PAPA' (ref. 2).

0.08 $nmol\,kg^{-1}$. In their comprehensive study of Mn in Pacific Ocean surface waters, Klinkhammer and Bender[12] noted that the correlation between Mn and ^{210}Pb suggested aeolian control of surface ocean Mn. They also reported that Mn concentrations were lowest in the Southern hemisphere: 0.3 $nmol\,kg^{-1}$, a value that is about four times higher than the 0.08 nmol we measured in the Drake Passage. To our knowledge, this Mn concentration is the lowest yet reported for surface water in the world ocean; it suggests that Mn deficiency may also be a factor contributing to the limitation of phytoplankton growth in the southern ocean.

In addition to the input from Fe-rich sediments in shallow waters and atmospheric dust in offshore waters, a third Fe supply mechanism exists in the southern ocean—Fe released from melting sea ice. On the basis of the amounts of Fe measured in shallow snow pits (0.02 $nmol\,Fe\,g^{-1}$) (ref. 13) and Holocene ice cores (0.03 $nmol\,Fe\,g^{-1}$) (ref. 14), Martin[3] estimated that the phytoplankton could fix about 150 $mmol\,C\,m^{-2}$ with the Fe made available as sea ice melts during the austral spring and summer (estimates based on 10% available Fe and a C:Fe ratio of 33,000:1). We report here an initial ice Fe concentration of 0.026 $nmol\,g^{-1}$ (Table 1), an amount that agrees well with the values mentioned above. This was glacial ice of unknown age, however, not annual sea ice. Determining the Fe content of annual sea ice is important in view of the amounts of ice involved: Munk[15], for example estimates that 2.1×10^{19} g of ice forms and melts back each year. Obviously, the biological availability as well as the Fe content of the annual ice will need to be known if accurate estimates are to be made of new phytoplankton productivity that could be supported by this potentially important Fe input mechanism.

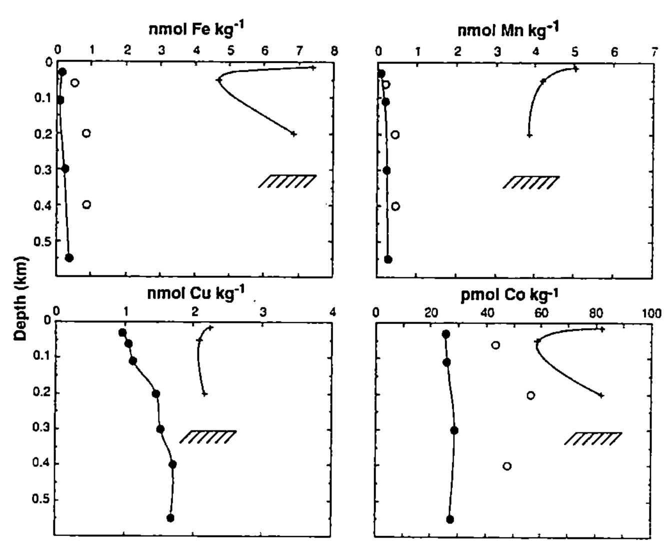

FIG. 2 Drake Passage Fe, Mn, Co and Cu concentrations (●) compared with those (+) from the Gerlache Strait (Station 3). Open circles are contaminated samples collected via Go-Flo No. 1.

In conclusion, the results presented here clearly support the observations of the 1925–27 *Discovery* Expedition scientists—that the neritic areas probably were (and are) rich in phytoplankton because of Fe introduced from land[8,16,17]. The very low dissolved Fe (and Mn) levels in the Drake Passage provide support for our argument[2,3] that present-day plant productivity is limited in offshore waters of the Antarctic because of Fe deficiency. Judging by the unused excess of major plant nutrients, this lack of essential Fe (ref. 18) seems to be severely limiting the power of the 'biological pump' and thus contributing to the raised atmospheric CO_2 concentrations typical of previous and present interglacial periods (preindustrial ≈280 p.p.m.) (ref. 19). In contrast, greatly enhanced Fe input from atmospheric dust[2,3,14] may have stimulated phytoplankton growth and increased the power and efficiency of the biological pump, thus contributing to the drawing down of atmospheric CO_2 during glacial maxima[19].

Note added in proof. We have since shown in experiments in the Ross Sea that Fe will indeed stimulate plankton productivity in the austral spring and summer in amounts that may be relevant to the removal of excess CO_2 from the atmosphere. Further details will be published elsewhere. □

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Glucagon stimulates the cardiac Ca^{2+} current by activation of adenylyl cyclase and inhibition of phosphodiesterase

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GLUCAGON exerts positive inotropic and chronotropic effects in the heart[1,2]. Like its glycogenolytic effect in liver cells[3], the cardiac effects of glucagon are often correlated with adenylyl cyclase stimulation[2,4–7]. Therefore, cyclic AMP-dependent phosphorylation of L-type Ca^{2+} channels[8–10] might be involved in the inotropic effect of glucagon. There have been no reports, however, of the effects of glucagon on the cardiac Ca^{2+} current (I_{Ca}). Also, the physiological effects of glucagon could involve mechanisms other than stimulation of adenylyl cyclase[11,12]. Here we show that glucagon enhances I_{Ca} in frog and rat ventricular myocytes. The effect of glucagon in rats resulted from a stimulation of adenylyl cyclase. In frogs, however, the effect of glucagon on I_{Ca} was smaller and occurred at a concentration tenfold lower than in rats, and adenylyl cyclase was not modified. In addition, cAMP potentiated the effect of glucagon on I_{Ca} in frog ventricle, which correlated with the observed inhibition by glucagon of low-K_m cAMP phosphodiesterase activity. Therefore, this is an example of a hormone that affects cardiac function in a similar way to a variety of synthetic cardiotonic compounds, such as milrinone and Ro-20-1724 (ref. 13). Inhibition of phosphodiesterase activity by glucagon may be essential in animals in which glucagon increases cardiac contractility but does not effectively stimulate adenylyl cyclase[7,14,15].

The effects of 1 and 10 μM glucagon on I_{Ca} were recorded from a frog (Fig. 1*a*) and rat (Fig. 1*b*) ventricular cell using the whole-cell patch-clamp technique. Glucagon increased I_{Ca} in both preparations in a dose-dependent and reversible way. Significant differences were found, however, between the two species. In frog, glucagon increased I_{Ca} with a 50% stimulatory concentration (EC_{50}) of 41 nM (Fig. 1*c*), whereas in rat, the EC_{50} was more than 10 times this value and the maximal stimulation of I_{Ca} was more than three times that in frog (Fig. 1*d*). Furthermore, not all the frog cells responded to glucagon, whereas every rat ventricular cell did. The lack of responsiveness to glucagon in some of the frog cells was probably due to a notably low level of cAMP (see below).

The effects of glucagon in rat quantitatively resembled the effects of isoprenaline, a β-adrenergic agonist. Furthermore, maximal concentrations of isoprenaline and glucagon did not have an additive effect on I_{Ca} (data not shown), and the effects of glucagon on I_{Ca}, like those of isoprenaline, were strongly antagonized by acetylcholine (ACh) (Fig. 2*a*). This indicates that glucagon and isoprenaline act through similar mechanisms in the rat. As β-adrenergic stimulation of I_{Ca} is essentially due to activation of adenylyl cyclase[8–10], we investigated the effects of glucagon on the activity of this enzyme in rat ventricle. As reported previously[2,4–7], glucagon increased adenylyl cyclase activity in a dose-dependent way (Fig. 2*b*), and its effects were antagonized by ACh[16].

In frog, the stimulatory effect of glucagon on I_{Ca} was not reduced by ACh (Fig. 2*c*), in contrast to the activation of I_{Ca} by isoprenaline[10]. Moreover, maximal activation of I_{Ca} by glucagon was about 15 times smaller than that evoked by isoprenaline (Fig. 2*c*). Finally, whereas isoprenaline enhanced adenylyl cyclase activity in a dose-dependent way in frog ventricle, glucagon was unable to modify either basal or isoprenaline-stimulated adenylyl cyclase activity in this preparation (Fig. 2*d*). Therefore, we concluded that the stimulatory effect of glucagon on I_{Ca} in frog cardiac cells was not mediated by enhanced cAMP production.

Cyclic AMP, however, did seem to be involved in I_{Ca} stimulation by glucagon in frog cells. This was suggested by a comparison of the effect of a first application of glucagon to a cell under basal conditions with a subsequent application of the peptide after I_{Ca} had been stimulated by isoprenaline or cAMP. In nine cells in which the basal I_{Ca} was 169.7±22.2 pA (mean ± s.e.m.), an initial application of 3 μM glucagon for 5–6 min increased I_{Ca} by only 7.6±7.2% on average, because five of these nine cells did not respond to the peptide (Fig. 3). After the peptide was washed out, application of submaximal concentrations of isoprenaline (0.1 or 1 μM) or perfusion of the patch pipette[17,18] with cAMP (1 or 3 μM) enhanced I_{Ca} to 969.2±237.1 pA. A subsequent application of glucagon further increased I_{Ca} by 36.4±8.8% (Fig. 3). Also, glucagon increased I_{Ca} more consistently in frog cells under stimulated conditions

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