Chapter 2

A Primer on Climate Change

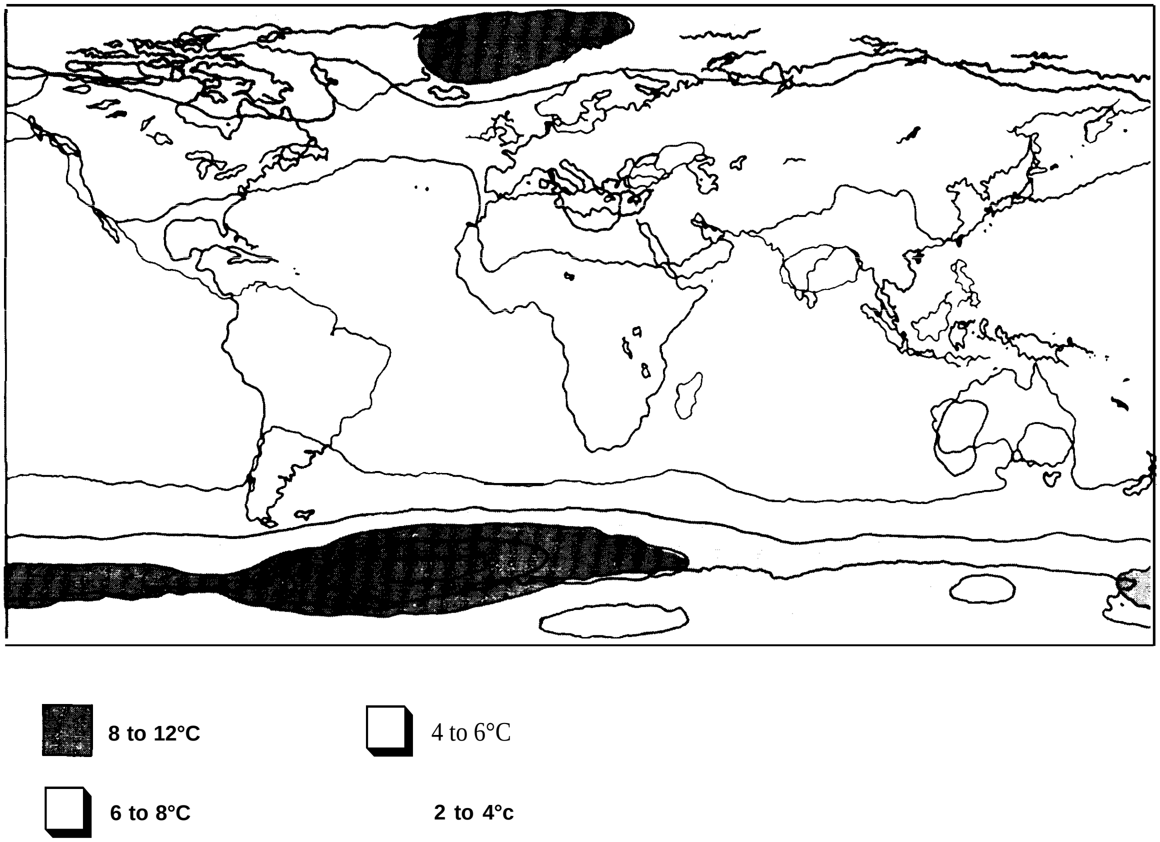

Photo credit: IPCC, *1990 from atmosphere-mixed layer ocean model of S. Manage.*

Projected surface temperature increases due to a doubling of $C0_2$

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Chapter 2

A Primer on Climate Change

SUMMARY AND INTRODUCTION

Scientists are confident that human activity is dramatically changing the chemical makeup of the Earth's atmosphere. Atmospheric concentrations of several "greenhouse gases,"[1] which trap heat in the atmosphere, have risen rapidly over the last 100 years. Some of these gases (carbon dioxide, methane, and nitrous oxide) occur naturally, but their rapid increase is generally a consequence of human activity. For example, the atmospheric concentration of carbon dioxide is currently increasing about 30 to 100 times faster than the rate of natural fluctuations indicated in the paleoclimatic record (7, 53); concentrations are already 25 percent above average interglacial levels and 75 percent above the level during the last glacial maximum (37). Likewise, the atmospheric concentration of methane is increasing more than 400 times natural rates of variability (13a, 37). Other greenhouse gases—chlorofluorocarbons (CFCs) and halons--are synthetic chemicals that have been introduced into the atmosphere only during the last 50 years. The United States currently accounts for about 20 to 25 percent of all greenhouse gas emissions associated with human activity.

Many climate models used to predict global average surface temperatures suggest an increase of 0.5 to 2 ‘F (0.3 to 1.1 ‘C) should have occurred over the past 100 years due to increased atmospheric concentrations of greenhouse gases. Natural climate variability and other factors (measurement errors, urban heat island effects, etc.) confound detection of the expected change. The Intergovernmental Panel on Climate Change, or IPCC (37),---(a group of several hundred scientists from 25 countries)--concluded that the global temperature record over this period indicates that the Earth actually has warmed by about 0.8 ‘F (0.45 ^{0}C),[2] which is within (but at the low end) of the range of estimates.[3] See table 2-1 for a summary of the IPCC findings.

Although there are many uncertainties about climate change, the IPCC (37) concluded that if present emission trends continue, global average temperatures could rise by roughly an additional 2.2 ‘F (1.0 ‘C) by the year 2030.

Unfortunately, scientists have much less confidence in predictions for specific regions than for global averages, in that regional climate change is heavily affected by shifting and difficult-to-predict atmospheric and oceanic circulation patterns. Greater warming is likely to occur in some geographic areas compared to others; negligible change or even cooling is expected in some places. Some regions may experience more drought, others more precipitation and perhaps changes in the frequency and

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[1] Greenhouse gases trap heat in the atmosphere instead of letting it radiate out into space. Much of the increase in these gases over natural levels is due to actions of humankind. The key greenhouse gases and their primary anthropogenic sources are:

- Carbon dioxide (CO_2)—which is responsible for an estimated 55 percent of the enhanced greenhouse effect from 1980 to 1990 (37), primarily from fossil fuel burning in industrialized counties and deforestation in less developed countries. CO_2 is increasing in the atmosphere at 0.5 percent/year.
- Methane (CH_4)—15 percent of the effect; emitted from rice paddies, ruminant animals, coal mining, natural gas leakage, landfills, and biomass burning. CH_4 is increasing at 0.9 percent/year.
- Nitrous oxide (N_2O)—6 percent of the effect; sources are nitrogenous fertilizers, fossil fuel combustion, and biomass burning. N_2O is increasing at 0.25 percent/year,
- Chlorofluorocarbons (CFCs)—24 percent of the effect; these are manmade chemicals used primarily for refrigeration and insulation. CFCs are increasing in the atmosphere at the rate of 4 percent/year. The revised Montreal Protocol (see box 2-C) will phase out these chemicals over the next two decades in participating counties.

[2] This estimate is based on a weighted average of measurements from sites around the globe, corrected to remove warming due to urban growth. The IPCC estimate did not include data for 1990, which is reported to be the warmest year of the instrumental record. Temperature data for the global land surface, total global surface (land and oceans), and troposphere indicate that 1990 was about 0.1 ‘C, 0.05 ^{O}C, and 0.02 ‘C warmer, respectively, than any prior year in the 1980s or in the entire record; satellite data suggest that 1990 was the fourth warmest year since observations began (3a, 10a, 13b, 30a),

[3] Several hundred scientists from 25 countries participated in this multi-year effort sponsored by the World Meteorological Organization and the United Nations Environment Program,

Table 2-l —Highlights of the IPCC 1990 Scientific Assessment of Climate Change

The IPCC is certain that:

- There is a natural greenhouse effect that already keeps the Earth warmer than it would otherwise be.
- Emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases.

The IPCC calculates with confidence that:

- Atmospheric concentrations of the long-lived gases (CO_2, N_2O, and the CFCs) adjust only slowly to changes in emissions. continued emissions of these gases at present rates would commit us to increased concentrations for centuries ahead.
- The longer emissions continue to increase at present-day rates, the greater reductions would have to be for concentrations to stabilize at a given level.
- immediate reductions (on the order of 60°/0) in emissions of long-lived gases (CO_2, N_2O, and the CFCs) from human activities would be required to stabilize their concentrations at today's levels; methane would require a 15 to 200/. reduction.

Based on current model results, the IPCC predicts that:

- Under the I PCC Business-As-Usual Scenario,[a] global mean temperature will increase about 0.3 ‘C per decade (with an uncertainty range of 0.2 to 0.5 ‘C per decade), reaching about 1 ‘C above the present value by 2025 and 3‘C before the end of the 21st century.
- Land surfaces will warm more rapidly than the ocean, and high northern latitudes will warm more than the global mean in winter.
- Global mean sea level will rise about 6 cm per decade over the next century, rising about 20 cm by 2030 and 65 cm by the end of the 21st century.

All predictions are subject to many *uncertainties* with regard to the timing, magnitude, and regional patterns of climate change, due to incomplete understanding of:

- sources and sinks of greenhouse gases,
- clouds,
- oceans, and
- polar ice sheets.

The IPCC judgment is that:

- Global mean surface air temperature has increased by about 0.45 ‘C (with an uncertainty range of 0.3 to 0.6 ‘C) over the last 100 years, with the five globally averaged warmest years occurring in the 1980s.
- The size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. Thus, the observed temperature increase could be largely due to natural variability; alternatively, this variability y and other human factors could have offset a still larger human-induced greenhouse warming. The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more.

[a] Assumes that emissions of all greenhouse gases continue at 1990 levels. See note 7 in text and ref. 37.

SOURCE: Intergovernmental Panel on Climate Change, *Scientific Assessment of Climate Change,* Summary and Report, World Meteorological Organization/U.N. Environment Program (Cambridge, MA: Cambridge University Press, 1990).

intensity of storms.[4] At this stage it is impossible to confidently project the magnitude of the impacts of global warming, the speed with which they will develop, or where they will manifest themselves most severely.

We appear to be pushing the climate system beyond the limits of natural rates of change experienced by the Earth for hundreds of thousands and probably millions of years (9, 37, 53). The projected rate of climate change may outpace the ability of natural and human systems to adapt in some areas (37, 81). While it maybe many years before climate monitoring proves global warming is statistically significant, each year that passes increases the severity of the policy actions that would be needed to slow or reverse these climate trends. The IPCC (37) estimates that stabilizing trace gas concentrations at current (perturbed) levels would require an immediate 60-percent reduction in carbon dioxide emissions, 15 percent in methane emissions, and 70 percent in nitrous oxide and CFC emissions.

THE GREENHOUSE EFFECT

What Is Climate and Climate Change?

The Earth's climate is driven by many factors. The primary force is radiant energy from the Sun, and the reflection or absorption and reradiation of this energy by atmospheric gas molecules, clouds, and the surface of the Earth itself (including, for

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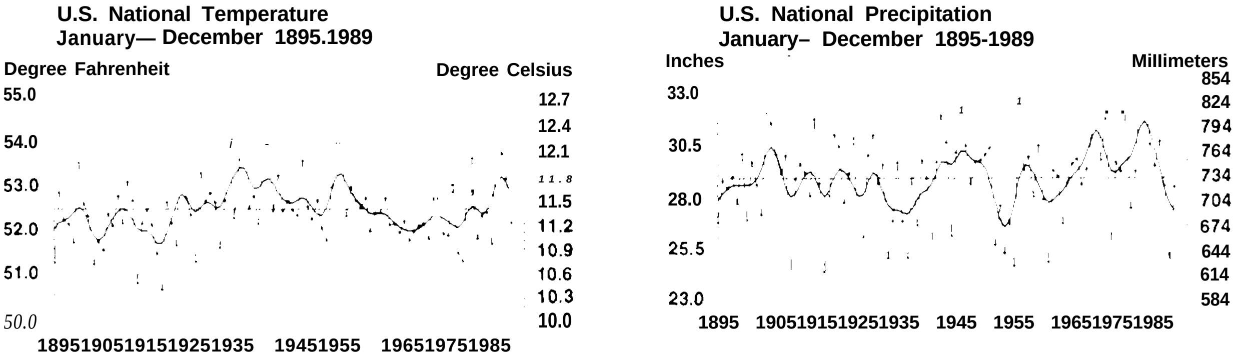
[4] General circulation models (GCMs) predict that warming could exacerbate summer drought over land at mid-latitudes primarily through a combination of earlier spring snowmelt and enhanced evaporation of soil water (30, 56). In Hansen et al. 's (30) model, both extremes are intensified; wet areas tend to get wetter, dry areas tend to get dryer. However, predictions of regional drought occurrence and intensity are uncertain because they are sensitive to uncertain components of GCMs, particularly soil moisture content, clouds, and ocean circulation patterns (30, 59). Precipitation data for land suggest some broad consistency with model projections, but with many unexplained discrepancies (17). Warming could also result in more intense or frequent storms of some types, including hurricanes and thunderstorms (20, 55, 30). Some studies indicate that maximum sustainable hurricane intensity should increase with global warming (20). Moreover, the region where hurricanes are viable may expand (30). However, present modeling results provide no consistent, convincing evidence that storms and related climate extremes will increase or decrease in frequency or intensity. Better understanding of regional climate change must await higher resolution climate models (37, 85).

Figure 2-1—U.S. Annual Temperature and Precipitation, 1895-1989



Fluctuation in temperature and rainfall can be dramatic from year to year even over an area as large as the United States (6 percent of the global land area and 2 percent of total global surface area). No trend can be interpreted from these data.

SOURCE: National Climatic Data Center, NOAA.

example, forests, mountains, ice sheets, and urbanized areas), A portion of the reradiated energy leaves the atmosphere. Over the long-term, balance is maintained between the solar energy entering the atmosphere and energy leaving it. Within the bounds of this balance, variations in global and local climate are caused by interactions among the atmosphere, snow and ice, oceans, biomass, and land. An example is El Niño, a large-scale warming of the tropical Pacific that occurs periodically, apparently due to complex interactions between the ocean and atmosphere (60).

A region's general climate is defined by aggregate weather patterns-e. g., snowfall, predominant wind direction, summertime high temperature, precipitation—averaged over several decades or longer. These patterns can vary substantially from one year to another in a given area. The mean annual temperature of the United States, for example, can differ by 2 to 3 ‘F from one year to the next and annual rainfall can differ by 4 or more inches (see figures 2-la and 2-lb).

When scientists talk about climate *change, they are* generally talking about trends that persist for decades or even centuries, over and above natural seasonal and annual fluctuations. One type of change arises from forces that are external to the Earth's climate system. The ice ages and glacial-interglacial cycles, for example, are thought to have been triggered in large part by changes in the seasonal and geographical distributions of solar energy entering the Earth's atmosphere associated with asymmetries in the Earth's orbit around the Sun. Also, major volcanic eruptions can pour aerosols (e.g., sulfur particles) into the stratosphere, partially blocking or screening sunlight from reaching the surface of the Earth and thus temporarily cooling the Earth's surface. Variations in volcanic activity, ice sheets, forest cover, marine phytoplankton populations, and/or ocean circulation, among other factors, may have interacted with solar variability (including changes in the Sun's brightness) to determine the Earth's past temperature record (4a, 11, 12, 24, 46a, 76, 108, 114). Scientific research continues to improve our understanding of climate as a very complex system (37, 38, 99, 102, 103).

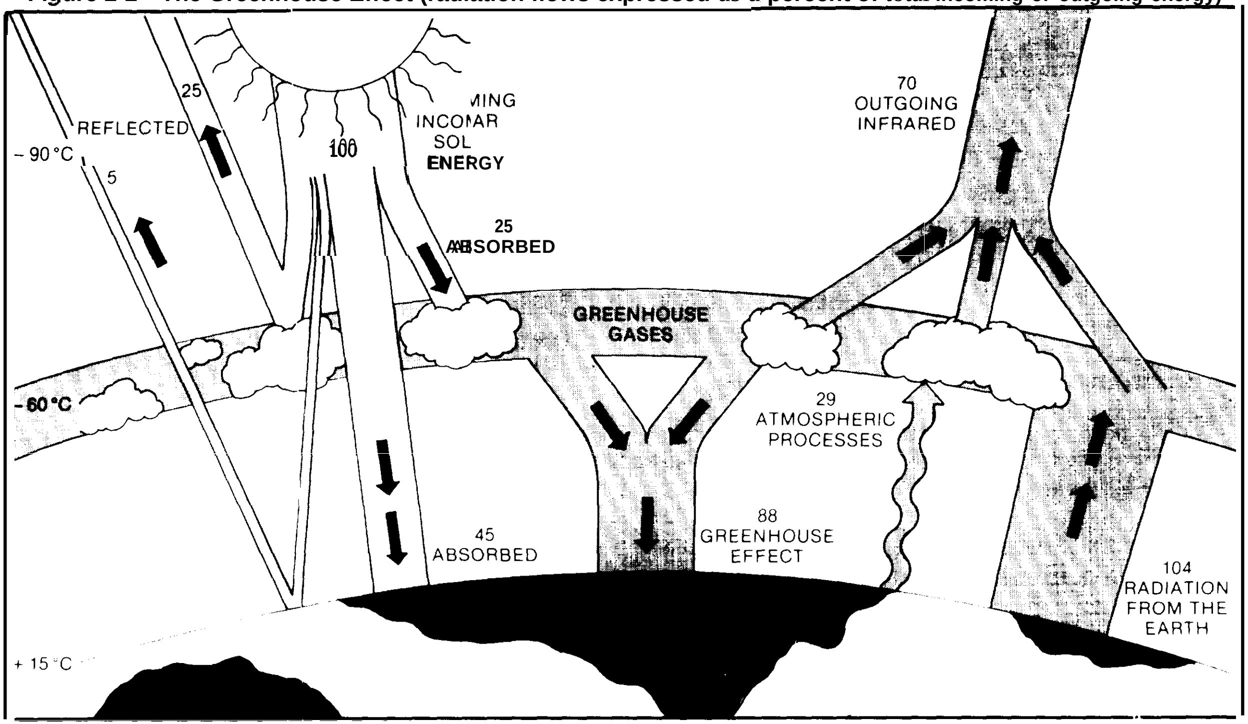
Emissions of greenhouse gases due to human activity constitute a *new* force for climate change, acting in addition to the natural climatic phenomena. Because of natural variability in climate, the IPCC (37) concluded that the observed 20th century warming trend will have to continue for one to two more decades before it can be unambiguously attributed to enhanced greenhouse gases (18, 52,62, 86, 87). However, given the potentially severe consequences of climate change, policymakers are faced with the challenge of making decisions under conditions of considerable scientific uncertainty.

Climate Change Due to Greenhouse Gases

Overview

About 30 percent of the solar radiation reaching the Earth is reflected by the atmosphere and Earth back to space, and the remainder is absorbed by the atmosphere, ice, oceans, land, and biomass of Earth (see figure 2-2). The Earth then emits long-wave

Figure 2-2—The Greenhouse Effect (radiation flows expressed as a percent of total Incoming or outgoing energy)



Incoming solar radiation is partially reflected back into space (30 percent) and partially absorbed by the atmosphere, ice, oceans, land, and biomass-of the Earth (70 percent). The Earth then emits radiant energy back into space. The “Greenhouse Effect” refers to the trapping of some of the radiant energy the Earth emits by atmospheric gases, both natural and anthropogenic. As a result of this effect, the Earth’s surface and lower atmosphere warms.

SOURCE: Office of Technology Assessment, 1991.

radiation, which is partially absorbed and ‘‘trapped’ by atmospheric gases.[5] The net result of these natural processes is the ‘ ‘greenhouse’ effect—a warming of the Earth’s atmosphere and surface. Without the natural heat trap of these atmospheric gases, Earth’s surface temperatures would be about 60 ‘F (33 ‘C) cooler than at present, and life as we know it today on Earth would not be possible.[6] Water vapor (in the form of clouds) and carbon dioxide (CO_2) are the major contributors to this effect, with smaller but still significant contributions, from other trace gases, such as methane (CH_4), nitrous oxide (N_2O), and ozone (O_3).

Human activities during the last century have resulted in substantial increases in the atmospheric concentrations of CO_2, CH_4, and N_2O, as well as the introduction and rapid increase of the synthetic chlorofluorocarbons (CFCs). All other things being equal, as concentrations of these gases increase, more radiation should be trapped to further warm the Earth’s surface and atmosphere. However, as more heat is trapped and the Earth and atmosphere warm, more thermal radiation should be emitted back to space, eventually restoring the energy balance or equilibrium, but with a warmer climate.

The basic “heat trapping” property of greenhouse gases is essentially undisputed. However, there is still considerable scientific uncertainty about how and when Earth’s climate will *respond* to enhanced greenhouse gases. The more uncertain aspects of climate response include: climate feedbacks that will help determine the ultimate magnitude of temperature change (i.e., ‘ ‘equilibrium” warming); the role of the oceans in setting the pace of Warming; and other climate changes that might accompany warming and how specific regions of the world might be affected.

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[5] Greenhouse gases both emit and absorb radiation. The net effect is absorption because they absorb relatively intense radiation from the warmer Earth and emit relatively weak radiation at cooler atmospheric temperatures. Thermal radiation declines as the temperature of the emitting object declines.

[6] This also explains differences among surface temperatures on Venus, Mars, and Earth.

"Benchmark" Warming-The Effect of Doubled CO_2 Concentrations

Predictions of future warming due to greenhouse gases are highly uncertain, largely because of the uncertainties inherent in both the climate models themselves and in the projection of future greenhouse gas emissions levels (box 2-A discusses climate change models). Future emissions will be tied to population and economic growth, technological developments, and government policies, all of which are difficult to project.

To avoid the pitfalls and complexity of estimating future emissions, and to provide a common basis for comparing different models or assumptions, climate modelers typically examine climates associated with preindustrial levels of atmospheric CO_2 concentration. These are compared to "equilibrium" climates—i.e., when the climate system has fully responded and is in equilibrium with a given level of radiative forcing associated with double those levels. Although such ''sensitivity analyses' provide useful benchmarks, they are unrealistic in that they *instantaneously* double CO_2 concentrations, rather than increase them gradually over time. In the last few years, scientists have intensified research using more realistic ''transient' climate models where CO_2 increases incrementally over time (28, 37, 90, 105).

Many models indicate that a rangeof3to8"F (1.5 to 4.5 °C) bounds the anticipated equilibrium warming in response to a doubling of CO_2 from preindustrial levels (37, 54, 84, 101). Uncertainty as to the actual figure is primarily due to uncertainty about feedbacks—processes that occur in response to initial warming and act either to amplify or dampen the ultimate equilibrium response. The lower end of the range (3 °F change) roughly corresponds to the direct impact of heat trapping

Box 2-A—Models of Climate Change

Climate models consist of sets of mathematical expressions that describe the physical processes associated with climate-e. g., seasonal changes in sunlight, large-scale movement of air masses, evaporation and condensation of water vapor, absorption of heat from the atmosphere into the oceans, etc. In the most detailed models, known as general circulation models (GCMs), the atmosphere is sectioned off into "cells" roughly 300-miles square at the Earth's surface, and the cells are stacked several layers deep. The vertical layers reach about 20 miles into the atmosphere. For each cell and period of time (e.g., an hour), the sets of mathematical expressions are solved to predict such variables as temperature, humidity, air pressure, and wind speed. In simulating a century's worth of climate, the process is repeated billions of times,

At the core of climate models are expressions of physical principles such as the conservation of energy or mass (e.g., of air or water vapor). Such "laws" govern interactions among the atmosphere, oceans, sea ice, land, and vegetation. However, using fundamental principles is too cumbersome to model some processes--because the real scale involved is much smaller than the dimensions of a GCM cell. In these cases, modelers are forced to rely on observed (i.e., empirical) relationships. For example, statistics on how cloud occurrence (i.e., types, altitudes) depend on temperature and humidity levels could be used to predict when clouds should be "created" during a model simulation. A potentially critical problem with using empirical relationships, rather than fundamental physical principles, is the possibility that observed relationships may not hold for conditions other than those under which the observations were made.

In climate models developed to date, atmospheric conditions have been treated more comprehensively than oceanic or biosphere (i.e., land and vegetation) conditions. Atmospheric conditions are the first to adjust to changes in radiative forcing such as increased greenhouse gas concentrations, and the seasonal cycle of climate provides a good test of the ability of models to simulate the short-time-scale processes involved. Although they are not treated in as much detail, some changes in the oceans and in the extent of sea ice are also predicted and fed back into further predictions. Efforts to improve oceanic components of models are a major focus of current research. Finally, conditions of land and vegetation are usually fixed before a simulation is run and are not changed during it. The rationale for holding these conditions fixed is that they are expected to respond to climate change comparatively slowly. However, these simplifications could mean that some important processes or feedbacks are ignored (15, 51, 55).

State-of-the-art climate modeling is focusing on: higher spatial resolution of models; coupled models that link atmosphere, ocean, land, and ice models; and more realistic model representations of key climate processes such as cloud formation and atmosphere-oceans-biomass interactions (37).

associated with doubled CO$_2$ with little amplification from feedbacks. The upper end of the range (8 °F) accounts for feedback processes that roughly triple the direct heat-trapping effect. Hypothesized feedbacks that could release extra CH$_4$ and C0$_2$ into the atmosphere are not included in present models (37, 5 1), so warming could be even more severe. On the other hand, clouds may block much more solar radiation than models presently assume and thereby reduce the warming (see ‘‘Climate Feedbacks’ below).

It is important to realize that a 3 to 8 ‘F warming only bounds model predictions of warming in response to this reference or benchmark CO$_2$ level. Higher CO$_2$ concentrations, or a combination of greenhouse gas levels equivalent to more than a doubling of C0$_2$, could lead to greater warming. Likewise, lower greenhouse gas concentrations lower the eventual warming. EPA (98) projected that in the absence of a slowdown in emissions growth, an ‘‘effective CO$_2$ doubling (i.e., accounting for increases in other trace gases as well as CO$_2$) could occur **as** early as 2030 assuming high rates of population and economic growth, or be delayed for about a decade if lower growth prevails. The IPCC “business as usual” emissions scenario[7] projects a global mean temperature increase above today’s level of about 0.54 ‘F (0.3 ‘C) per decade, or an increase of roughly 2.2 ‘F (1.0 ‘C) by 2030 and 6.6 °F (3.0 °C) by ***2100 (37).***

Detecting Climate Change-Warming Over the Past Century

Change in global average surface air temperature is the most common measure of climate change. There has been much debate over whether warming consistent with greenhouse theory predictions actually has been observed in the global temperature record of the past century. High regional variability of both the ‘‘natural’ climate and of ‘‘enhanced greenhouse’ effects make detection of climate change difficult (37). Nonetheless, the six warmest years of the past century occurred since 1980 (37, 40) and, overall, global warming appears to have occurred over the last century (see figure 2-3) (30).[8] Based on a review of all major global temperature series, for both land and ocean, the IPCC (37) concluded that global mean temperature has increased by 0.54 to 1.08 ‘F (0.3 to 0.6 ‘C) over the last 100 years.[9] However, the IPCC noted that ‘ ‘the size of the observed warming is also of the same magnitude as natural climate variability.

The midpoint of the IPCC range is at the low end of most estimates from *models* of the warming that should have occurred to date,[10] even when the delaying effect of the oceans is taken into account. For example, Wigley and Schlesinger (1 10) estimated that between 1850 and 1980, a global temperature increase of about 0.7 to 2.0 ‘F (0,4 to 1.1 ‘C) should have been caused by emissions of CO$_2$ and other greenhouse gases.[11] Dickinson and Cicerone (18) analyzed the effects of increased greenhouse gases and estimated a similar expected warming trend of 0.5 to 1.8 ‘F (0.3 to 1.0 ‘C) for the period 1900 to 1985. In general, models that use historical increases in greenhouse gas concentrations as inputs (as opposed to instantaneous doubling calculations) show a warming of about 0.4 to 1.1 ‘C (depending on model assumptions) through the year 1990 (26, 37, 83, 110, 111).

Nonetheless, given uncertainties in the models, the magnitudes of observed and predicted warming are considered ‘‘broadly consistent’ (37, 86, 87), Most puzzling, however, is the interruption in the warming trend that occurred during the middle of

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[7] The IPCC ‘‘business as usual’’ scenario assumes that emissions of selected greenhouse gases (CO$_2$, CH$_4$, N$_2$O) continue at 1990 levels from 1990 to *2100*. For CFCs, the scenario assumes that the Montreal Protocol is implemented, albeit with only partial participation (see box 2-C). The atmospheric concentration of CO$_2$ would double (over preindustrial levels) by about 2060, but the ‘‘effective’ CO$_2$ concentration (the cumulative effect of all trace gases) would double by 2025. The IPCC temperature projections cited here assume a “best estimate” climate sensitivity of 2.5 ‘C for equilibrium warming.

[8] The Hansen estimates (29) were compiled using data from land-based sites; no da@ from ships were included, Comparison with the trend estimated by Jones et al. (38& 39), who used data taken aboard ships as well as on land, suggests that this omission had only a small effect on the overall trend. The method used to combine individual station data attempted to minimize errors due to uneven coverage. Preliminary surface temperature data indicate that 1990 was *the* warmest year of the past century (3a, lOa, 30a).

[9] Urban heat island effects can be large in specific areas (42, 112a) but are estimated to account for no more than 0.05 to 0.1 °C in the global averages (40, 41, 43).

[10] Some scientists believe the actual warming has been closer to the low end of this range due to errors from uncorrected urban heat island effects (5) (but see footnote 9), ocean temperature measurement problems (1 16), and various discontinuities or inconsistencies in the temperature data (2 1, 62).

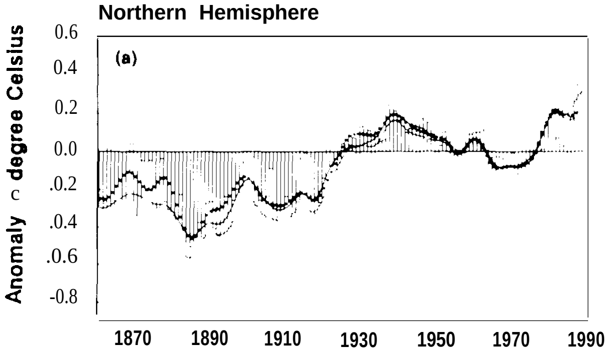
[11] Based on model predictions that a temperature increase in the range of 3 to 8 °F (1.5 to 4.5 ‘C) would ultimately result from instantaneously doubling atmospheric CO$_2$ concentrations; and including a range of time lags due to the uncertain effect of the oceans in delaying warming.

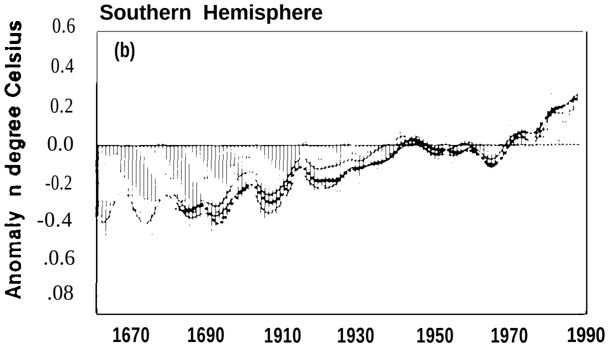
this century (see figure 2-3), when the Northern Hemisphere cooled and the Southern Hemisphere temperature was ‘‘ flat.’ This underscores the possibility that other ‘natural ‘‘ influences-e. g., changes in volcanic dust, solar radiation, or ocean circulation—have affected 20th century climate, The IPCC (37) concluded that ‘‘the observed [temperature] increase could be largely due to this natural variability; alternatively this variability and other human factors could have offset a still larger human-induced greenhouse warming. ’ The IPCC (37) further concluded that ‘‘ [t]he fact that we are unable to reliably detect the predicted [enhanced greenhouse] signals today does not mean that the [enhanced] greenhouse theory is wrong, or that it will not be a serious problem for mankind in the decades ahead. ”

Hansen and Lebedeff (29) examined the observed changes in average temperatures at different latitudes and found that the past century’s warming was especially enhanced at high northern latitudes, which is consistent with model results. However, the trend is not smooth. Cooling actually occurred in the high northern latitudes between 1940 and 1965. And the 1980s’ warming was driven by changes in the low latitudes, with relatively level temperatures or cooling in much of the mid- to high-northern and southern latitudes (3, 29). A significant reduction in summer/winter temperature differentials (over the past century is also consistent with model calculations (29).

Finally, oxygen isotope data recovered from air trapped in Greenland and Antarctic ice allow scientists to place the temperature record of the past century in geologic perspective (50, 100). The IPCC midpoint estimate of global warming over the past century (0.8 O$_F$ or 0.45 ‘C) is about one-fourth as large as temperature variations (3.6 °F or 2 °C minimum to maximum) estimated to have occurred during the past 10,000 years. Thus, attributing some part of the warming since the late 1800s to natural variations would be consistent with the longer term record. The IPCC (37) concluded that ‘‘[a] global warming of larger size has almost certainly occurred at least once since the end of the last glaciation without any appreciable increase in greenhouse gases. Because we do not understand the reasons for these past warming events, it is not yet possible to attribute a specific proportion of the recent, smaller warming to an increase of greenhouse gases.

Figure 2-3—Global Temperature Anomalies by Hemisphere, 1861-1989


Northern Hemisphere


Southern Hemisphere

Temperatures over land expressed as differences relative to 1951-1 980: Northern Hemisphere, Southern Hemisphere. Three research groups have produced similar analyses of hemispheric land surface air temperature variations. All three analyses indicate that during the last decade globally averaged land temperatures have been higher than in any decade in the past 100 to 140 years.

SOURCE: IPCC, 1990: annual values from P.D. Jones (bars); smoothed curves of values from P.D. Jones (1861-1989) (solid lines), Hansen and Lebedeff (1860-1987) (dashed lines), and Vinnikov et al, (1861 -1987 Northern Hemisphere and 1881-1987 Southern Hemisphere) (dots).

Climate Feedbacks

“Direct’ heat trapping, or “radiative forcing” refers to the expected warming due to greenhouse gas emissions if potential climate feedbacks—processes that occur in response to warming either augmenting or diminishing the effect—are ignored. [12] The radiative forcing effect of greenhouse gases

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[12] Radiative forcing or heat trapping is calculated with models of the energy balance Of the Earth/atmosphere system. These models calculate surface temperature adjustments to increased greenhouse gas concentrations from information about the radiative absorption characteristics of the gas molecules, and globally averaged profiles of gas concentration versus height in the atmosphere. The models also require information about preexisting conditions—e.g., atmospheric temperature profiles; the amount of solar energy entering the atmosphere and the amount reflected from the Earth’s surface and from atmospheric aerosols and gases; and the rate at which heat is redistributed through mechanical mixing processes.

added to the atmosphere since the late 1800s is equivalent to about a 1.4 ‘F (0.8 ‘C) equilibrium increase in global average surface temperatures (18, 70, 71).

However, scientists expect that some climate feedbacks will operate. Enhanced radiative forcing is expected to lead to changes in oceanic and atmospheric circulation patterns, the hydrologic cycle of precipitation and evaporation, vegetation cover, and snow and ice clover, all of which could, in turn, stimulate further, complex climate change.[13]

Most climate models suggest that, overall, feedback will amplify warming by a factor of up to 3 (26, 31, 37). Two fairly well understood feedbacks result from increases in atmospheric water vapor and the melting of snow and ice. As temperatures increase, air can hold more water vapor (itself a greenhouse gas). This can more than double the effect of radiative forcing (25, 37, 72).[14]

Melting of snow and ice due to warmer temperatures enhances warming in two ways:

1. reducing the reflectivity of the Earth’s surface (land or ocean), so less solar radiation is reflected and more is absorbed; and
2. reducing the insulating effect that sea ice has on the ocean, so heat escapes from high-latitude oceans more readily.

Snow and ice feedbacks result in only a 10 to 20 percent increase in warming on a global scale, but they can increase local warning at high latitudes by up to a factor of 4, particularly in winter (19,72, 78).

Indeed, the greatest warming due to increasing greenhouse gas concentrations is predicted to occur in winter, at high latitudes. In particular, General Circulation Models’ (GCMs) highest estimates of 8 ‘F global warming in response to doubled CO_2 rest on predictions that wintertime warming in high latitudes will exceed 15 ‘F, with lesser changes occurring during other seasons and at lower latitudes (82, 84).

Twentieth century warming has not been large enough to cause widespread, detectable melting of high latitude snow and ice, with the notable exception of the retreat of some alpine glaciers (although with periods of readvance [113]). Sea ice, snow cover, and ice sheet data either indicate no clear overall trends or are too limited or unreliable for identifying trends (37). There is recent evidence that at least parts of the Antarctic and Greenland ice sheets are actually thickening (37, 67a, 118), possibly because of increased snowfall due to warming in those areas (1 19). (This somewhat counterintuitive result can be explained if: a) warmer surface temperatures increase evaporation from the oceans, which would increase absolute humidity and precipitation; and b) the precipitation falls as snow, not rain, so long as temperatures are still below freezing [37]). Recent modeling results from coupled atmosphere-ocean GCMs suggest that amplified high latitude warming may not occur at least in the Southern Hemisphere around Antarctica (37, 57,90, 105), with the implication that temperatures in this region will remain below freezing.

Finally, how climate will respond to greenhouse forcing depends, in part, on what will happen to clouds (37). Clouds play a dual role in Earth’s energy balance: depending on their shape, altitude, and location, their dominant effect can either be to reflect solar radiation or to absorb or trap thermal radiation (from Earth). Recent satellite data demonstrate that the dominant effect of clouds at present is to reflect solar radiation and hence help cool the Earth, and that the magnitude of this cooling is about three to five times the expected warming effect of doubled CO_2 (73). However, as conditions change, the cooling effects of clouds may increase or decrease. If all types of clouds simply increase in area, or if lower, broader stratus clouds increase, they will reflect more sunlight back into space and cool the Earth. If taller, narrower clouds or cirrus clouds form, they will actually exacerbate the warming effect. Overall, GCMs are extremely sensitive to assumptions about cloud cover; a recent model intercomparison concluded that clouds can be either a strong positive or negative feedback on global Warming (13, 49). Depending on the model, clouds can halve the warming expected from doubled CO_2 (64) or double it (72, 73).

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[13] The complexity and viability of climate change suggests that simultaneously monitoring a large number of relevant parameters will increase the chances of detecting significant change (6, 37, 43, 115).

[14] Some (52, 66) believe that the water vapor feedback will actually diminish rather than amplify CO_2 warming, due to drying of the air at high altitudes and increased intensity of convection These are topics of continuing scientific research and debate.

Several feedbacks involving emissions of greenhouse gases are so speculative that they have not been incorporated into most climate models. These potential feedbacks are discussed below, in the sections on $C0_2$ and CH_4. If worst case conditions hold, they could greatly increase atmospheric CO_2 and CH_2 concentrations, resulting in twice as much warming as current GCMs predict (98).

Delays in Climatic Response

Based on the 1.4 ‘F increase in radiative forcing estimated to have occurred from 1880 to 1980, and assuming that positive feedbacks could amplify warming by a factor of up to three, a global average warming of about 1.4 to 4 ‘F is eventually expected as a result of the greenhouse gas concentration increases of the *past* century. (This estimate does not include any warming from current and future emissions.) As noted, this degree of warming has not yet been seen. In fact, scientists do not yet expect to see it, primarily because: 1) the natural variability of climate would mask or could even offset some of the change due to greenhouse gases; and 2) heat uptake by the oceans would delay the warming of the air.

The oceans have an enormous capacity to absorb and store heat. However, it takes several years for the ocean’s rapidly mixed surface layer (i.e., the top 100 meters) to equilibrate, on average, with warmer air temperatures, and it takes decades to centuries for the deep oceans to reach full equilibrium(31). Thus, global average surface temperatures would continue to increase for decades after greenhouse gas concentrations were stabilized. For example, scientists estimate that only about half the 1.4 to 4° F warming expected from emissions over the last century should have been realized by now because of this ocean effect (18, 26, 31, 110). The actual observed warming has been at the low end of this range, suggesting one or more of the following:

- the ‘‘enhanced greenhouse effect is considerably weaker than models predict, due perhaps to stronger negative feedbacks;
- natural variability is offsetting a large part of the enhanced greenhouse;
- other anthropogenic factors (e.g., sulfur aerosols) are offsetting some of the enhanced greenhouse; [15]
- ocean thermal lag is longer than thought.

Sea Level

Sea level, averaged globally, is estimated to have risen 4 to 8 inches (10 to 20 cm) over the past century (22, 37, 61). Scientists express high confidence that sea level will rise as a result of warming, but questions of how much and how rapidly are controversial (37, 61). The IPCC (37) has attributed 20th century sea level rise primarily to thermal expansion of ocean water as it warms and to partial melting of alpine glaciers. Hoffman et al. (32) predicted that sea water expansion and glacial melting could cause sea level to rise about 4 to 8 inches (10 to 20 cm) by 2025, and 16 to 80 inches (40 to 200 cm) by 2075. The IPCC reviewed all available evidence and estimated about the same sea level rise by 2030 (3.2 to 11.6 inches, or 8 to 29 cm with a best estimate of 18 cm) but a considerably smaller rise by 2070 (8.4 to 28,4 inches, or 27 to71 cm with a best estimate of 44 cm). This lower estimate includes the counteracting sea level drop due to (warming-induced) increased snow accumulation in Antarctica (37).16 The possibility that a polar ice sheet (such as the West Antarctic ice sheet) could slide into the ocean and raise sea level is very speculative. The IPCC (37) concluded that ‘‘[a] rapid disintegration of the West Antarctic ice sheet due to global warming is unlikely within the next century, and cautioned that sea level projections more than a few decades into the future ‘ ‘are fraught with many uncertainties. . .“

THE GREENHOUSE GASES

Historical and current growth rates in greenhouse gas concentrations (see table 2-2) fuel concerns about the possibility that human activity has been and will go on altering climate. Increases in CFC concentrations are unambiguously due to human activity, as they are synthetic chemicals that do not occur naturally. Human activity also is thought to be largely responsible for raising concentrations of N_2O, CH_4, and $C0_2$ above preindustrial levels,

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[15] The IPCC (37) concluded that the climatic effects of manmade sulfur emissions are ‘highly uncertain, ‘‘ but that ‘ ‘it is conceivable that this radiative forcing has been of a comparable magnitude, but of opposite sign, to (he greenhouse forcing earlier in this century. ” Over the longer term, the IPCC concluded that greenhouse forcing is likely to be larger on a global basis, but that forcing from sulfur emissions could be significant on a regional basis. Predictions are difficult due to uncertainties about the direct and indirect radiative effects of sulfur aerosols (including their impact on clouds) as well as future levels of sulfur emissions,

[16] Recent research (63) suggests a sea level rise toward the lower end of the IPCC range of estimates for 2030.

Table 2-2—Major Greenhouse Gases

Gas	Assumed concentration in 1880[a]	Concentration in 1990[b]	Projected concentration in 2030[c]	Annual growth rate as of 1990b [d]	Emissions from human activity in 1985	U.S. share of emissions in 1985	Contribution to warming 1880 -1980[a]
Carbon dioxide (CO_2)	260-290 ppm	353 ppm	440-450 ppm	0.5 %/yr	6-9 billion metric tons C[b]	*20%*[c]	*66%*
Methane (CH_4) . . . , ...	1.2 ppm	1.72 ppm	2.5-2.6 ppm	0.9%/yr	*350* million metric tons CH_4[e]	1 0%[c]	15%
Nitrous oxide ($N_2$0)	290 ppb	310 ppb	340 ppb	0.25 %/yr	4-10 million metric tons N[b]	NE[g]	*3%*
CFC-11	0	0.28 ppb	0.5 ppb	4 *%/yr*	*3,000* metric tons[f]	22%[c]	4%
CFC-12	0	0.48 ppb	1.0-1.1 ppb	4 %/yr	4,000 metric tons[f]	*30°/0'*	*50/0*
Others	NE[g]	NE	NE	NE	NE	NE	7%

[a] V. Ramanathan et al., "Trace Gas Effects on Climate, " in *Atmospheric Ozone* 1985, Global Ozone Research and Monitoring Project Report No. 16, World Meteorologic' Organization, National Aeronautics and Space Administration (Washington, DC: 1985).

[b] Intergovernmental Panel on Climate Change, *Scientific* Assessment *of Climate* Change, Summary and Report, World Meteorological Organization/U.N. Environment Program (Cambridge, MA: Cambridge University Press, 1990).

[c] U.S. Environmental Protection Agency, Office of Policy Planning and Evaluation, *Policy Options for Stabilizing Global Climate,* Draft Report to Congress (Washington, DC: June 1990).

[d] Impact on warming over the next three decades of reducing U.S. EPA's (1990) projected annual emissions of each gas by an amount equal to 20 percent of 1985 levels. Expressed as a f raction of the impact of reducing projected annual carbon dioxide emissions by 20 percent of 1985 levels.

[e] R.J. Cicerone and R .S. Oremland, "Biogeochemical Aspects of Atmospheric Methane, " Global *Biogeochemical Cycles* 2:299-327, *1988,*

[f] J.K. Hammitt et al., *Product Uses and Market Trends for Potential Ozone-depleting Substances, 1985-2000* (Santa Monica, CA: RAND Corp., May 1986).

[g] NE = no estimate.

Table 2-3--Alternative Estimates of Global Warming Potential (GWP) of Selected Greenhouse Gases

	Lifetime (years)	IPCC 100-year GWP	OTA estimates of GWP for the timeframe noted based on cumulative emissions between 1995 and 2015		
			2015-2100	2025-2100	2035-2100
CO*	120	1	1	1	1
CH_4	10	21	12	6.9	4.6
N_2O	150	290	290	300	300
CFC-11	60	3,700	3,600	3,400	3,200
CFC-12	130	7,600	7,800	7,900	7,900
HCFC-22	15	1,500	1,000	620	390
HCFC-123	1.6	87	6	0	0
HFC-134a	16	1,300	860	550	350
HFC-143a	41	2,900	2,700	2,400	2,200
HFC-152a	1.7	140	11	0	0

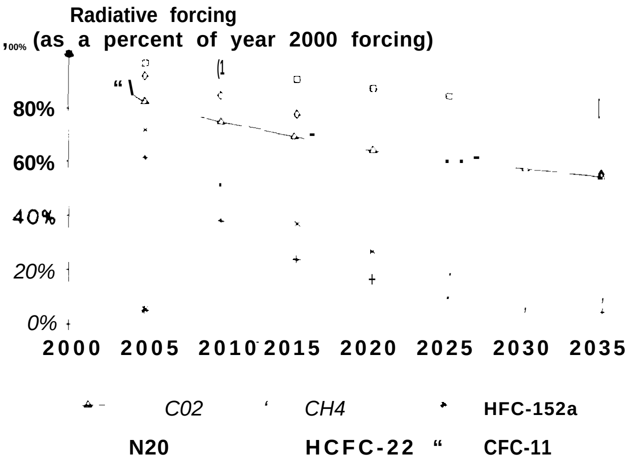
NOTE: The 100-year GWP estimate is slightly different than the IPCC 100-year estimate due to slight differences in modeling the lifetime of CO_2. The 120 year lifetime for CO_2 is approximate.

SOURCE. Office of Technology Assessment, 1991, using data from IPCC, 1990,

although natural sources of these gases also exist (14,47, 74, 88, 107). U.S. emissions (see table 2-2) are disproportionate to its 5 percent share of the world's population; in particular, U.S. emissions of CO_2 and CFCs account for about one-fifth and one-fourth of the world's estimated totals, respectively.

The warming effect of a greenhouse gas depends on several factors, including its concentration, radiative absorption and emission characteristics, and, in some cases, radiative interferences with other gases.[17] Radiative forcing calculations (see table 2-2) suggest that increased CO_2 accounts for about two-thirds of the equilibrium warming ultimately expected to result from growth in greenhouse gas concentrations over the past century. Growth in CH_4 concentrations has contributed an additional 15 percent, CFC-11 and CFC-12 together about 10 percent, and N_2O about 3 percent (70).

Figure 2-4—Decline in Radiative Forcing Through Time From a Pulse of Greenhouse Gas Emitted in 2000



The radiative forcing from each gas is considered equal to 100 percent when it is emitted in the year 2000. The graph illustrates the decline in radiative forcing over the next 35 years as the greenhouse gases decompose in the atmosphere.

SOURCE: Office of Technology Assessment, 1991, using data from IPCC, 1990.

Reducing greenhouse gas emissions can reduce the level of equilibrium warming projected for 2030. However, the effects of reducing different greenhouse gases vary (see table 2-3 and figure 2-4). The IPCC has proposed a method for comparing the warming from equal quantities of greenhouse gases. It defines Global Warming Potential (GWP) as the ratio of the amount of warming from a pound of a greenhouse gas to the warming from a pound of CO_2, over a period of 20, 100, and 500 years. It prefers to use the 100-year- timeframe for its policy analysis, which is shown in the second column of table 2-3. However, while GWP may be a good way for comparing the effects of different gases emitted well into the next century-when the effects from warming are likely to be greater-it may not be the appropriate choice for comparing the merits of alternative near- term policy measures (i. e., with in the 25-year timeframe of this assessment).

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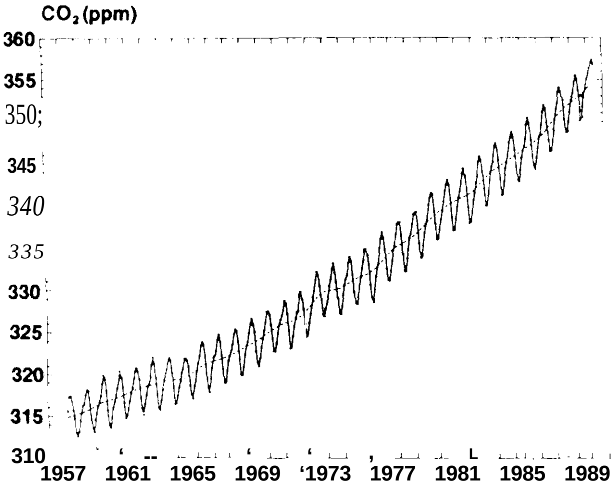
[17] CH_4 and N_2O interfere with each other, so that the impact of increasing the concentration of one depends on how much the concentration of the other gas is increased at the same time For the other gases, interferences are insignificant when incremental increases in concentration are considered.

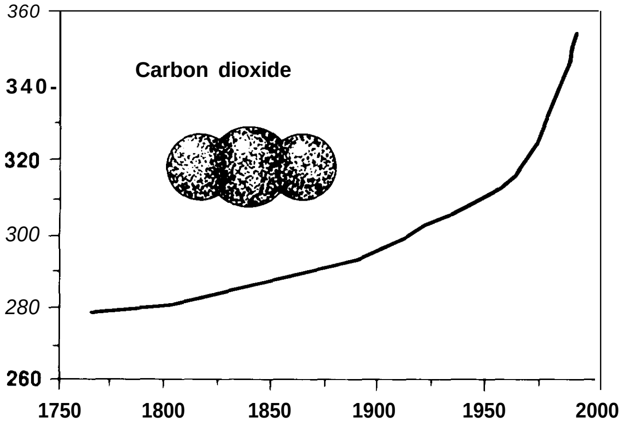
Figure 2-5-Carbon Dioxide Concentrations at Mauna Loa, Hawaii



The solid line depicts monthly concentrations of atmospheric CO_2 at Mauna Loa Observatory, Hawaii. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the Northern Hemisphere. The increasing concentration of atmospheric $C0_2$ at Mauna Loa since the 1950s (dashed line) is caused primarily by the CO_2 inputs from fossil fuel combustion.

SOURCE: P. Tans, National Climatic Data Center, GMCC, 1990.

Figure 2-6-Carbon Dioxide Concentration (parts per million by volume)



The history of atmospheric $C0_2$ presented here is based on ice core and atmospheric measurements. The data show that $C0_2$ increased slowly in the 1800s and more rapidly in the 1900s when temperate forests were converted to agricultural land. The rapid rise since the 1950s is due primarily to fossil fuel combustion and tropical deforestation. The current rate of increase is unprecedented in the ice core records.

SOURCE: Office of Technology Assessment, 1991, from IPCC, 1990.

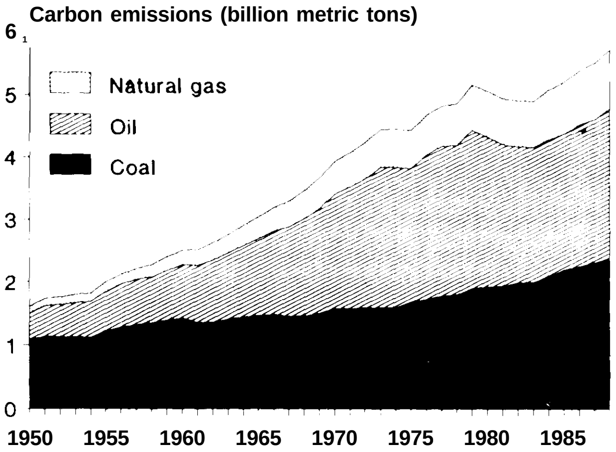
Some gases decay much more rapidly than others (see figure 2-4). For example, if we define the radiative forcing from a pound of CO_2 emitted in 2000 to be equal to 100 percent, by 2010 the amount left in the atmosphere will have radiative forcing equal to 75 percent. Similarly, by 2025 the radiative forcing from N_2O is about 85 percent of its original value 25 years earlier and CFC-11 is about 65 percent of its original value. But note that the shorter lived gases, such as HFC-152a (a replacement for CFCs) and CH_4, behave differently. By 2010 HFC-152a will have almost completely decomposed. By 2025, the radiative forcing from CH_4 will be about 10 percent of the amount 25 years earlier.

The IPCC measure assumes that an increment of warming today is equal to an increment of warming in the future. We have constructed our own formulation of GWP that we feel is more appropriate for evaluating the near-term policies presented in this report. Our measure focuses on the amount of warming that would be prevented during a specified period of concern during the 21st century, by eliminating a pound of greenhouse gas emissions each year between 1995 and 2015. Because it is not possible to pick one particular year when one might begin to be concerned about global warming effects, table 2-3 presents three versions of our measure, starting at either 2015,2025, or 2035. Again note the differences in the shorter lived gases. Methane is less than half the IPCC's 100-year estimate and the effects of several of the short-lived CFC substitutes drop considerably. Thus, over the near-term, Congress may wish to focus efforts on the longer lived greenhouse gases—$C0_2$, N_20, and **CFCs.**

Carbon Dioxide

Along with water vapor and clouds, CO_2 is a major natural greenhouse agent, without which Earth would be uninhabitable. However, CO_2 concentrations are estimated to have increased by about 25 percent since the mid-1800s, from around 280 ppm to about 350 ppm now (see figures 2-5 and 2-6). The continuous record of CO_2 concentrations measured at Mauna Loa since 1958 shows a steady year-to-year increase superimposed on a clear sea-

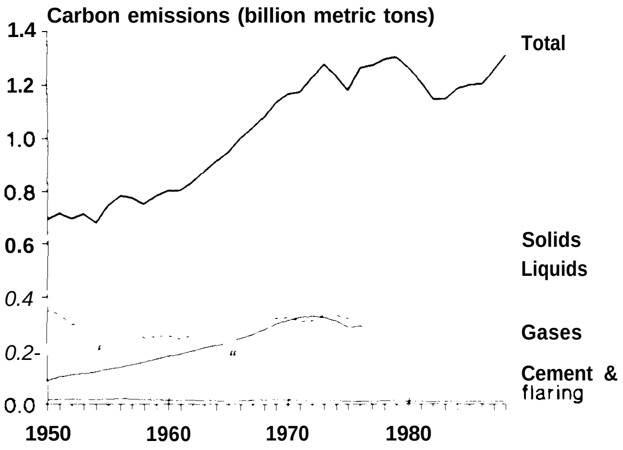
Figure 2-7—Global Carbon Emissions From Fossil Fuel



CO_2 emissions from fossil fuel combustion alone have grown from less than 0.1 billion metric tons C in the mid-1850s to approximately 6 billion metric tons C in 1989. Emissions have more than tripled in the last 40 years.

SOURCE: Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center, "Trends '90 A Compendium of Data on Global Change" (Oak Ridge, TN:1990).

Figure 2-8--U.S. Carbon Emissions From Fossil Fuel



U.S. emissions of carbon from fossil fuels are currently about 1.3 billion metric tons C. Emissions have doubled since the industrial revolution.

SOURCE: Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center, "Trends '90: A Compendium of Data on Global Change" (Oak Ridge, TN: 1990).

sonal cycle.[18] Most of the increase occurred in the 20th century (37, 45,80, 88) and is attributed largely to fossil fuel consumption (see figure 2-7).

CO_2 concentrations in air bubbles trapped in Antarctic ice indicate that present CO_2 levels are already higher than at any time in the past 160,000 years. Past CO_2 concentrations ranged from roughly 200 ppm during glacial episodes to 280 ppm during interglacial periods and were roughly correlated with temperature (7, 37, 53). Unless steps are taken to reduce emissions, CO_2 concentrations in 2030 are projected to be about 450 ppm, up more than 60 percent from preindustrial levels and 30 percent from 1985 levels (28, 37, 70, 98).

CO_2 accounted for an estimated two-thirds of the enhanced radiative forcing that occurred from 1880 to 1980, with the share declining to about 50 percent during the last decade as CFCs grew in importance (29, 70). With anticipated controls on CFC emissions, however, CO_2's comparative contribution is expected to rebound in the future (98). Assuming feedbacks amplify the direct radiative forcing effect by a factor of 1 to 3, climate models suggest that the 30 percent increase in CO_2 concentration projected for the period from 1985 to 2030 would add 0.45 to 1.3 'C to the equilibrium warming already expected from current greenhouse gas levels (98).

Of the total (estimated) cur-rent CO_2 emissions due to human activity (5.8 to 8.7 billion metric tons of carbon), 5.2 to 6.2 billion metric tons is due to fossil fuel burning, and 0.6 to 2.5 billion metric tons is due to deforestation (37).[19] Fossil fuel emissions are estimated to have increased more than 50-fold since the middle of the last century and are expected to reach 9 to 12 billion metric tons of carbon in 2025 without deliberate action to reduce them (98).

The United States, with less than 5 percent of the world's population, is responsible for almost 25 percent of fossil fuel CO_2 emissions, more than any other nation (58). U.S. emissions dropped during the two energy crises but have recently increased (see figure 2-8). Current emissions from deforestation in the United States are considered negligible (see ch. 7). Electricity production (for industrial, residential, and commercial use) dominates U.S. $C0_2$ emissions, followed by transportation, and then by direct

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[18] The seasonal variation reflects winter-to-summer changes in photosynthesis (CO_2 storage) and respiration (CO_2 release) in live plants.

[19] Others (35, 36) estimate that deforestation could contribute up to 2.8 billion metric tons of carbon (see ch. 7). Note that 1 billion metric tons of carbon is equivalent to 3.7 billion metric tons of CO_2 (37).

fossil fuel use in industrial and buildings applications. Oil and coal combustion each account for roughly 40 percent of U.S. emissions, natural gas the other 20 percent (see ch. 3).[20]

The United States is projected to contribute about 2 billion metric tons of carbon in 2025, slightly more than its current contribution in absolute terms, but a smaller fraction of the world's total than at present (98; also see ch. 3). China and other developing countries, the U. S. S. R., and centrally planned European countries are projected to be major emitters in 2025 (98; see ch. 9).

Calculating atmospheric concentrations of CO_2 from anthropogenic emission levels is complicated; annual emissions from human activity are small compared with natural exchanges of carbon among the atmosphere, oceans, and biosphere (see figure 2-9). These natural exchanges are substantial, yet not very well understood (16, 37, 68). For example, about 100 billion metric tons of carbon in the atmosphere is stored annually in living vegetation through the process of photosynthesis; an approximately equal amount of carbon is put back into the atmosphere through plant respiration and decay of dead vegetation (34). (The seasonal variation in the Mauna Loa CO_2 data (see figure 2-5) is caused by the seasonal imbalance between these processes, which roughly even out on an annual basis.)

An estimated 90 billion metric tons of carbon is exchanged between the oceans and the atmosphere each year (4). Over the past 30 years, the net effect of this exchange has been uptake and absorption by the oceans of roughly 2 to 3 billion metric tons of carbon from the atmosphere per year. If biosphere/atmosphere exchanges are ignored, this means that effectively about 45 percent of each year's CO_2 emissions from fossil fuel combustion have been offset by absorption by the oceans (4). However, the fraction of fossil fuel CO_2 that is absorbed by the ocean appears to be declining (46). One partial explanation may be that the surface layer of the ocean has warmed, and warmer water absorbs less CO_2

Recent analyses suggest that the oceans are not the only major sink for CO_2 and that terrestrial ecosystems may absorb a larger amount of CO_2 than previously thought (91). The IPCC (37) estimated that about 30 percent of today's CO_2 emissions is absorbed by the oceans and 23 percent by the land biota, and that 47 percent remains in the atmosphere. However, sequestering by the land biota is not well understood, and the biota could become saturated at some point in the future. In this event, the atmospheric accumulation would increase even faster, unless the oceans could somehow make up the difference (or CO_2 emissions declined). Appendix 2-A discusses the idea of fertilizing areas in the Antarctic Ocean with iron, in order to stimulate phytoplankton productivity and increase carbon sequestration in the ocean.

Greenhouse gas/global warming feedbacks may affect the natural balance between CO_2 storage and release. For example, some plants respond to increased atmospheric CO_2 by storing more carbon, at least under laboratory and horticultural greenhouse conditions; at the same time, warmer temperatures can speed up respiration and decay and hence accelerate the release of CO_2 to the atmosphere (see ch. 7). Some scientists hypothesize that feedback mechanisms are already operating and that they may explain: 1) the increase over the past three decades in the difference between wintertime peak and summertime low CO_2 concentrations (46); and 2) the recent acceleration of annual growth in CO_2 concentrations, despite leveling off of fossil fuel emission rates (35).

Because of the long atmospheric lifetime for CO_2 (50 to 200 years), the IPCC (37) estimated that anthropogenic CO_2 emissions would have to be reduced to 50 percent of their present level by the year 2050 in order to limit the atmospheric CO_2 concentration in 2050 to "only" 420 ppm (50 percent above the preindustrial level). The IPCC (37) estimated that an immediate 60 to 80 percent reduction in anthropogenic CO_2 emissions would be necessary to stabilize atmospheric CO_2 concentrations at 1990 levels (353 ppm).

Methane

Methane concentrations have steadily risen at about 1 percent per year, from about 1.52 ppm in 1978 to about 1.68 ppm in 1987 (see figure 2- 10). Ice core data show that CH_4 concentrations have approximately doubled over the past two centuries and are currently higher than at any time during the past 160,000 years. Like CO_2 concentrations, they have

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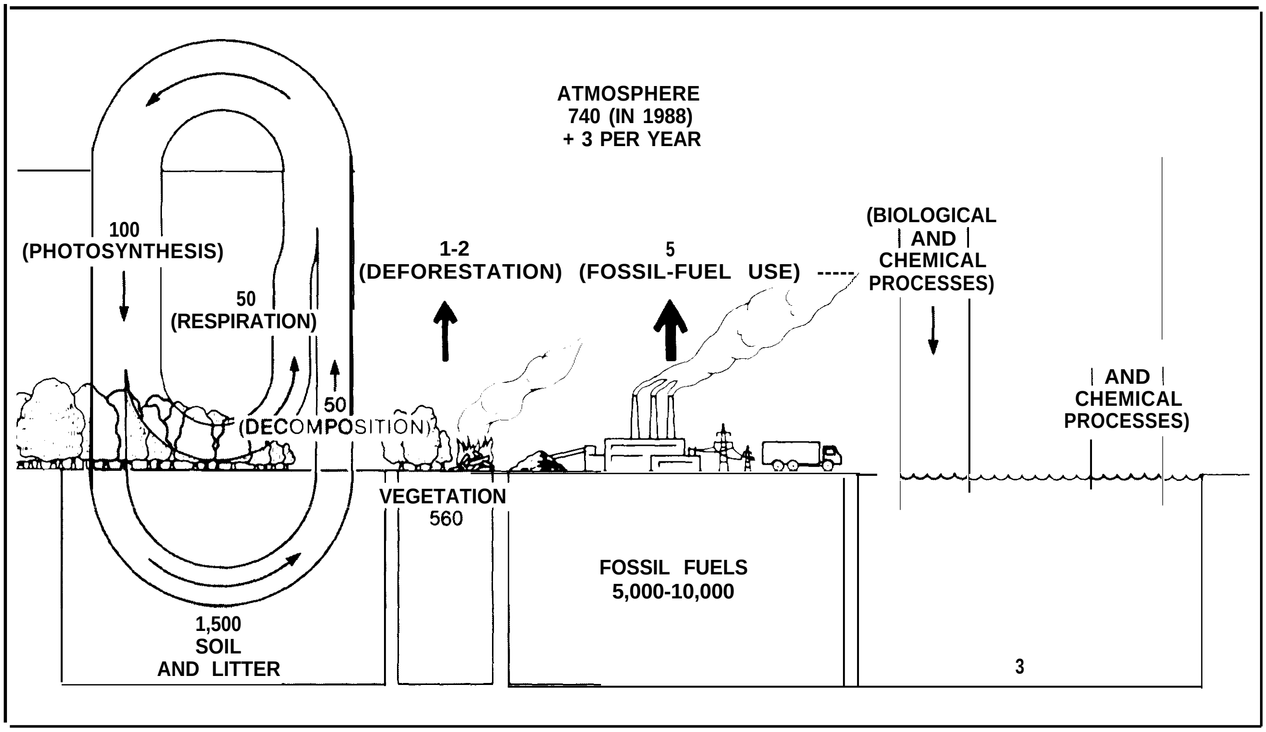
riper each unit of energy produced, though, CO_2 emissions from coal combustion are highest, followed by oil and then natural gas.

Figure 2-9--The Global Carbon Cycle



The carbon fluxes and reservoirs are shown in billions of metric tons C.

SOURCE: Office of Technology Assessment, 1991.

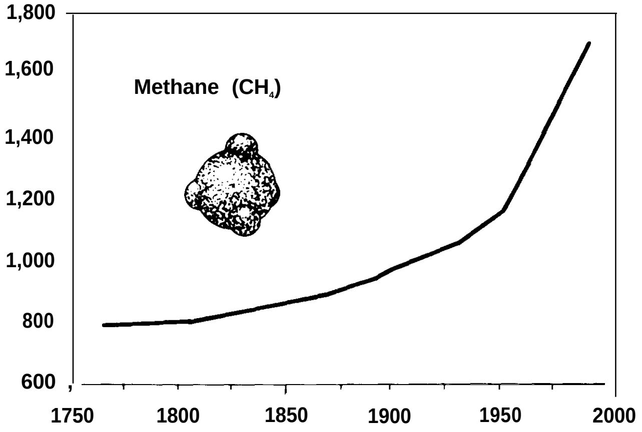
been roughly correlated with temperature over this period (37, 75, 89).

Per molecule, CH_4 is about 25 times more effective in trapping heat than CO_2 (98). Increases in CH_4 over preindustrial levels contributed about 15 percent of the total greenhouse gas forcing estimated to have occurred from 1880 to 1980 (70, 71). In the absence of steps to reduce CH_4 emissions, average CH_4 concentrations in the year 2030 are projected to reach about 2.5 ppm (28, 70, 71, 98). This nearly 50-percent rise above current atmospheric concentrations would increase expected equilibrium warming by about 0.2 to 0.5 ‘F above currently projected levels.

Current CH_4 emissions are estimated to range between 290 and 965 million metric tons per year (8, 14, 37, 98). Rice paddies and domestic animals (mainly cattle and sheep) are thought to be the largest sources related to human activity (see ch. 8), although natural gas production and delivery, coal production, and landfills also contribute substantially (see table 2-4). The United States apparently contributes about 6 percent of the CH_d emissions due to human activity, mostly from landfills, natural gas and coal production, and domestic animals. Without action to reduce emissions, EPA (98) projects that annual worldwide CH_4 emissions will increase by about 10 to 30 percent by 2025, with a slight decline in the relative U.S. share. The largest increases axe projected from landfills and production and distribution of fossil fuels; smaller increases are projected from domestic animals and rice production.

Methane molecules emitted today will remain in the atmosphere for an average of 10 years. Methane removal occurs primarily via a chemical reaction with a hydroxyl radical (OH-), which is a short-lived fragment of a water vapor molecule (69). However, the average lifetime of CH_4 molecules may be increasing, due to reductions in hydroxyl radical levels (69). Hydroxyl radicals can be lost due to reactions with CH_4 or carbon monoxide (CO), and emissions of both gases are thought to be increasing. Currently, OH^- depletion is estimated to have an effect equivalent to emitting a few additional million

Figure 2-10-Atmospheric: Methane Concentration
(parts per billion by volume)



SOURCE: Office of Technology Assessment, 1991, from IPCC, 1990

Table 2-4-Estimated Annual Global Methane Emissions and U.S. Contribution to Man-Made Sources

Source	Range in annual emissions (million metric tons)	Us. contribution (percent of global number)
Natural wetlands	100-200	
Termites	1o-1oo	
Oceans	5-20	
Fresh water	1-25	
Methane hydrate destabilization	0-1oo	
Domestic animals	65-100	9
Rice paddies	60-170	1
Biomass burning	20-80	<1
Coal mining	19-50	
Natural gas drilling, venting transmission losses	25-50	2 2[a]
Landfills	20-70	37
Total	290-965	6

[a] Includes both coal mining and natural gas sources.

SOURCES: R.J. Cicerone and R.S. Oremland, 1988; D.W. Barns et al., 1989; Intergovernmental Panel on Climate Change, 1990.

metric tons of CH_4 per year, but this could increase in the future (14).

Climate change feedbacks could also potentially increase CH_4 emissions levels. Warmer temperatures could increase emissions from wetlands and rice paddies, because the rate at which organic matter is decomposed in these environments increases with temperature (15). However, warming and a drier climate could decrease emissions from high-latitude tundra soils, as a result of lowered water tables (109). Warmer temperatures could also release CH_4 from permafrost where it is stored as ‘‘methane-hydrates (37). With a global average temperature increase of 5 ‘F (3 *C), as much as 100 million metric tons of CH_4 per year (48) to several times this amount (76) could be released from methane-hydrate deposits. In order to stabilize atmospheric CH_4 concentrations at current levels, the IPCC (37) estimated that an immediate 15 to 20 percent reduction in global anthropogenic CH_4 emissions would be necessary.

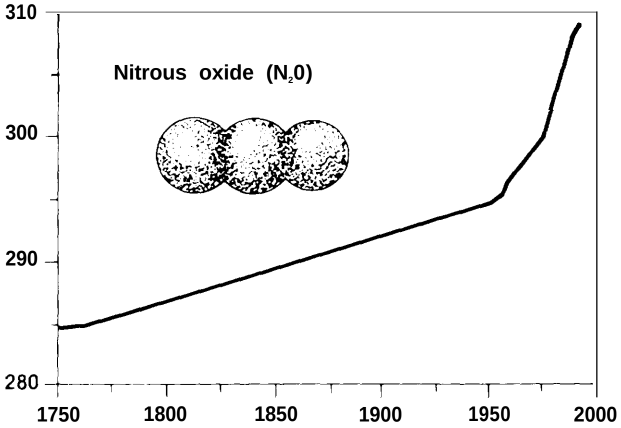
Nitrous Oxide

Nitrous oxide concentrations apparently began to rise rapidly in the 1940s, and increased about 0.2 to 0.3 percent per year during the mid-1980s. Current concentrations are about 310 ppb, compared to about 285 ppb during the late 1800s (see figure 2-1 1). Ice core measurements indicate that the preindustrial N_2O level was relatively stable at about 285*5 ppb for at least the past 2,000 years (37). Thus, today's N_2O atmospheric concentration appears to be without historical precedent. Unless N_2O emissions are reduced, concentrations are projected to rise to between 340 and 380 ppb by 2030 (28, 70, 71, 98).

Per molecule, the radiative forcing effect of N2O is about 200 times greater than that of CO_2 (98). The almost 10 percent increase in N_20 concentration that has occurred over the past century contributed about 2.5 percent of the total greenhouse gas forcing during that period (70, 71). Adding 35 ppb to the atmospheric N_2O burden by 2030 would increase the projected equilibrium warming by about 0.1 to 0.2 *F (().()55 to 0.11°C).

N_2O emissions levels are extremely uncertain; EPA (98) estimated the total to be 11 to 17 million metric tons per year, primarily from microbial soil vitrification and denitrification. Several kinds of human activity also result in N_2O emissions. Both the use of nitrogenous fertilizers for agriculture (ch. 8) and microbial activity in groundwater aquifers contaminated by nitrogenous compounds are sources associated with human activity (79). N_2O is also produced during fossil fuel combustion, although the magnitude of emissions from this source is highly uncertain (65). Biomass burning releases N_2O as well, but clearing of primary tropical forests could lower subsequent N_2O emissions if the soils then emit N_2O at a slower rate (77). In fact,

Figure 2-11—Atmospheric Nitrous Oxide concentration (parts per billion by volume)



SOURCE: Office of Technology Assessment, 1991, from IPCC, 1990.

Table 2-5—Estimated Sources and Sinks of Nitrous Oxide

Source/sinks	Annual emissions (million metric tons per year)
Sources:	
Coal and oil combustion	0.10-0.3
Biomass burning	0.02-0.2
Fertilized croplands	0.01 -2.2
Forest soils	2.9-5.2
Oceans	1.4-2.6
Total	4.4-10.5
Sinks:	
Removal by soils	No estimate
Photolysis in the stratosphere	7-13
Atmospheric increase	3-4.5
Total	10-17.5

SOURCE: Intergovernmental Panel on Climate Change, *Scientific Assessment of Climate Change,* Summary and Report, World Meteorological Organization/U.N. Environment Program (Cambridge, MA: Cambridge University Press, 1990).

emissions from fossil fuel and biomass combustion appear to be considerably less than once thought.

The IPCC (37) concluded that N_2O emissions of 10 to 17.5 million metric tons N per year are needed to account for the observed increase in atmospheric N_2O concentration. Yet the IPCC could identify only 4.4 to 10.5 million metric tons N per year from known sources (see table 2-5). The IPCC (37) concluded that the data suggest the likelihood of unaccounted for or underestimated sources of N_2O. Despite uncertainties as to what these are, the IPCC concluded that "the observed increase in N_2O concentrations is caused by human activities.

N_20 has an atmospheric lifetime of about 150 year; (37, 117). It is destroyed via reactions that occur in the stratosphere (70, 71) and possibly via removal by soils (37). The IPCC (37) estimates that to stabilize N_2O concentrations at current levels, an immediate 70 to 80 percent reduction in anthropogenic N_2O emissions would be needed.

Chlorofluorocarbons and Halons

Chlorofluorocarbons (CFCs) and halons are long-lived synthetic chemicals containing chlorine, fluorine (and in the case of halons, bromine), and carbon. They are released to the atmosphere from many sources: venting during servicing of appliances such as refrigerators or air-conditioners; leaks from such appliances (while in use or after disposal); production of 'open-cell' foams; deterioration of 'closed-cell' foams; and during use as aerosol propellants, solvents, and fire extinguishers. Emissions could be avoided from many of these applications, for example, through recapture and recycling or through incineration rather than disposal. Such measures are seldom taken.

CFCs and halons were first introduced in the 1930s, and worldwide production increased steadily until the mid- 1970s (see table 2-6 and figures 2-12 and 2-13), when the use of CFCs in nonessential aerosols was banned in the United States and a few other counties. Largely because of this ban, which was enacted in response to concerns about the destruction of stratospheric ozone, growth rates in atmospheric concentrations of CFCs have slowed, from an average of about 10 percent per year (between 1975 and 1985) to about 4 percent per year now. Atmospheric concentrations of the most widely used CFCs (CFC-11 and CFC-12) were 230 and 400 ppt, respectively in 1986, and 280 and 484 ppt in 1990 (37).

Outside the United States, however, both CFC- 11 and CFC-12 are still commonly used in aerosol sprays. CFC- 11 use in the United States is dominated by production of synthetic rigid foams for cushioning and insulation, while the largest use of CFC- 12 is for motor vehicle air-conditioning.

CFCs and halons have extremely long lifetimes, typically on the order of 65 to over 100 years (see table 2-6), before they are eventually destroyed in

Table 2-6--Chlorinated and Brominated Compounds

Compound	Formula	Atmospheric concentration (ppb)[a]	Annual growth rate (%)[a]	Ozone depletion potential (ODP)[b]	Global warming potential (GWP)[b]	Atmospheric lifetime (years)[a]	Worldwide[d] use in 1985 (billion grams)	U. S., share[d] of use (percent)
CFC-11	CFC-11	0.28	4	1	1.0	60	340	22
CFC-12	CFC-12	0.48	4	0.9- 1.0	2.8-3.4	130	440	30
CFC-113	CFC-113	0.06	10	0.8-0.9	1.3-1.4	90	160	45
HCFC-22	HCFF-22	0.12	7	0.04-0.06	0.32-0.37	15	206	NA[c]
Carbon tetrachloride	CCl_4	0.15	2	1.0- 1.2	0.34-0.35	50	1,030	27
Methyl chloroform	CH_3CCl_3	0.16	4	0.10-0.16	0.026-0.033	7	540	50
Halon-1211	CF_2ClBr	0.002	12	2.2-3.0	NA[c]	25	11	25
Halon-1301	CF_3Br	0.002	15	7.8-13.2	NA	110	11	50

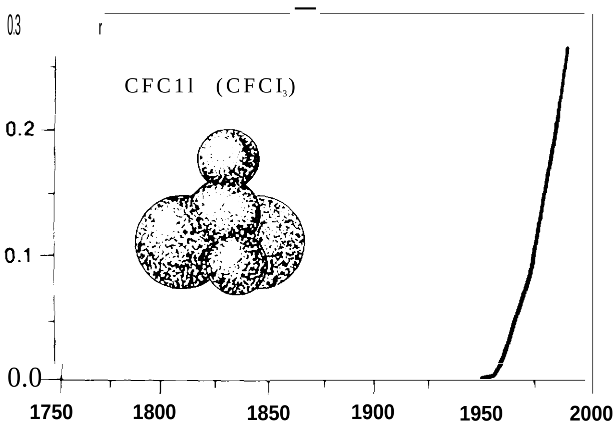
[a] Intergovernmental Panel on Climate Change, *Scientific Assessment of Climate Change, Summary and Report*, World Meteorological Organization/U.N. Environment Program (Cambridge, MA: Cambridge University Press, 1990).

[b] NASA, *Present State of Knowledge of the Upper Atmosphere 1990.' An Assessment Report* (Washington, DC: 1990). Ozone depletion potential and global warming potential per unit mass emitted, relative to that of CFC-11.

[c] NA - not available.

[d] J.K. Hammitt et. al., *Product Uses and Market Trends for Potential Ozone-depleting Substances, 1985-2000* (Santa Monica, CA: RAND Corp., May 1986); data for HCFC-22 for 1984, from U.S. Environmental Protection Agency, Office of Policy Planning and Evaluation, *Policy Options for Stabilizing Global Climate*, Draft Report to Congress (Washington, DC: February 1989).

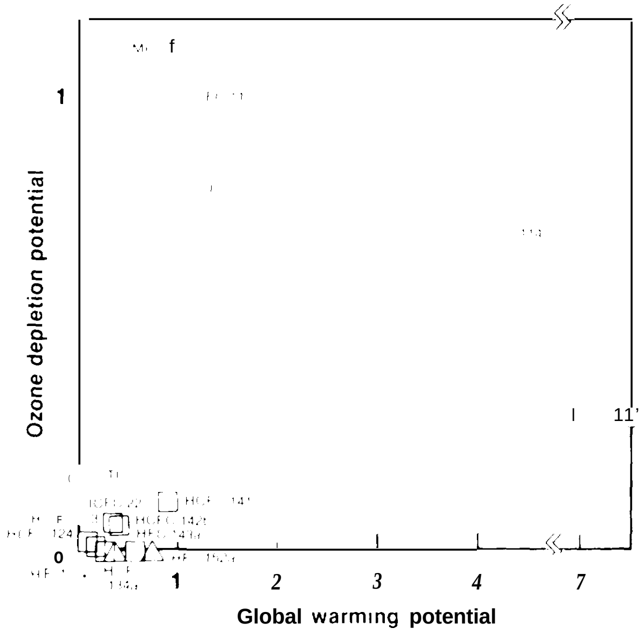
Figure 2-12—Concentration of CFC-11 in the Atmosphere (parts per billion by volume)



Total reported production of CFC-11 and CFC-12 increased rapidly throughout the 1960s and 1970s, reaching a maximum of 813,000 metric tons in 1974. Aerosol applications declined since the mid-1970s, while nonaerosol applications continued to increase.

SOURCE: Office of Technology Assessment, 1991, from IPCC, 1990.

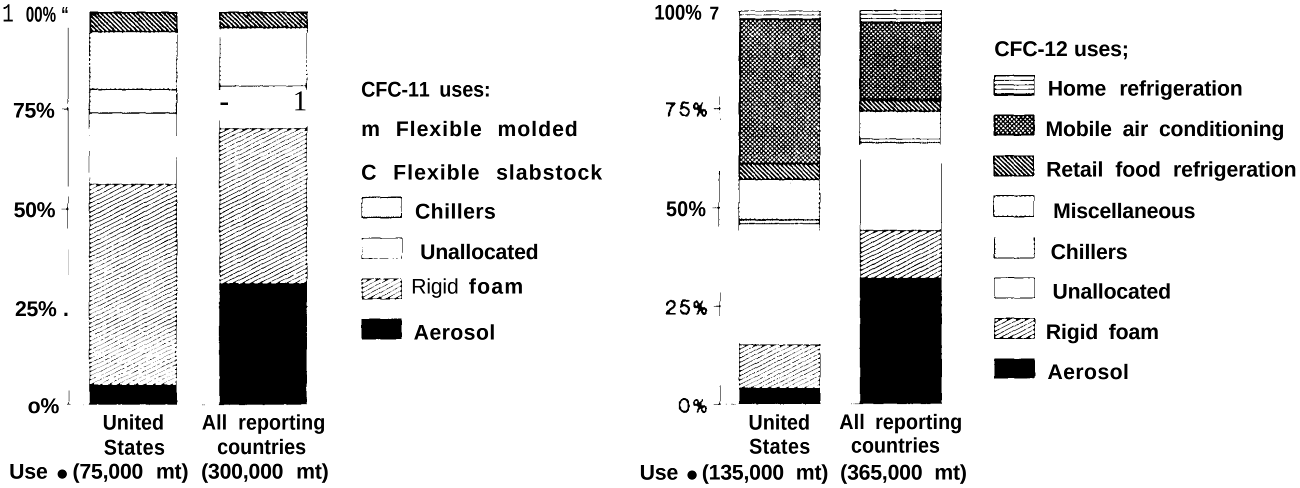
Figure 2-14—Ozone Depletion Potential and Global Warming Potential of CFCs and Replacement Compounds (HFCs and HCFCs)



Note that there is a strong correlation between ozone depletion effect and global warming potential; this relates to the lifetime of the compound in the atmosphere. Those with few chlorine and/or bromine atoms decompose more quickly (therefore causing less environmental damage) than fully chlorinated or brominated compounds.

SOURCE: Intergovernmental Panel on Climate Change, 1990; and Office of Technology Assessment, 1991.

Figure 2-13—Estimated CMA Reporting Country and U.S. Use of CFC-11 and CFC-12, by Product



SOURCE: J.K. Hammitt et al. ***Product Uses and Market Trends for Potential Ozone-depleting Substances,* 1985-2000** **(Santa Monica, CA: RAND Corp., May 1986).**

the stratospheric reactions that also deplete stratospheric ozone (see box 2-B). Evidence regarding ozone destruction mounted steadily in the 1980s (see box 2-B). In response, 47 countries negotiated the Montreal Protocol on Substances that Deplete the Ozone Layer, which was signed in September 1987 and strengthened in 1990 (see box 2-C).

The radiative forcing effect of CFCs is on the order of 10,000 times greater, per molecule, than that of CO_2 (70). CFC-11 and CFC- 12 contributed about 9 percent of the total radiative forcing increase that occurred over the last hundred years (70). Recently, however, their contribution has been much higher—approximately 25 percent over the last decade (30). Based on EPA projections conducted before the Montreal Protocol was strengthened in 1990, the added contribution of CFCs from the late 1980s through 2030 was projected to be an equilibrium warming increment of about 0.2 to 0.5 ‘F (0.1 to 0.3 °C) (98). Other chlorinated and brominated compounds have had less impact to date because their concentrations in the atmosphere are low, but molecule-for-molecule they can contribute as much to ozone depletion and global warming as CFC-11 and CFC- 12. Concentrations of some of these compounds are growing rapidly (see table 2-6).

The hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs) being considered as CFC replacements have shorter atmospheric lifetimes, generally 1 to 40 years for HFCs and HCFCs, compared to 65 to 130 years for CFCs (37) (see figure 2-14 and table 2-6). Thus, a rapid phaseout of CFCs coupled with aggressive substitution of HFCs and HCFCs (especially those with the shortest atmospheric lifetimes) would be expected to significantly lower net atmospheric concentrations of radiatively active gases, with a commensurate reduction in ozone depletion and global warming potential (37).

Photo credit: A, Kovacs

Carbon dioxide trapped in air bubbles in Antarctic ice indicates that present CO_2 concentrations are higher than at any time in the past 160,000 years. Ice core data also show that CH_4 concentrations have approximately doubled over the past two centuries; measurements for N_20 suggest that atmospheric concentrations remained stable for 2,000 years and started to climb during the industrial revolution.

Box 2-B—Stratospheric Ozone Depletion

Stratospheric ozone (0_3) shields the Earth from solar radiation in the biologically harmful range of ultraviolet wavelengths known as W-B (the wavelength band extending from about 280 to 320 rim). In humans, the harmful effects of exposure to W-B radiation include sunburn; premature aging of the skin; nonmelanoma skin cancer; occular disorders, including cataracts; and suppression of immune system responses. Though uncertain, malignant melanoma skin cancer may also be linked to W-B exposure. Excessive W-B exposure can also damage plants and animals in terrestrial and aquatic ecosystems.

Ninety percent of the protective ozone is contained in the stratosphere.[1] The natural balance of stratospheric ozone is maintained through a continuous cycle of production and destruction involving solar radiation, molecular oxygen (02), and naturally produced molecules containing hydrogen, nitrogen, chlorine, and bromine atoms. CFCs, halons, methyl chloroform, and carbon tetrachloride-all of which are synthetically produced chlorinated or brominated compounds-an severely alter this balance by speeding up ozone destruction. Because they are catalysts (i.e., they are not destroyed by the reactions in which they participate), one chlorine or bromine molecule can destroy thousands of molecules of ozone.[2]

The amount of UV-B radiation that reaches Earth's surface depends on season, time of day, latitude, and altitude. At present, on a clear day at the equator, only about 30 percent of the UV-B that enters Earth's atmosphere reaches its surface. Fractions as low as 10 percent reach the surface at higher latitudes or when clouds are present. However, for each l-percent reduction in ozone concentrations, the penetration of biologically active UV-B is predicted to increase by roughly 2 percent. In turn, the Environmental Protection Agency (33) estimates that with a 2-percent increase in W-B radiation, the incidence of nonmelanoma skin cancer in the United States would increase by about 2 to 6 percent over the current rate of roughly 400,000 new cases per year; and that the incidence of malignant melanoma in the United States would increase by 1 to 2 percent over the current rate of about 26,000 new cases and 6,000 fatalities per year.[3]

In October 1987, the amount of ozone over Antarctica fell to the lowest levels ever observed. Averaged over 100 latitude bands extending south from 60°, 70°, and 80°S, respectively, total column ozone (i.e., the amount of ozone directly overhead at a given site) had dropped by 24,40, and 50 percent compared to October 1979. At some locations and heights, the depletion reached 95 percent. observational evidence very strongly suggests that chemical mechanisms involving chlorine from human-made sources are the primary cause of this rapid decline (106). In particular, chlorine and bromine released from CFCs and halons are primed for ozone destruction by chemical interactions with cloud particles. With the extremely cold temperatures of the Antarctic winter, clouds form readily in the polar stratosphere. The greatest ozone depletion occurs during the austral spring, when the air above the Antarctic is chemically primed and isolated from air at lower latitudes, and sunlight is available to participate in ozone-destroying reactions. More normaI ozone levels were observed in 1988, indicating that meteorological conditions have to be "right" for severe ozone depletion to occur. The Antarctic ozone hole appeared in both 1989 *and* 1990, the first time such depletion was observed in two consecutive years. The 1990 hole was nearly as severe as the record levels found in 1987 and persisted longer.

Observations in the Arctic in December 1988 and February 1989 indicated that Arctic stratospheric ozone also had fallen, although on a much smaller scale than in the Antarctic. Observers found increased amounts of potential ozone-destroying compounds (C1O and OC1O), suggesting that the potential exists for significant destruction of ozone in the Arctic (106).

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[1] The stratosphere is the region of the atmosphere that extends from about 8 to 17 km (depending on latitude) and up to about 50 km above the Earth's surface. The remaining 10 percent of the ozone is found in the troposphere, the region of the atmosphere extending from Earth's surface up to the base of the stratosphere.

[2] The "greenhouse" gases CO_2, CH_4, and N_2O also affect stratospheric ozone. Increasing CO_2 or CH_4 would tend to increase rather than reduce stratospheric ozone. CO_2 cools the stratosphere, which generally slows the rates of ozone-destroying reactions. CH_4 helps tie-up chlorine in "inactive" molecules that do not react with ozone. Increasing N_2O can either increase or reduce stratospheric ozone, depending on the relative amounts of chlorine and nitrogen oxides present.

[3] People with light skin, red or blond hair, and blue or green eyes are most susceptible to developing nonmelanoma skin cancer. A1 ‘0 2 percent mortality rate is associated with the disease.

(Continued on next page)

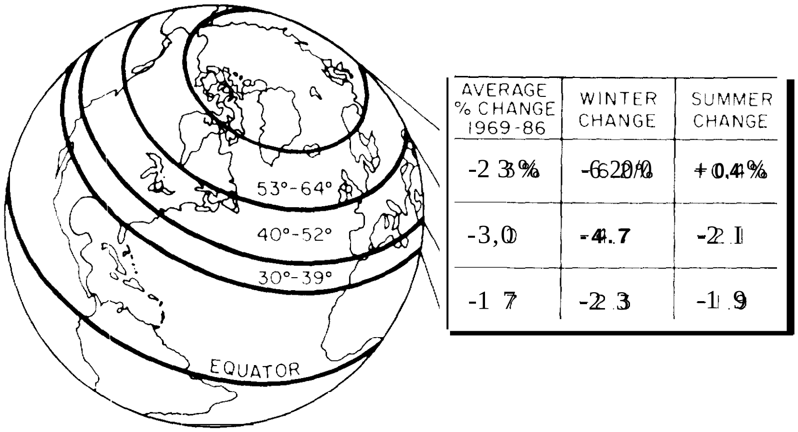
Box 2-B—Statospheric Ozone Depletion-Continued

Measurements of total column ozone show that ozone has declined at mid-latitudes in the Northern Hemisphere, with the reduction being especially pronounced in winter (see figure 2B-1). While computer models of stratospheric ozone have predicted an ozone decrease due to CFC emissions, the observed wintertime depletion is up to three times greater than has been predicted (106). The IPCC (37) concluded that, after allowing for natural variability, the Northern Hemisphere (300 to 64° N latitude) mean winter ozone level decreased by about 3.4 to 5.1 percent between 1%9 and 1988 (with no statistically significant trends during the summer).

The compounds implicated in stratospheric ozone depletion have two characteristics: they contain chlorine **or** bromine, and they are not broken down before they reach the stratosphere. Table 2-6 presents estimates of the ‘‘ozone depletion potential" (ODP) per molecule, relative to that ofCFC-11, of eight widely used compounds. ODP depends on the number of chlorine or bromine atoms in the molecule, its atmospheric lifetime (i.e., how long it takes before it is broken down or removed from the atmosphere), and the mechanisms involved in breaking it down. The compounds of greatest concern are extremely long-lived, with lifetimes on the order of 100 years, and are only broken down by reaction with intense solar radiation in the stratosphere. Thus, even though the Montreal Protocol has been strengthened to accelerate elimination of long-lived CFCs (see box 2-C), it will take a century for prior emissions to dissipate from the atmosphere.

Figure 2B-1—Estimated Percentage Changes **in Total Column Ozone at Northern Mid-Latitudes, 1969-66**

DECLINE IN THE OZONE SHIELD



AVERAGE % CHANGE 1969-86	WINTER CHANGE	SUMMER CHANGE
-2.3%	-6.2%	+0.4%
-3,0	-4.7	-2.1
-1.7	-2.3	-1.9

Changes in total ozone concentration, 1969-66, by latitude bands in Northern Hemisphere. Winter months: December, January, February, March. Summer months: June, July, August.

SOURCE: R.T. Watson et al., *Present State of Knowledge of the Upper Atmosphere* 1988: *An Assessment Report* (Washington, DC: National Aeronautics and Space Administration, 19SS), figure supplied byF.S. Rowland, 1990.

Box 2-C—The Montreal Protocol on CFCs

In response to growing international concern about the role of chlorofluorocarbons (CFCs) in destroying stratospheric ozone, 47 nations reached agreement on a set of CFC control measures in September 1987. Entitled the Montreal Protocol on Substances that Deplete the Ozone Layer, the control measures laid out a schedule of production and consumption reductions for many CFCs (95). Nations with high CFC use, such as the United States, were to reduce production and consumption of certain CFCs and halons to 50 percent of 1986 levels by 1998.[1] Those developing nations with low per-capita use were allowed to increase their use through 1999 and then were to cut back to 50 percent of 1995-97 levels over the following 10 years.

While the agreement represented a milestone in international environmental cooperation, many observers felt that the scope and time frame of the reduction schedule was insufficient to protect the ozone layer from further damage. For example, EPA estimated that even under the best participation scenario, future concentrations of CFCs 11 and 12 would double and triple, respectively, by 2030 without additional action (see figure 2C-1) (98). OTA concluded that the uncertainties of the agreement were such that under the most optimistic conditions the consumption of CFCs 11 and 12 could range from a 20-percent *increase* to a 45-percent *decrease* from 1986 levels (95). Finally, IPCC (37) has estimated that "[t]o stabilize, and then reduce, the current atmospheric concentrations of the fully halogenated CFCs (e.g., 11, 12, and 113) would require approximate reductions in emissions of 70 to 75 percent, 75 to 85 percent, and 85 to 95 percent, respectively. "

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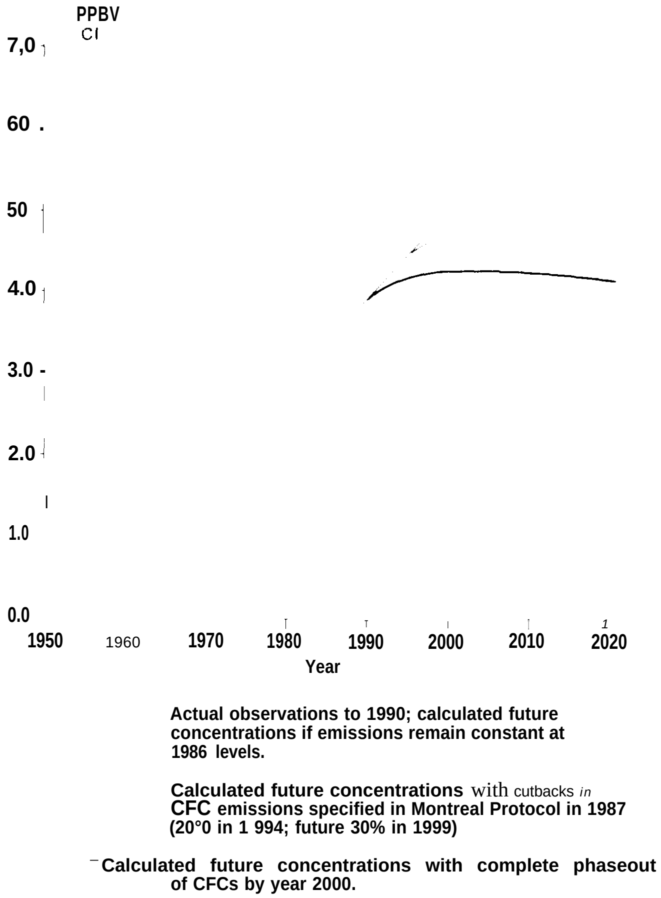
[1] Substances controlled under Annex A are: CFCs -11, -12, -113, -114, -115 and halons 1211, 1301, 2402.

(Continued on next page)

Figure 2C-1—Atmospheric Concentrations of Chlorocarbon Molecules



SOURCE: Office of Technology Assessment, 1991, from F.S. Rowland, 1990.

Box 2-C—The Montreal Protocol on CFCs-Continued

With these concerns in mind, delegates met in June 1990 to finalize a significantly stronger version of the Montreal Protocol (2, 93, 94). The new agreement regulates 10 additional CFCs and requires participating countries with high use per capita (greater than 0.3 kilograms) to reduce production and consumption by 20 percent of 1986 levels in the next 3 years, achieve a So-percent reduction by 1997, and a 100-percent phaseout by the year 2000.[2] HaIon production and consumption are to be frozen at 1986 levels by 1992 and steadily phased out by 2000, except for certain "essential uses," to be determined. Methyl chloroform (an industrial solvent that destroys stratospheric ozone) and carbon tetrachloride have been included in the Protocol for the first time; they will be phased out by 2000 and 2005, respectively. Parties to the Protocol are also required to declare their intent to phase out hydrochlorofluo rocarbons (HCFCs), which are less damaging, shorter lived substitutes for CFCs, no later than 2040.

Countries with low per-capita consumption of CFCs (i.e., developing nations) are given a lo-year grace period on all 1990 Montreal Protocol deadlines to allow them to meet their "basic domestic needs" (i.e., they are not to build up an export industry, but may produce CFCs for internal consumption). Such countries will also be assisted in their transition to CFC substitutes by a Multilateral Fund, financed by industrialized nations and designed to facilitate technology transfer and ease the financial burden of compliance with the control measures. This fired is meant to encourage key nations such as China and India to join the 65 signatories to the agreement.[3] For the first 3 years the fund is expected to total $160 million, but it could increase to $240 million if China and India decide to participate (94).[4] Their cooperation is considered vital if the Montreal Protocol is to achieve its long-term objectives of stabilizing global CFC emissions and allowing the stratospheric ozone layer to fully recover.

Trade with nonparties (those nations which have not signed or acceded to the agreement) is also restricted by the Protocol. Imports from and exports to nonparties of controlled substances is prohibited as of January 1990, and a list of products ***containing*** such substances is to be developed and their import banned by 1993. The feasibility of listing and banning products ***produced with*** CFCs and halons (e.g., computer chips) will be under consideration until 1994.[5]

In the new Clean Air Act Amendments, the U.S. Congress included provisions to control ozone-depleting substances that are slightly more stringent than those in the revised Montreal Protocol. First, the reduction schedule calls for specific reductions in each year until production ends. Second methyl chloroform is to be phased out 3 years earlier than required by the international agreement (i.e., by 2002 instead of 2005). Finally, a reduction schedule is laid out for HCFCs, with a freeze in 2015 and production prohibited in 2030 (10 years earlier than the Montreal Protocol's suggested but not binding deadline). Congress has also authorized $30 million over the next 3 years to support the Multilateral Fund; the amount will be raised to $60 million if India and China officially join. The House so far has appropriated $10 million for fiscal year 1991. Public Law 101-513 (Sec. 534) states that "not less than $10 million" of the funds appropriated to fund the Foreign Assistance Act shall be used to fund activities related to the Montreal Protocol.

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[2] Substances controlled under Annex B are: CFCs -13,-111,-112,-211,-212, -213,-214,-215,-216, -217, carbon tetrachloride, and 1,1,1 -trichloroethane (methyl chloroform).

[3] Current parties include the U.S.S.R., Polar@ Hungary, and Germany, as well as large developing nations such as Argentina, Bangladesh, Brazil, Egypt, Indonesia, Mexico, and the Philippines. Notably absent, as of December 1990, are Turkey (the only OECD non-signatory), China, and India.

[4] These totals are based on estimates extrapolated from case studies conducted by EPA and agreed on by the conferees. On the basis of the United Nations assessment scale, the United States would be responsible for a quarter of the voluntary contribution (R.J. Smith, U.S. Department Of State, personal communication, *Aug. 23,* 1990).

[5] This time schedule is for Annex A substances only (see footnote 1). Trade restrictions on Annex B substances will be implemented according to a slower schedule (generally a 2-year lag) to accommodate their recent inclusion and relatively rare use.

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APPENDIX 2-A: FERTILIZING THE OCEANS WITH IRON

The idea of "fertilizing" some Antarctic oceanic areas with iron to increase phytoplankton productivity and CO_2 uptake has recently attracted scientific and popular attention. The purpose of such an undertaking would be to offset anthropogenic emissions of carbon into the atmosphere.[1] Some opponents view this idea as an untested but tempting "tech-fro" that might delay policies to reduce fossil fuel use in industrialized countries (e.g., 4, 5). Proponents contend that ocean fertilization experiments to address emission offsets should begin now (3), because global carbon emissions might increase even if greenhouse policies are enacted.

Phytoplankton and Nutrients

The relationship between phytoplankton and the availability of such nutrients as iron, nitrogen, and phosphate is the key to the fertilization hypothesis.[2] Nearshore Antarctic waters, for example, tend to have relatively high concentrations of dissolved iron (apparently from upwelling of iron-rich sediments from the shallow bottom), as well as nitrogen and phosphorus, so high phytoplankton productivity is both possible and common (7, 10). In turn, this supports an enormous amount of marine life, including krill, whales, seals, and penguins.

In contrast, many offshore ocean waters lack sufficient nutrients to sustain high productivity. However, some offshore waters—notably in the Antarctic and Gulf of Alaska-while low in iron, have relatively high concentrations of nitrogen and phosphorus. But, they still exhibit low productivity. Martin et al. (8) conducted some short-term laboratory bottle experiments using water collected from the Gulf of Alaska and concluded that lack of iron was limiting phytoplankton growth, Martin et al. (10) also hypothesized that low levels of iron in offshore Antarctic waters prevent phytoplankton from using more than a small portion of available nutrients,

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Hence the idea to stimulate phytoplankton growth in offshore Antarctic waters by slowly releasing iron and ''fertilizing' the water. In theory, this could allow phytoplankton to use a greater share of other nutrients, and permit both phytoplankton populations and carbon uptake from the water to increase substantially.

However, uncertainties about the effects of a large-scale operational program exist from many perspectives. For example:

- Experimental--Is iron really the limiting factor? The data demonstrating iron limitation are from small, short-term laboratory experiments from one region and may not be generalizable (2, but see 9). Whether other factors might limit productivity over large areas even when sufficient iron is available is unknown. Increasing the scale from small lab studies to large field studies also poses problems, not least of which is conducting well-designed "control' experiments. And, even if iron is the limiting factor, a recent National Research Council (NRC) workshop noted the uncertainties in estimating how much iron might be needed and how much carbon would be taken up in a large-scale operation (1, also see 5a, 1la).[3]
- Practical-Can the iron be made available? Since iron is not readily soluble, one constraint is a mechanism for retaining iron in a biologically available form and for keeping it on or near frequently rough surface waters long enough to be used by phytoplankton (hours to several days). Another constraint could be economics (e.g., costs of iron and of transporting it to appropriate areas) (1).
- Environmental-What changes might occur in the ecosystem? Whether iron might preferentially enhance growth of some phytoplankton species over others and/or change the composition of existing marine food chains is unknown. Little is known about ecological relationships among phytoplankton populations, Some participants at the NRC workshop noted that the effect of rapidly increasing phytoplankton populations on organisms such as krill, a major component of antarctic food chains, cannot be predicted at this time (1, 4).
- Geochemical--Will carbon be sequester in sufficient amounts for sufficient periods? Removal of large amounts of carbon for decades to centuries would be desirable. A recent study (1 la; also see 5a), however, points out that Antarctic surface waters have a limited capacity to take up atmospheric CO_2 and that sequestration of carbon in deeper portions of the Antarctic depends on the rate at which surface and deeper waters mix (i.e., the rate of vertical mixing). It concludes that this rate is too slow to have a significant effect on atmospheric CO_2 concentrations. In addition, whether carbonaceous compounds

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[1] Phytoplankton arc short-lived, microscopic marine plants that use CO_2 during photosynthesis. Their remains, which retain some of the carbon, can fall to the ocean's bottom, thus serving as a ' 'sink" for carbon.

[2] Phytoplankton live near the ocean's surface, where conditions are conducive to photosynthesis (e.g., proper temperate, sufficient light, CO_2 dissolved in the water, and nutrients, which often control their rate of growth).

[3] The workshop was held in October 1990 in h-vine, California. Two NRC committees (the Committee on Global Change and the Panel on Policy Implications of Global Warming) have been involved during the past year or so in examining the idea, but the NRC has not yet released any public reports.

will accumulate on the ocean floor and serve as a long-term carbon "sink" depends in part on the concentration of dissolved CO_2 in the water column (11). Moreover, if upwelling brings other nutrients to the surface, it might also bring up carbon-rich sediments and release CO_2 back to the atmosphere,

Policy **Implications**

Marine phytoplankton form the basis of most oceanic food chains, from which much of the world's commercial fisheries are derived. Fertilizing the oceans to increase carbon storage might be justified if it was relatively certain that only '' minimal environmental impacts would occur. But uncertainties about the probability and magnitude of potential impacts are great. The cost-effectiveness of large-scale fertilization is unknown, because widely accepted estimates of its effects on CO_2 uptake (and on marine ecosystems) and of its implementation costs are not available today.

Participants at the NRC workshop suggested that a ' 'transient iron experiment,'" with a suggested area of about 400 square kilometers, be under-taken to gather morc informatation and data on the iron 1 imitation hypothesis. They did not envision detrimental environmental impacts from such an experiment but noted that the impacts of a large-scale treatment cannot be evaluated at this time given our current lack of knowledge (12). The American Society of Limnology and Oceanography is planning a symposiurn in early 1991 to focus on the issue of what controls phytoplankton production in nutrient-rich areas of the open ocean.

Field studies of a few years duration would probably yield useful information about the effects of iron enrichment on the short-term] productivity of phytoplankton In otherwise nutrient-rich waters: this would be an appropriate topic for biological and oceanographic research. [Linger studies would probably be needed to ascertain longer-term impacts on phytoplankton and marine ecosystems in general. The relative utility of a large operation at that time would depend in part on how successfully we develop energy-efficient and renewable energy technologies and practices and better land use management practices-choices that clearly can be implemented today (see ch. 1).

Appendix 2-A References

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