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In response to questions about the effects of long-term, global-scale changes in the atmosphere raised in congressional hearings, a group of leading experts held a two-day workshop to survey the state of our current knowledge about atmospheric changes and their implications. The workshop participants attempted to identify the currently available knowledge and understanding that might be relevant to the development of public policy and to lay out clearly the limits of our knowledge. The review summarizes the principal conclusions that emerged from the workshop.

The review focuses on the sources, concentrations, and changes of those gases most directly linked to human activities, i.e., carbon dioxide, ozone, and the chlorofluorocarbons; the direct physical effects of changes in trace gases; and the impacts of rising concentrations of trace gases. The review discusses the uncertainties associated with our knowledge of current trends and possible future changes, including ozone trends and the Antarcti ozone hole, and the impacts of rising concentrations of trace gases.

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Current Issues In Atmospheric Change

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Summary and Conclusions
of a Workshop
October 30-31, 1986

Board on Atmospheric Sciences and Climate
Commission on Physical Sciences, Mathematics, and Resources
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Preface

For well over a century, there has been a growing concern about the effects of human actions on the global atmosphere. Initially, discussion centered on the influence of carbon dioxide emissions from fossil fuel combustion on climate. In recent years, numerous further questions have been raised about the effects of long-term, global-scale changes in the atmosphere.

Many of these issues were raised in congressional hearings in the spring of 1986, which prompted a request from a group of U.S. Senators to the National Academy of Sciences for an informative review of the problem area (see Appendix A). In response, the Board on Atmospheric Sciences and Climate convened a group of leading experts in a two-day workshop held at the National Academy of Sciences on October 30-31, 1986. The workshop program was designed to survey in a balanced fashion the state of our current knowledge about atmospheric changes and their implications. The workshop participants attempted to identify clearly the currently available knowledge and understanding that might be relevant to the development of public policy. At the same time, they sought to lay out clearly the limits of our knowledge.

This brief overview document was developed on the basis of the workshop presentations, and it represents the consensus of the workshop participants. The summary should thus be viewed as

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a symposium proceedings rather than as a standard NRC report, which reflects the deliberations and scientific consensus of a carefully selected committee over an extended period of study. It is intended primarily as a background for informative briefings to be presented to the Congress in response to the original request. However, the participants hope that it will also prove useful to a broader audience who share the concerns of the scientific community and the Congress for the continued welfare of humanity on a small but precious planet.

I am most grateful to the workshop participants for their thoughtful presentations and stimulating discussions at the workshop, and for their subsequent contributions to the development of this summary document. I am sure that they also share my appreciation for the efforts of Dr. John S. Perry and the staff of the National Research Council's Board on Atmospheric Sciences and Climate in support of this endeavor.

William D. Nordhaus
Chairman
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Contents

Introduction

Observations in recent years have revealed unmistakable evidence of increasing emissions and concentrations of a number of atmospheric trace gases such as carbon dioxide and the chlorofluorocarbons (CFCs). Earlier concerns were heightened by realization of the growing influence of a range of trace gases on climate and by the very recent and totally unexpected detection of a major depletion of stratospheric ozone over the Antarctic that occurs during the early part of the southern hemisphere spring. Scientific models indicate that changes in trace gases may lead to major and troubling changes in global climate, and that worldwide ozone depletion might produce potentially serious health effects. At a workshop held at the National Academy of Sciences on October 30-31, 1986, a group of invited experts reviewed these observations in the context of the current scientific understanding of these changes and their major implications relevant to policy. This report summarizes the principal conclusions that emerged from the workshop.

1
Trends in Significant Gases

The concentrations of a number of gases are currently increasing in the atmosphere. While they make up but a tiny fraction of the atmosphere, they share a number of important characteristics:

- They are long-lived, so that they become well mixed throughout the global atmosphere.
- They are reliably observed to be changing in concentration.
- They interact strongly with thermal radiation and in some instances with solar radiation, so that their effects are important even at low concentrations.

Such gases include those listed in Table 1.1. Changes in these gases on a global scale have been well established by numerous independent measurements; there is today no doubt about their increasing concentrations. In addition, ozone in the troposphere (at concentrations of 10 to 100 parts per billion) may be increasing at about 1 percent per year, at least in the northern hemisphere. Stratospheric ozone is highly variable, and systematic global-scale trends have not been unequivocally established. This review will focus on those gases most directly linked to human activities, i.e., carbon dioxide, ozone, and the chlorofluorocarbons.

Extremely sharp reductions in seasonal minima in stratospheric ozone have recently been observed over the Antarctic in

TABLE 1.1 Key Atmospheric Trace Gases Whose Concentrations are Increasing

Gas	1985 Concentration	Current Rate of Increase	
CO_2	345 parts per million	1.4 ppm/yr	0.4%/yr
CH_4	1.65 parts per million	18 ppb/yr	1.1%/yr
N_2O	305 parts per billion	0.6 ppb/yr	0.2%/yr
CFC-11	220 parts per trillion	11 ppt/yr	5%/yr
CFC-12	380 parts per trillion	19 ppt/yr	5%/yr

NOTE: Concentrations are global averages. Rates of increase vary somewhat from year to year; values here are representative. (Source: Chapter 3, pp. 56-116 of Atmospheric Ozone 1985, World Meteorological Organization, Geneva, 1094 pp., 1985b.)

the southern hemisphere during the late winter and early spring (September-October), while smaller losses have been observed during the remainder of the year over the Antarctic. Preliminary analyses of satellite data suggest stratospheric ozone depletions of a few percent over the remainder of the globe, but the existence or extent of global ozone depletion has not yet been firmly established.

2
Sources of the Trace Gases

Although the concentrations of many of the trace gases are known to vary due to natural causes, it is well established that many of the current systematic trends in trace gases are caused by human activities.

Carbon dioxide (CO_2) is produced by the combustion of fossil fuels (coal, oil, and gas), as well as by the conversion of forests to other uses. Economic activity currently injects about 5 billion tons of carbon into the atmosphere each year in the form of carbon dioxide. About half of the emitted carbon dioxide stays in the atmosphere, with the rest probably being absorbed by the oceans or taken up in plants. There is no significant doubt that a large part of the observed increase in carbon dioxide arises from human activities.

Methane ("natural gas," or CH_4) is produced by a wide variety of processes, such as bacterial activity in bogs and rice paddies, and in the digestive tracts of animals and insects. Measurements suggest that atmospheric methane is derived mostly from such biological sources. Although their causes are not well understood, changes in methane concentrations correlate plausibly with changes in world population and agricultural activity. Methane releases due to coal mining and natural gas usage may also be important.

The *chlorofluorocarbons* (CFCs) are a group of synthetic compounds used for refrigeration, insulation, foams, and other industrial purposes, and as propellants for items like deodorants. Although the nonessential use of CFCs as aerosol propellants has been banned in the United States, Canada, and Scandinavia, their long atmospheric lifetimes coupled with continued propellant use in other countries and growth in other applications continue to produce further increases in atmospheric concentrations. These gases diffuse into the stratosphere, where they are destroyed by solar ultraviolet radiation, releasing chlorine, which acts to deplete stratospheric ozone. The prime concerns are directed toward the extremely stable CFCs such as CCl_3F (CFC-11), CCl_2F_2 (CFC-12), and CCl_2FCClF_2 (CFC-13).

Nitrogen oxide (N_xO_y) increases arise because of major imbalances in the natural nitrogen cycle. The long-lived, unreactive nitrous oxide (N_2O) is formed naturally by biochemical activity and anthropogenically from combustion and from the increasing use of nitrogen fertilizers. The highly reactive nitric oxide (NO) and nitrogen dioxide (NO_2) are formed during the burning of fossil fuels.

Tropospheric ozone (O_3), an effective greenhouse gas, although relatively short-lived in the atmosphere, is observed to be increasing at many locations in the northern hemisphere. Theoretical models connect ozone increases near the Earth's surface with hydrocarbon and nitrogen oxide (NO_x) releases, and observed increases in ozone are correlated with vehicular traffic and industrial activity.

Stratospheric ozone (O_3) is the product of the continuous interaction of solar ultraviolet radiation with atmospheric oxygen and is destroyed by a number of chemical processes, including several of natural origin. It is thought that injections of CFCs will substantially augment the natural chlorine removal process, with a progressive depletion of stratospheric ozone.

The reasons for the recently observed Antarctic ozone decline are not completely understood, with current theories involving chemical reactions originating with CFCs and bromine compounds, complex dynamic processes, solar variations, or some combination of these causes. Resolution of these questions will require observations in the Antarctic stratosphere. With careful observations, most major uncertainties about the general causes of ozone changes in Antarctica should be resolved within a few years.

3
Direct Physical Effects of Changes in Trace Gases

The gases discussed here are called "radiatively active trace gases" because they affect the Earth's absorption of incoming solar or outgoing thermal radiation and thus influence both climate and the penetration to the surface of harmful ultraviolet radiation in the 280- to 320-nm (UV-B) wavelength range.

All these trace gases absorb thermal radiation from the Earth and re-emit it both upward to space and downward to the Earth's surface. The net effect is to warm the temperature of the Earth's surface through what is called the "greenhouse effect." We already benefit from the greenhouse effect, for were we not already blanketed by the atmosphere, the Earth would be very much colder. Nor is this simply a theoretical speculation. The effect of trace gases on radiation is well established from laboratory measurement; satellite observations clearly show that atmospheric gases are absorbing radiation at the predicted wavelengths; and we need only examine the extremely high surface temperatures of our neighboring planet Venus to see the effects of having a dense atmosphere of such greenhouse gases. Moreover, the cold climate of the last ice age was accompanied by relatively low carbon dioxide amounts, and the warm climate of the Cretaceous era may have been in part due to very high carbon dioxide concentrations.

Until a decade ago, the greenhouse effect of increasing carbon dioxide was the primary focus of our attention. However, with the identification of the strong greenhouse effect of CFC-11 and CFC-12 in 1975, attention to other gases greatly increased. The important non-carbon dioxide trace gases are methane, the CFCs, nitrous oxide, and ozone. Recent studies (e.g., World Meteorological Organization, 1985a) indicate that increases in non-carbon dioxide trace gases in the atmosphere, taken together, are about as important in warming the Earth as is the increase in carbon dioxide.

The influence of changes in concentrations of such trace gases on climate has been investigated by means of numerical models of various kinds based on our best understanding of the processes involved. These models have been substantially validated in their ability to simulate the pattern of contemporary climate and certain past eras of significantly different climate and can be looked upon as comprehensive summaries of our present knowledge of the atmosphere. Because of the enormous physical complexity of climate, our imperfect understanding of parts of the climate system, and the limited computational capability of even the fastest computers, these models will continue to have significant limitations. Many deficiencies remain in the models, including representation of such phenomena as ocean circulation, ice and snow formation, regional rainfall, clouds, and soil moisture storage. Most of these deficiencies only reflect the lack of sufficient data to provide the necessary detailed coverage of the entire globe and cannot be quickly remedied. The most significant remaining uncertainty, however, is the treatment of the formation of clouds and how their number and size might change with the increasing addition of further greenhouse gases to the atmosphere.

Nevertheless, simulations of the effects of increases in the greenhouse gases permit a number of plausible inferences to be drawn with considerable confidence. In most model studies to date, atmospheric carbon dioxide concentrations have been doubled (e.g., from 300 to 600 parts per million) and then maintained at that concentration until a new equilibrium climate is established in the model. We expect such results to apply equally well to a combination of carbon dioxide and other trace gases where the total effect on the radiation budget is equivalent to a doubling of carbon dioxide.

Some of the possible climate responses to increased greenhouse gases are rather well understood; others remain controversial. Listed below, in approximate order of current scientific confidence, are some important inferences on climate changes due to increased greenhouse gases drawn from these studies.

- *Large Stratospheric Cooling* (virtually certain). Reduced ozone concentrations in the upper stratosphere will lead to reduced absorption of solar ultraviolet radiation and therefore less heating. Increases in the stratospheric concentration of carbon dioxide and other radiatively active trace gases will increase the radiation of heat from the stratosphere. The combination of decreased heating and increased cooling will lead to a major lowering of temperatures in the upper stratosphere.
- *Global-Mean Surface Warming* (very probable). For a doubling of atmospheric carbon dioxide (or its radiative equivalent from all of the greenhouse gases), the *long-term* global-mean surface warming is expected to be in the range of 1.5 to 4.5°C. The most significant uncertainty arises from the effects of clouds. Of course, the *actual* rate of warming over the next century will be governed by the growth rate of greenhouse gases, natural fluctuations in the climate system, and the detailed response of the slowly responding parts of the climate system, i.e., oceans and glacial ice.
- *Global-Mean Precipitation Increase* (very probable). Increased heating of the surface will lead to increased evaporation and, therefore, to greater global mean precipitation. Despite this increase in global average precipitation, some individual regions might well experience decreases in rainfall.
- *Reduction of Sea Ice* (very probable). As the climate warms, total sea ice is expected to be reduced.
- *Polar Winter Surface Warming* (very probable). As the sea ice boundary is shifted poleward, the models predict a dramatically enhanced surface warming in winter polar regions. The greater fraction of open water and thinner sea ice will probably lead to warming of the polar surface air by as much as 3 times the global mean warming.
- *Summer Continental Dryness/Warming* (likely in the long term). Several studies have predicted a marked long-term drying of the soil moisture over some mid-latitude interior continental regions during summer. This dryness is mainly caused by an earlier termination of snowmelt and rainy periods, and an earlier

onset of the spring-to-summer reduction of soil wetness. Of course, these simulations of long-term equilibrium conditions may not offer a reliable guide to trends over the next few decades of changing atmospheric composition and changing climate.

- *High-Latitude Precipitation Increase* (probable). As the climate warms, the increased poleward penetration of warm, moist air should increase the average annual precipitation in high latitudes.

- *Rise in Global Mean Sea Level* (probable). A rise in mean sea level is generally expected due to thermal expansion of sea water in the warmer future climate. Far less certain is the contribution due to melting or calving of land ice.

4
Current Issues

Because of the complexities of both atmospheric chemistry and the dynamical processes of the atmosphere itself and because many changes are greatly influenced by human actions, our present ability to forecast the specifics of future changes is extremely limited. In this section the uncertainties associated with our knowledge of current trends and possible future changes are discussed.

OZONE TRENDS AND THE ANTARCTIC OZONE HOLE

Total ozone amounts around the globe have been measured by ground-based instruments at an internationally coordinated network of stations for the past 30 years, and in a few instances for as long as 50 to 60 years. Satellite sensors have provided some two-dimensional measurements since about 1970 and have furnished ozone data continuously since 1978. These data can be coordinated with ground-based observations. Low-resolution estimates of the vertical distribution of ozone are obtained from the ground-based network and from satellite observations. Balloon-borne instruments occasionally provide high-resolution data concerning the vertical distribution of ozone. Because of the high natural variability of ozone concentrations, it has been difficult to validate models or to detect any systematic trends.

The discovery of the ozone "hole" in the Antarctic stratosphere was a complete surprise to scientists and presents an important challenge to current models of atmospheric processes. We are, unfortunately, hampered by the limited observational network, especially in the south polar region, in seeking an explanation of this phenomenon. In the next year or two, research flights in the Antarctic stratosphere itself will be needed to determine the mechanisms of the recently observed ozone changes. On a longer term, continued research and monitoring will be required to reach an understanding of the processes determining global ozone concentrations.

CLIMATE CHANGE

Detection of climate changes and validation of the models employed for climate prediction are closely linked. Our understanding is severely hampered by the fact that the climate system is currently in disequilibrium in two respects. First, significant factors influencing climate, such as trace gas concentrations and surface characteristics, are known to be changing rapidly as a result of human actions. Secondly, it is believed that these are inducing slow changes in the heat content of the ocean and ice masses that may be significantly impeding and complicating the progress of observable climate changes. Moreover, we know that global climate is highly variable even in the absence of human influences. Thus, we cannot yet reliably distinguish with high confidence climate fluctuations stemming from natural causes from those induced by human activities.

Confident detection of human influences on climate will require not only careful monitoring, but also the development of climate models that can enable us to sort out the effects of other variables. Among the major factors that impede the effort to detect human influences on contemporary climate are the following:

- *Solar Radiation.* Satellite measurements of total solar radiation have been reliably maintained only since the late-1970s and show variability in the range of 0.2 to 0.3 percent.
- *Ocean-Atmosphere Interactions.* The ocean serves as a vast reservoir for both carbon and heat, and is inadequately treated in current models. Moreover, ocean monitoring is currently inadequate for detection of long-term changes.

- *Volcanic Disturbances.* Volcanic activity often injects large amounts of aerosols into the high atmosphere that produce transient and detectable changes in climate, but the extent to which volcanic activity has influenced contemporary climate variations over the recent past is uncertain.
- *Regional Turbidity Changes.* Increases in airborne particles—such as observed over industrialized areas and over the Arctic basin—could affect the absorption of solar radiation and thus influence climate.
- *Surface Changes.* Land use changes alter surface reflectivity (albedo), along with water uses and flows. The albedo is also affected by changes in ice and snow cover.
- *Cloudiness.* Clouds are only crudely modeled at present, and reliable data on cloud distribution are only just becoming available. Yet changes in the amount, distribution, or optical characteristics of clouds could powerfully influence climate.
- *Natural Variability.* Even after all known sources of variability are accounted for, some fluctuations in the climate record remain unexplained. These may stem from unrecognized variables, or may simply represent unpredictable components of natural variability in the climate system.

MONITORING AND DETECTION OF CHANGES IN THE ATMOSPHERE AND CLIMATE

Careful long-term monitoring of climate is needed not only for the detection of climate changes, but also for the development of improved models. Monitoring also permits the early detection of unanticipated effects such as the Antarctic ozone hole. Since increases in greenhouse gases and their effects on climate are slow processes, it is clear that long-term monitoring will be required to detect effects. Attention should therefore focus on quantities that have been adequately observed on a global scale, and whose expected response to greenhouse forcing is well understood. Some of these are as follows:

- *Sea Level.* Global warming would be expected to raise sea level through melting of land-borne ice and thermal expansion of the ocean's upper layers. A slow rise of 10 to 25 cm has been observed over the last 100 years.
- *Upper-Air Temperatures.* Only about 40 years of observations are available. Warming trends in tropospheric temperatures

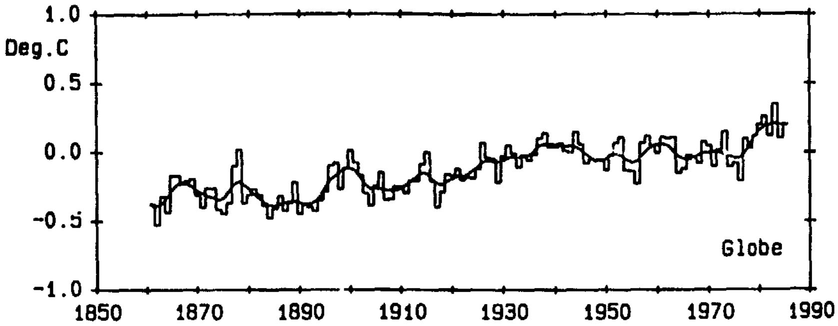

FIGURE 1 Trend in global-mean surface temperature (Jones et al., 1986).

may be discerned in recent years, together with decreasing stratospheric temperatures in the southern hemisphere.

- *Surface Temperatures.* Recent analyses employing both marine and terrestrial data indicate a long-term (100 year) upward trend in global mean surface temperature, with a total warming of about 0.5°C over a century (Figure 1). Warming appears to have accelerated in the last few years, with the warmest years of the entire record occurring in the last five years. Earlier studies based on less complete data sets and employing different analysis methods yielded somewhat different results, reflecting the inherent difficulty of estimating a global average from scattered observations.

The above observations are consistent with the hypothesis that increased greenhouse warming is taking place. However, it must be pointed out that natural climatic fluctuations are constantly taking place, and that alternative explanations are available for each of these observations. For example, changes in ocean circulation could greatly complicate the interpretation of the temperature record. Thus, the evidence for detection of greenhouse changes, while quite plausible, is circumstantial in nature. Continued work on monitoring and development of models will be needed before human effects on climate can be unequivocably disentangled from natural variations.

Nevertheless, the convergence of different lines of evidence and the absence of credible contradictory evidence are in themselves impressive. The passage of time and the slow accumulation of observations have not shaken, but rather increased, the credibility of theories that predict major climatic changes in the future.

5

Impacts of Rising Concentrations of Trace Gases

As we move from observation to prediction, and from analysis of physical-climate systems to analysis of socioeconomic systems, the confidence in our understanding and forecasting ability drops off markedly. Nonetheless, if we are to make reasoned judgments about public and private steps to adapt to, mitigate, offset, or prevent changes in atmospheric composition and behavior, we must attempt to peer into the future and to hazard guesses about the impacts of changes in the offending trace gases on the world we live in.

In our analysis, a number of different layers can be separated: (1) the implications of depletion of ozone; (2) direct effects of changing climate; (3) impacts through both natural, relatively unmanaged ecosystems and managed ecosystems like agriculture; (4) direct impacts on other sectors of the socioeconomic system; (5) impacts on human health; and (6) the vast uncertainties posed by changing climate.

IMPLICATIONS OF OZONE DEPLETION

Among the most fully studied implication of a changing atmosphere is the effect of decreasing ozone (Environmental Studies Board, 1984; Titus, 1986; World Meteorological Organization, 1985b). Ozone absorbs radiation strongly in the ultraviolet band, and light in the UV-B (280 to 320 nm) band has been found to be absorbed by cells and to be associated with diverse and generally deleterious biological effects. Depletion of ozone would certainly increase the intensity of damaging radiation reaching the Earth's surface. In humans these effects range from mild sunburn to skin cancer. Exposure to UV-B radiation is the primary cause for basal cell and squamous cell skin cancers, of which there are 300,000 to 400,000 new cases each year in the United States at the present time. Exposure to UV-B may also play a role in the development of malignant melanoma, but the causal relationship is less certain than with the other two forms of skin cancer. In other organisms, such as certain plants and marine organisms, exposure to UV-B radiation may adversely affect development and reproductive success. In animals, numerous skin diseases are caused or aggravated by exposure to the sun. Specific effects include immunological changes and skin cancers (both melanoma and nonmelanoma) in humans, as well as damage to plants, animals, and marine organisms. Major increases in human skin cancer incidence have been projected as a result of ozone depletion (Environmental Studies Board, 1984).

DIRECT IMPACTS OF CLIMATIC CHANGE

At the outset, we must recognize that people care deeply about the environment in which they live. Major changes in local climates—whether they be more prolonged heat waves, fewer snowstorms, shifting monsoons—would affect the daily lives of hundreds of millions of people.

We cannot say at this time whether these direct impacts will pose major or minor burdens on people. Some "optimists" would downplay the direct importance, noting the slow pace of change, the enormous ability of people to adapt, and the wide range of climates in which people already live and thrive; they would also note the southward migration of Americans in the last two decades and point to surveys indicating people's preference for warmer climates. After all, people constantly adjust to immense changes of climate between day and night, summer and winter, and home to holiday resort. Moreover, the world has already accommodated to a substantial climatic change from the cold years of the "Little Ice

Age" of the seventeenth to eighteenth centuries to the significantly warmer climates of today.

Others, let us call them "pessimists," would argue that large areas may be afflicted with markedly unfavorable climates—for example, hotter and drier climates, reduced water supplies, and a greater number of extreme conditions like droughts and heat waves. Simple statistical reasoning suggests that small shifts in mean values can imply large changes in the frequencies of extreme events. Indeed, the major impacts of climatic change might arise from an increased likelihood of extreme events. Pessimists might further argue that some of our social systems are ill-designed to cope with a major change toward higher temperatures.

Although many speculative examples may be cited, we have at present no basis for reliably assessing the net effect of the direct impacts of climate. Nevertheless, given plausible quantitative estimates of changes in environmental parameters, explorations of implications for human society would be useful.

IMPACTS THROUGH ECOSYSTEMS

The major social impacts of the rising trace gases will be effected through the climate changes discussed above. Few doubt that we have set in motion a train of consequences that include rising average temperatures, rising sea level, and a major redistribution of local climates. Less secure are the predictions that our continental climates will be drier, that the central United States may be significantly more drought-prone as summer soil moisture drops, and that river systems will see major changes in average flow patterns—some higher, some lower.

The first area of concern is agriculture, particularly rain-fed (nonirrigated) agriculture. Studies suggest that there may be drops in yields of some crops in a warmer and drier climate; however, the higher carbon dioxide levels are generally thought to act as a powerful fertilizer for most crops (corn being the major exception). At present, the average long-term effect of increasing carbon dioxide concentrations, that is, the yield averaged over large areas such as Europe or North America, is unpredictable: increasing carbon dioxide will fertilize plants while climate changes may hurt them. These competing influences may mask shifting effects on individual farmers, regions, or even small nations. A farmer of Illinois or Kansas, bankrupted by a carbon dioxide-induced drought, would take little comfort in the higher yields harvested by Canadian wheat farmers. Similarly, a wheat farmer on a desertified plot in Rajasthan held by his family for centuries would benefit little from the higher rice yields in Taiwan.

The impacts of climatic change on ecosystems other than agriculture are even more difficult to predict. Evidence suggests a poleward migration of forest extent, although the time lags may be on the scale of centuries. Changes may affect fisheries, e.g., by altering ocean circulation, but the dominant pathways have not been identified. Inland lakes may rise or fall markedly, and some of our treasured dams may empty while others spill over. However, without better regional climate prediction, we cannot now make forecasts for individual lakes or dams or regions.

Groups who have studied sea-level changes appear more confident about the direction and magnitude of changes—this greater predictability arises because the oceans respond on a global scale to changes in global climate. Over the last century, sea levels have risen 10 to 25 cm (4 to 10 in.). Current knowledge suggests a rise in sea level of 50 to 80 cm (20 to 32 in.) over the next century. Rising sea levels would increase coastal erosion and cause marked shoreline recession in vulnerable areas. In estuaries and tidal rivers, saline water might advance significantly. Clearly, these problems would be particularly unwelcome for those low-lying areas (e.g., the coastal United States, the Netherlands, and Bangladesh) that are particularly vulnerable to spring tides and storm surges.

OTHER SOCIOECONOMIC IMPACTS

The bulk of economic activity as measured by gross output originating—97 percent for the United States and 93 percent for the world—is in sectors other than agriculture, forestry, and fisheries. In terms of direct effects (that is, those directly affecting productive processes as opposed to those indirectly affecting production through purchased materials or services), these activities can be divided into those modestly affected by climatic changes and those negligibly affected.

Those experiencing modest direct effects, accounting for approximately 30 percent of U.S. GNP, include construction, transportation, energy systems, and recreation activities. To take the first as an example, construction will be affected because the seasons impose a distinct annual cycle on building activities, with reduced levels of activity taking place in frosty periods. Hence, where construction seasons are short, changes in the length of the warm season can have major effects. By contrast, unless snow-making could come to the rescue, skiers could find their favorite mountains offering shorter ski seasons.

Most of the U.S. economy would in a direct way be negligibly affected by the changes outlined above. As an extreme example, cardiac surgery takes place in artificially controlled climates, and changes in the natural climate of the kind foreseen would have little direct effect on operating conditions. Similar effects would obtain for underground mining, most manufacturing activities, communications, financial services, and many government activities.

It must be emphasized that this untroubled outlook for the bulk of economic activity in advanced economies would hold only if the general economic climate does not deteriorate in a major way. Should rapid breakdowns in ecologically related sectors spill over into the general economy, the outlook would have to be more guarded. Could drastic changes in water availability produce "water shocks" similar in magnitude to the "oil shocks" of the 1970s? Or, as some think more likely, would the pace of change be sufficiently slow that our social and economic structures could adapt readily to the changing ecosystems in which they are embedded? Answers to these "systems" questions involve a most complex web of ecosystem-economic interactions and are beyond the ability of current social science to predict with confidence.

IMPACTS ON HUMAN HEALTH

Suggestive relationships between climate variations and human health indicators can readily be identified. For example, mortality from many diseases has a seasonal pattern. However, long-term climatic changes in temperate latitudes are unlikely to have major health implications. More troubling might be the expansion of tropical climates and the concurrent expansion of the ranges of tropical disease vectors. Such changes would mostly affect developing countries that already face daunting health problems. Effects of increased ultraviolet radiation due to ozone depletion have been noted above.

UNPREDICTABLE OUTCOMES

Among the sources of heightened concerns in recent years are a number of troubling but largely unpredictable factors:

- We are pushing our climate and environment—the surroundings in which we live, work, and play—into a region literally unexperienced during the history of *homo sapiens*. To find a climate as warm on the average as that projected for a century hence, we would have to go back many millions of years. Moreover, the rates of change of our climate are likely to be larger than any documented changes.
- The systems producing the climatic change are ones with tremendous inertia. Once injected into the atmosphere, the increased CFCs and nitrous oxide concentrations have lifetimes of around a century, while increased carbon dioxide concentrations would take many centuries to return to their preindustrial values. Moreover, the underlying technologies, particularly our energy systems, are ones that are deeply embedded in our society; they change slowly, as we see by the fact that only one wholly new energy form (nuclear power) has been introduced in the last century. Similarly, many elements of our infrastructure, e.g., dams, and seaports, have extremely long lifetimes. If we make mistakes, we will have to live with them for a long time.
- Most important, we are reluctant to accept a reassuring forecast for a warmer globe because of imponderables. We know that major changes are likely to produce major unforeseen consequences—indeed the unforecasted Antarctic ozone hole may be just such an example of an unforeseen consequence of changes acting on a complex system.

One might speculate about a host of other possible unforeseen consequences such as the following: In a high-carbon dioxide world, would we be overrun by carbon dioxide-fertilized weeds? Or would pests become more virulent? Would some traumatic climatic response be triggered as temperatures rise above historical experience, perhaps a response triggered by melting ice and snow? Would deserts insidiously spread to envelop major populated areas or croplands? Would the West Antarctic icepack calve, raising sea levels by up to 20 feet? (This is currently considered highly unlikely within the next few hundred years.) Would the higher temperatures lead to melting of the Arctic icepack in summer and produce major unpredictable changes in weather patterns of the northern hemisphere? Would small shifts in the courses of ocean currents produce major changes in regional climates?

Will rapid CFC growth trigger an ozone collapse? Are there unknown impacts of changing concentrations of ozone at the surface or in the upper atmosphere on plants, animals, or people? Will higher bombardment of plants and animals by ultraviolet radiation produce unanticipated health effects? Is there an unforeseen interaction among higher tropospheric temperatures, lower stratospheric temperatures, and rising concentrations of various chemical compounds? Will rapidly changing climate patterns produce tensions spilling over to political and military conflicts?

This list could be extended indefinitely, yet we still suspect that many unforeseen consequences will remain uncovered even by these speculative forays.

6
Do We Know Enough to Act?

CURRENT RESEARCH AND VIEWS

In its 1983 report, the National Research Council's Carbon Dioxide Assessment Committee summarized its judgment of the issue as follows:

> Overall, we find in the carbon dioxide issue reason for concern, but not panic. Although the prospect of historically unprecedented climatic changes is troubling, the problems that may be associated with it are of quite uncertain magnitude, and both climate change and increased carbon dioxide may also bring benefits. . . . In our judgment, the knowledge we can gain in coming years should be more beneficial than a lack of action will be damaging; a program of action without a program for learning could be costly and ineffective. . . . (O)ur recommendations call for "research, monitoring, vigilance, and an open mind."

In the years since the *Changing Climate* report, the scientific community's perception of the issue has indeed evolved substantially along the lines envisaged by its authors. It was felt that, as time passed and information accrued, the center of concern would slowly shift from study of scientific questions toward exploration of policy implications and options. This evolution has indeed occurred. As noted above, the continued intensive refinement of the observational record has yielded a steady convergence of highly suggestive circumstantial evidence that major climatic changes are indeed in progress. Major national and international research efforts in climate have greatly improved our understanding of the climate system's behavior, and have reinforced the concerns first voiced by scientists over a century ago. The U.S. Department of Energy (1985) has published a massive compendium of its research program's results; a comprehensive international assessment has been conducted under the auspices of a group of international intergovernmental and nongovernmental organizations (the World Meteorological Organization, the United Nations Environment Program, and the International Council of Scientific Unions); and a standing international Advisory Group on Greenhouse Gases has been established.

This intensive worldwide effort has reaffirmed the earlier judgments and revealed no credible contrary indications. The tone of this evolution is indicated by the following excerpt from the report of the international assessment in the fall of 1985 (World Meteorological Organization, 1985a):

> . . . (T)he understanding of the greenhouse question is sufficiently de oped that scientists and policy-makers should begin an active collaboration to explore the effectiveness of alternative policies and adjustments.

SHOULD WE ACT NOW?

The litany of uncertainties enumerated above is not intended to paralyze the decisionmaker. Rather, it should remind us of the enormous difficulties faced by those who wish to take action now, not later. Moreover, in reminding ourselves of the remaining uncertainties, we should not lose sight of the enormous amount we have learned in very recent years—not only about climate, but also about the human influences on climate. We have learned, for example, that exponential growth in fossil fuel consumption is not inexorable—carbon dioxide emissions from combustion were virtually unchanged from 1973 to 1985. We have not only learned that other trace gases are powerful influences on climate; we have also learned much about the possibilities for their control, e.g., by technological substitution and regulation in the case of the CFCs.

Indeed, it is possible that our demonstrated ability to change the global atmosphere presages a future capability to manage it to our advantage. The potential for collective action leading to improving our global climate faces numerous obstacles, however, for such action is the product of the combined effect of the individual actions of many nations. Control of emissions or hypothetical future management of the atmosphere and climate would require protracted reliable cooperation on a global scale that is unprecedented in the political history of nations.

But when should we act? Now? In a year? In a decade? In a century? We do not presume to answer such a value-laden question. Rather, we pose it in an alternative fashion by asking, "How much are we likely to learn in the near future?" Is a future panel likely to find a "smoking gun," concluding beyond a reasonable doubt that what are now seen as potential impacts are instead so likely or so threatening that a course of action is unequivocably obvious? Our tentative view on this question is the following:

- There is without question a rapid buildup of trace atmospheric gases such as carbon dioxide, methane, and the CFCs. In addition, the depletion of ozone over the Antarctic in the last few years is confirmed by statistically significant and independent measurements.
- There is a high degree of confidence in the basic propositions about the effects of trace gases, both on global climate and on ozone depletion. Put differently, it would be very surprising if a National Research Council panel a few years hence pronounced the underlying propositions put forth here about climate and ozone depletion dead wrong.
- At the same time, the quantitative magnitudes and timing of effects are moderately uncertain. Whether globally averaged temperatures will rise a degree or several degrees by the middle of the twenty-first century, what the exact extent of ozone depletion will be by 2020, whether sea level will rise a foot or several feet over the next century—these are events about which we are confident with respect to the direction, but not to the exact magnitude.
- We have little confidence in predictions about many details of the forecasts: local changes by city or state, exact shifts of desert regions or of extent of monsoons, changes in river flows, or overall economic impacts.
- It seems likely that the impacts of climatic change will fall most severely on immovable, and therefore inflexible, elements of both natural and man-made infrastructures. These include water systems (rivers, dams, and irrigation projects), marine and coastal

structures, and agricultural systems. In addition, national parks and biosphere reserves are usually established to preserve some asset of unique physical or biological importance, often depend on climatic factors, and cannot be easily moved or replaced.

• We are on the whole confident that changes of the anticipated magnitude will produce major unforeseen consequences—in climate, in ecosystem responses, in human responses, and in local or national economic impacts. We are confident that these impacts pose generally greater risks for poor countries, which largely depend on natural ecosystems and lack resources to insulate themselves from climate shifts, than for wealthy nations. But whether the consequences will in the end prove grave or only modest, and on whom the consequences will fall, we cannot say. Moreover, we doubt whether the full range of the unanticipated consequences can be fathomed until they are well upon us.

• In the short run, the most prudent scientific response is to strengthen our commitment to basic and applied sciences with an eye to improving our understanding of these phenomena and their impacts on our society and its environment. Our ability to understand this enormously complex physical-biological-social system rests ultimately on the base of deep understanding of the basic scientific relationships. (For example, the major discovery of recent years, the Antarctic ozone hole, was made by basic scientists in routine monitoring.) Important activities would involve continued and enhanced national and international investment in knowledge about theories, modeling, and observation of atmospheric chemistry, climate systems, ecosystems, and socioeconomic responses. This investment in basic science might be coupled with investigation of new technologies that would mitigate the buildup of atmospheric trace gases, particularly focusing on the non-carbon dioxide trace gases.

• Consideration of more direct policy actions might best start with the CFCs. They are uncommonly powerful greenhouse gases, their effect on stratospheric ozone is well established, and they are entirely man-made. National and international policies to limit CFC emissions should be carefully weighed.

• Although we did not investigate in detail the costs and benefits of alternative policies, many of the workshop participants believe that steps should be taken now to slow emissions or mitigate the potential impacts of the rising atmospheric trace gases discussed in the workshop. While individual participants might differ on the exact timing and stringency of such steps, *all of the participants believe that a thorough study of the impacts of and appropriate responses to rising atmospheric trace gases is among the most pressing issues on the national research agenda.*

This report has focused on the issues surrounding the presentation and interpretation of the data and theories about the increasing concentrations of atmospheric trace gases. As has been here emphasized, this subject involves enormously complex questions of understanding dynamic processes and forecasting future trends and their physical, social, and economic implications. With this appraisal, we come to the frontier between science and policy and stop there. On the other side of the frontier lies the even more complex task of weighing social priorities and deciding how to act; that task has been left to those for whom this report is written.

In transmitting this report, however, we also would convey our belief that the problem of rising trace gases will prove to be one of the major problems faced by human society in the decades to come, and one that should now be weighed with deliberate care by the world's political leaders and, indeed, by all who are concerned with the stewardship of our planet.

References

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Appendix A
Letter Requesting the Assistance of the National Academy of Sciences

United States Senate

COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS
WASHINGTON, DC 20510

June 2, 1986

Dr. Frank Press
President
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Dear Frank:

This is to request the assistance of the National Academy of Sciences in developing and coordinating and conducting a workshop on the possible consequences of fundamental changes in the world's atmosphere caused by the use of fossil fuels, increasing levels of carbon monoxide and other greenhouse gases, and other industrial activities.

Traditionally, the Academy has served the Congress and the public in interpreting difficult scientific and technical issues, and especially in helping us understand the risks associated with them. For several years, we have known that the atmosphere of the planet was being altered by human activities. But recently, the statements from segments of the scientific community have evinced an unprecedented level of alarm. There have been suggestions that the future of mankind itself could literally be at stake in this extraordinarily complex scientific debate.

Frankly, if the risks are truly this great--and this has certainly been implied in recent reports and meetings--it is extraordinarily important for the Congress, the press and the public to understand this. On the other hand, overstating the risks, or doing so prematurely, would be a great disservice. It is for this reason that we are requesting your help and that of the Academy.

We are deeply disturbed that neither other Members of the Congress nor the press seem to be aware of some of the most extraordinary statements ever made by respected and reputable scientists and scientific organizations. Only one example of this is a statement contained in a recent State-of-The-Art report on the carbon dioxide problem issued by the Department of Energy as follows:

> Human effects on atmospheric composition and the size and operations of the terrestrial ecosystems represent major excursions that may yet overwhelm the life-support system crafted in nature over billions of years.

Another recent statement, issued by 150 scientists from a dozen different nations, meeting under the auspices of the World Meteorological Society and the United Nations Environment Program, warned that man may induce "a rise of global mean temperature...which is greater than any in man's history conducting a "global experiment" with the Earth's atmosphere.

Frankly, we are accustomed to conservative, cautious statements from the scientific community. Remarks such as those we have just cited, made in official documents, indicate that at least some segments of the scientific community believe that the risk posed to mankind and the plant's environment may be of immense and unprecedented proportions.

It is for this reason that we are asking for the assistance of the Academy in collecting and analyzing this data, as well as communicating it to the Congress and the public in an understandable way. One option would be to conduct a one or two day workshop for Members of Congress, their staffs, and the press, which would identify research priorities and evaluate current evidence. Members of the staff of the Committee on Environment and Public Works have discussed these issues with Dr. Devra Davis of the Board on Environmental Studies and Toxicology. If you are agreeable, they could continue to develop the details of a process for the conduct of appropriate and follow-up activities. We would be pleased to contact appropriate organizations to provide funding.

Thank you in advance for your consideration of this request. If we may be of any assistance or provide further information, please feel free to call upon us.

Sincerely,

John H. Chafee

Robert T. Stafford

Lloyd Bentsen

Dave Durenberger

George J. Mitchell

Max Baucus

Patrick Leahy

Albert Gore, Jr.

Appendix B
Current Issues in Atmospheric Change Workshop: Program and Attendees

WORKSHOP PROGRAM

Thursday, October 30, 1986

1:00 p.m.	1.	*Opening Remarks* Frank Press, NAS Robert M. White, NAE William D. Nordhaus, Yale
1:30 p.m.	2.	*Observed Trends in Atmospheric Trace Gases* Ralph J. Cicerone, NCAR
2:15 p.m.	3.	*Implications for Ozone Depletion* F. Sherwood Rowland, Univ. of California/Irvine
3:00 p.m.		BREAK
3:15 p.m.	4.	*Current and Projected Future Ozone Levels* Michael C. McElroy, Harvard

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4:00 p.m.	5.	*Implications for Global Climate* Robert Cess, SUNY
4:45 p.m.	6.	*Prediction of Changing Regional Climate* Jerry Mahlman, NOAA/GFDL
5:30 p.m.		INFORMAL RECEPTION

Friday, October 31, 1986

8:30 a.m.	7.	*Uncertain[illegible]ection of Climatic Change* V. Ram[illegible]ity of Chicago
9:15 a.m.	8.	*Obser[illegible]* Thom[illegible]st Anglia
10:00 a.m.		BREAK
10:15 a.m.	9.	*Economic and Social Implications* Stephen H. Schneider, NCAR Lester B. Lave, Carnegie-Mellon Univ.
11:45 a.m.	10.	*Summary and Synthesis* William D. Nordhaus, Yale
12:45 p.m.		WORKING LUNCH (Invited Participation)
2:00 p.m.		Planning for Congressional Briefing and Development of Workshop Statement (Invited Participation)
4:00 p.m.		ADJOURN

LIST OF ATTENDEES

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Mr. Philip Cummings
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Mr. Eric Erdheim
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