Changing Climate

Report of the Carbon Dioxide Assessment Committee

Board on Atmospheric Sciences and Climate
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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Executive Summary

1. Carbon dioxide (CO_2) is one of the gases of the atmosphere important in determining the Earth's climate. In the last generation the CO_2 concentration in the atmosphere has increased from 315 parts per million (ppm) by volume to over 340 ppmv. (Chapters 3, 4)

2. The current increase is primarily attributable to burning of coal, oil, and gas; future increases will similarly be determined primarily by fossil fuel combustion. Deforestation and land use changes have probably been important factors in atmospheric CO_2 increase over the past 100 years. (Chapters 2, 3)

3. Projections of future fossil fuel use and atmospheric concentrations of CO_2 embody large uncertainties that are to a considerable extent irreducible. The dominant sources of uncertainty stem from our inability to predict future economic and technological developments that will determine the global demand for energy and the attractiveness of fossil fuels. We think it most likely that atmospheric CO_2 concentration will pass 600 ppm (the nominal doubling of the recent level) in the third quarter of the next century. We also estimate that there is about a 1-in-20 chance that doubling will occur before 2035. (Chapters 2, 3)

4. If deforestation has been a large net source of CO_2 in recent decades, then the models that we are using to project future atmospheric concentrations are seriously flawed; the fraction of man-made CO_2 remaining airborne must then be lower, and CO_2 increase will probably occur more slowly than it otherwise would. (Chapter 3)

5. Estimates of effects of increasing CO_2 on climate also embody significant uncertainties, stemming from fundamental gaps in our understanding of physical processes, notably the processes that determine cloudiness and the long-term interactions between atmosphere and ocean. (Chapter 4)

6. Several other gases besides CO_2 that can affect the climate appear to be increasing as a result of human activities; if we project

increases in all these gases, climate changes can be expected significantly earlier than if we consider CO_2 alone. (Chapter 4)

7. From climate model simulations of increased CO_2 we conclude with considerable confidence that there would be global mean temperature increase. With much less confidence we infer other more specific regional climate changes, including relatively greater polar temperature increase and summer dryness in middle latitudes (e.g., the latitudes of the United States). (Chapter 4)

8. Results of most numerical model experiments suggest that a doubling of CO_2, if maintained indefinitely, would cause a global surface air warming of between 1.5°C and 4.5°C. The climate record of the past hundred years and our estimates of CO_2 changes over that period suggest that values in the lower half of this range are more probable. (Chapters 4, 5)

9. By itself, CO_2 increase should have beneficial effects on photosynthesis and water-use efficiency of agricultural plants, especially when other factors are not already limiting growth. (Chapters 3, 6)

10. Analysis of the effects of a warmer and drier climate on rain-fed agriculture in the United States suggests that over the next couple of decades negative effects of climate change and positive effects from CO_2 fertilization both will be modest and will approximately balance. The outlook is more troubling for agriculture in lands dependent on irrigation. Longer-term impacts are highly uncertain and will depend strongly on the outcome of future agricultural research, development, and technology. (Chapter 6)

11. Changes in temperature and rainfall may be amplified as changes in the annual discharge of rivers. For example, a 2°C warming could severely reduce the quantity and quality of water resources in the western United States. (Chapter 7)

12. (a) If a global warming of about 3 or 4°C were to occur over the next hundred years, it is likely that there would be a global sea-level rise of about 70 cm, in comparison with the rise of about 15 cm over the last century. More rapid rates could occur subsequently, if the West Antarctic Ice Sheet should begin to disintegrate. (Chapter 8)

(b) Such a warming might also bring about changes in Arctic ice cover, with perhaps a disappearance of the summer ice pack and associated changes in high-latitude weather and climate. (Annex 1)

13. Because of their large uncertainties and significant implications, it is important to confirm the various predictions of climate changes at the earliest possible time and to achieve greater precision. This can best be done through carefully designed monitoring programs of long duration emphasizing the ensemble of variables believed to influence climate or to reflect strongly the effect of CO_2. (Chapter 5)

14. The social and economic implications of even the most carefully constructed and detailed scenarios of CO_2 increase and climatic consequences are largely unpredictable. However, a number of inferences seem clear:

(a) Rapid climate change will take its place among the numerous other changes that will influence the course of society, and these other changes may largely determine whether the climatic impacts of greenhouse gases are a serious problem.

(b) As a human experience, climate change is far from novel; large numbers of people now live in almost all climatic zones and move easily between them.

(c) Nevertheless, we are deeply concerned about environmental changes of this magnitude; man-made emissions of greenhouse gases promise to impose a warming of unusual dimensions on a global climate that is already unusually warm. We may get into trouble in ways that we have barely imagined, like release of methane from marine sediments, or not yet discovered.

(d) Climate changes, their benefits and damages, and the benefits and damages of the actions that bring them about will fall unequally on the world's people and nations. Because of real or perceived inequities, climate change could well be a divisive rather than a unifying factor in world affairs. (Chapter 9)

15. Viewed in terms of energy, global pollution, and worldwide environmental damage, the "CO_2 problem" appears intractable. Viewed as a problem of changes in local environmental factors--rainfall, river flow, sea level--the myriad of individual incremental problems take their place among the other stresses to which nations and individuals adapt. It is important to be flexible both in definition of the issue, which is really more climate change than CO_2, and in maintaining a variety of alternative options for response. (Chapter 9)

16. Given the extent and character of the uncertainty in each segment of the argument--emissions, concentrations, climatic effects, environmental and societal impacts--a balanced program of research, both basic and applied, is called for, with appropriate attention to more significant uncertainties and potentially more serious problems. (Chapter 1)

17. Even very forceful policies adopted soon with regard to energy and land use are unlikely to prevent some modification of climate as a result of human activities. Thus, it is prudent to undertake applied research and development--and to consider some adjustments--in regard to activities, like irrigated agriculture, that are vulnerable to climate change. (Chapters 1, 9)

18. Assessment of the CO_2 issue should be regarded as an iterative process that emphasizes carry over of learning from one effort to the next. (Chapter 1)

19. Successful response to widespread environmental change will be facilitated by the existence of an international network of scientists

conversant with the issues and of broad international consensus on facts and their reliability. Sound international research and assessment efforts can turn up new solutions and lubricate the processes of change and adaptation. (Chapter 1)

20. With respect to specific recommendations on research, development, or use of different energy systems, the Committee offers three levels of recommendations. These are based on the general view that, if other things are equal, policy should lean away from the injection of greenhouse gases into the atmosphere.

(a) Research and development should give some priority to the enhancement of long-term energy options that are not based on combustion of fossil fuels. (Chapters 1, 2, 9)

(b) We do not believe, however, that the evidence at hand about CO_2-induced climate change would support steps to change current fuel-use patterns away from fossil fuels. Such steps may be necessary or desirable at some time in the future, and we should certainly think carefully about costs and benefits of such steps; but the very near future would be better spent improving our knowledge (including knowledge of energy and other processes leading to creation of greenhouse gases) than in changing fuel mix or use. (Chapters 1, 2, 9)

(c) It is possible that steps to control costly climate change should start with non-CO_2 greenhouse gases. While our studies focused chiefly on CO_2, fragmentary evidence suggests that non-CO_2 greenhouse gases may be as important a set of determinants as CO_2 itself. While the costs of climate change from non-CO_2 gases would be the same as those from CO_2, the control of emissions of some non-CO_2 gases may be more easily achieved. (Chapters 1, 2, 4, 9)

21. Finally, we wish to emphasize that the CO_2 issue interacts with many other issues, and it can be seen as a healthy stimulus for acquiring knowledge and skills useful in the treatment of numerous other important problems. (Chapter 1)

1 Synthesis

Carbon Dioxide Assessment Committee

1.1 INTRODUCTION

For more than a hundred years scientists have been suggesting that slight changes in the chemical composition of the atmosphere could bring about major climatic variations. Since the turn of the century, the focus has been particularly on worldwide release of carbon dioxide (CO_2), as a result of burning of coal, oil, and gas and changes in land use that release CO_2 from forests and soils.* In recent decades many aspects of the argument that enough CO_2 will be released to bring about unwanted and unwonted changes in climate have been filled out and strengthened; at the same time, new questions about segments of the argument have arisen, and possible benefits have been identified, including directly favorable implications for plant growth from increasing CO_2.

At this stage in the history of the CO_2 question, many readers are familiar with its basic aspects, so we have limited this introduction to two fundamental points. The first is that CO_2, along with water vapor, ozone, and a variety of other compounds, is a key factor in determining the thermal structure of the atmosphere. These so-called "greenhouse" gases do not strongly absorb incoming radiation for most of the shortwave solar spectrum, but they are more effective absorbers of the long-wavelength (infrared) radiation of the Earth's surface and atmosphere (see Figure 1.1). The mix and distribution of the gases account in no small part for the generally hospitable climate of Earth and the inhospitable climate of other planets. Concern arises about human activities that release greenhouse gases because important absorption bands for CO_2 and other atmospheric gases are far from saturation; increasing the concentration of the gases will continue to affect the net emission or absorption of energy from a given layer of the atmosphere and thus the climate. The second fundamental point is that the atmospheric concentration of CO_2 is rising. Figure 1.2 shows an exceptionally accurate and reliable record of measurements

*See "Annex 2, Historical Note," for the early history of the CO_2 issue.

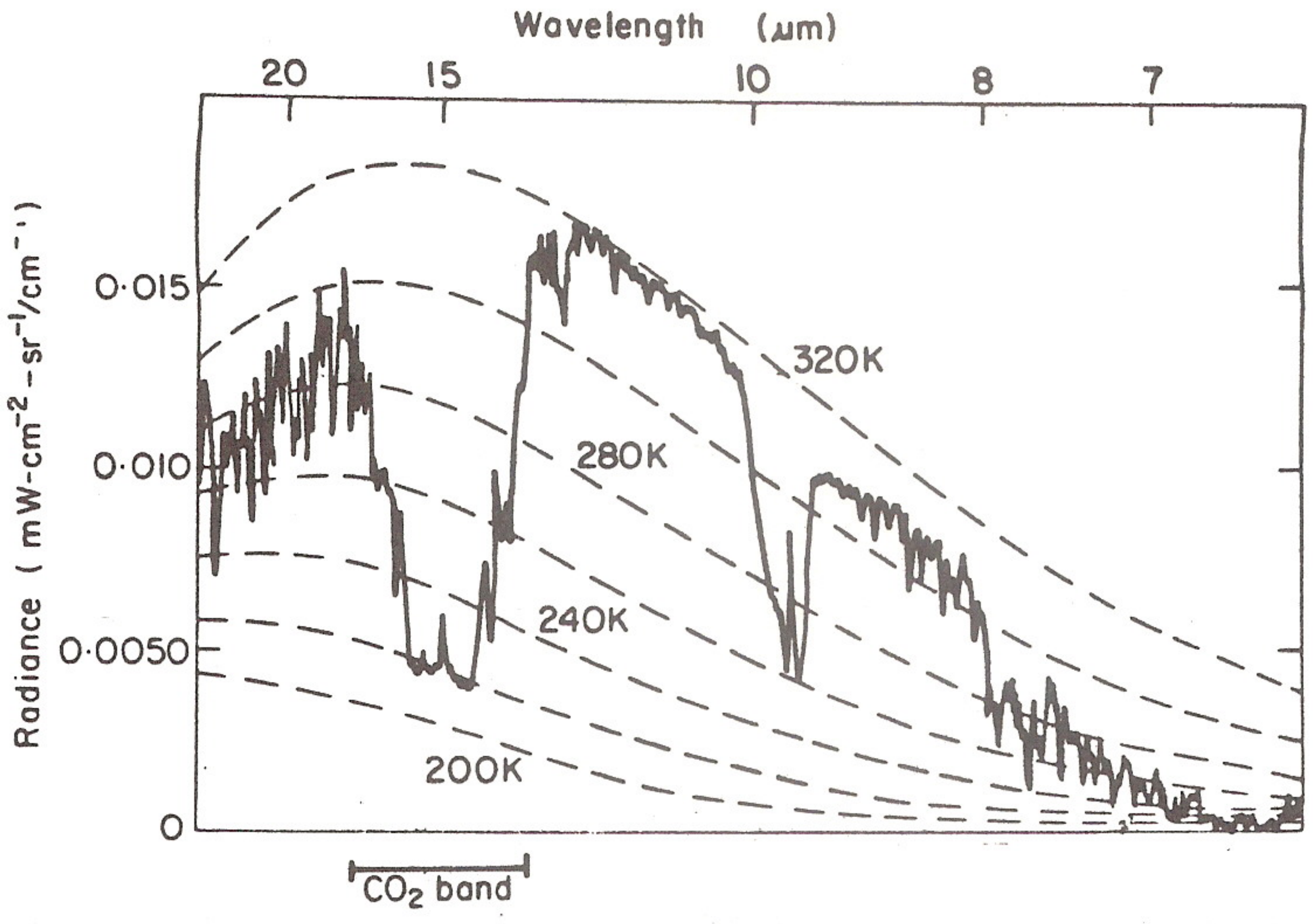

FIGURE 1.1 Infrared spectrum of the Earth as taken by a scanning interferometer on board the Nimbus-4 satellite over the North African desert. Also shown (dotted lines) are the blackbody radiances that would be observed at various temperatures. Thus, in the 10-13-μm region, the atmosphere is transparent and the radiance corresponds closely to that expected from the hot desert surface (at 320 K or 47°C). In the CO_2 band, however, the radiance is from the stratosphere at a temperature of 220 K, and energy from the Earth's surface is blocked. Other important infrared-absorbing trace gases include water vapor, nitrous oxide, methane, the chlorofluorocarbons, and ozone (in the troposphere). (From Paltridge and Platt, 1976, after Hanel et al., 1972).

starting in 1958. In short, there is a strong physical basis for attention to the CO_2 question in both theory and measurement.

Another, quite different, aspect of the CO_2 issue that requires introduction is that the time horizons of the subject and, therefore, of this report are very long. We talk about American agriculture in the year 2000, global energy use to 2100, and possible changes in sea level over the next three to five centuries. Is it meaningful to talk of such remote times? We think it is, and we have tried to devise approaches that take the time dimension seriously, although much of the report had to be speculative. Is it necessary to look so far into the future? Again, we think the answer is yes. Once the CO_2 content of the atmosphere rises significantly, it is likely to remain elevated for centuries; so from a physical point of view one must consider the long run. From the perspective of human activities, the time periods to be considered are also necessarily long. It takes many decades to replace the capital and infrastructure associated with a particular form of energy, and the time to develop large-scale water supply systems can be equally great. No policy, no matter how forceful, will make the issue of climate change disappear for at least decades to come. Finally, in considering the environment, one must think in terms of long-term

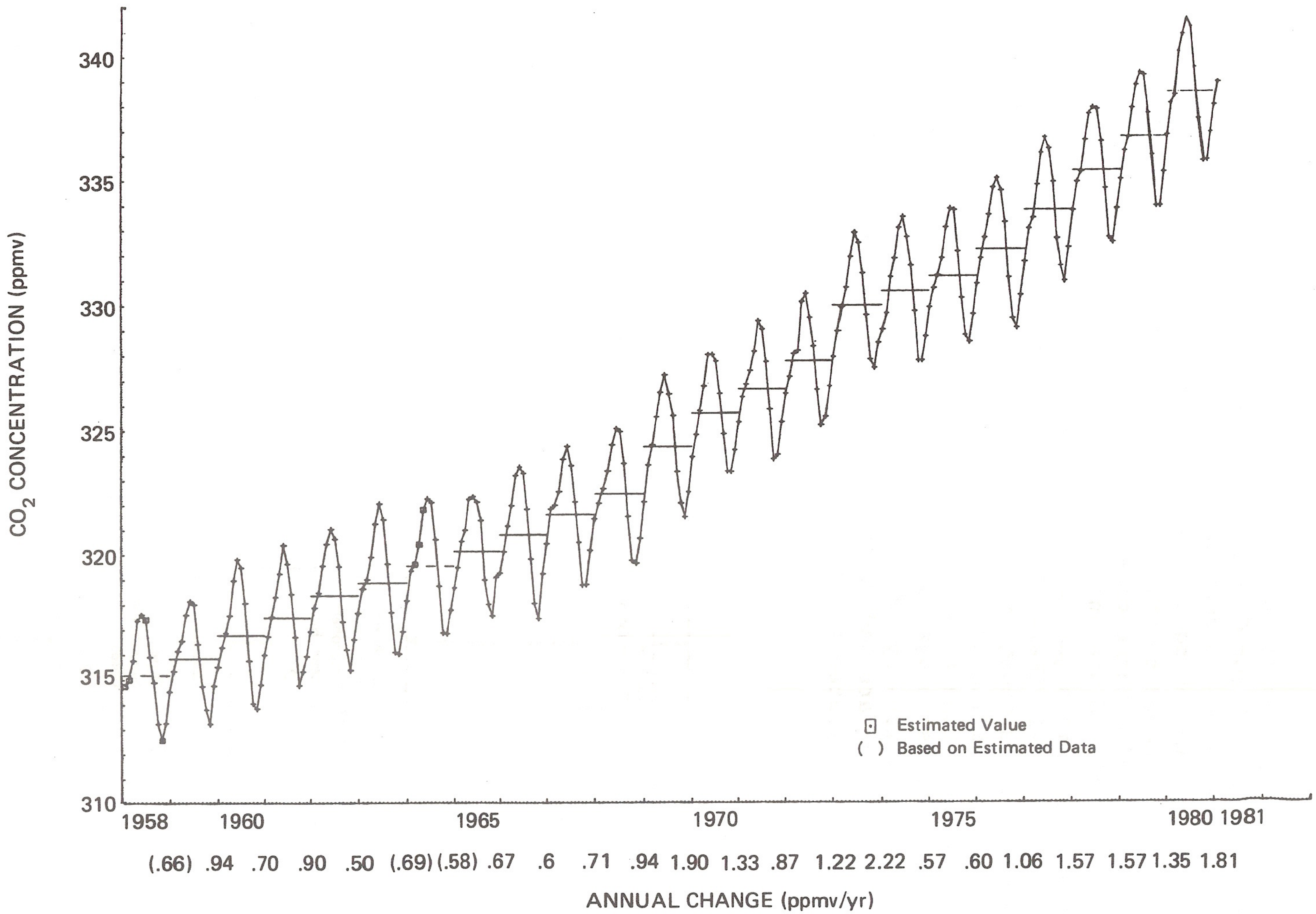

FIGURE 1.2 Mean monthly concentrations of atmospheric CO_2 at Mauna Loa. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the northern hemisphere. See Section 1.2.2 for discussion of annual cycle. (Source: Geophysical Monitoring for Climate Change, National Oceanic and Atmospheric Administration.)

sustainable strategies. While adverse consequences of 100 years from now are obviously less pressing than those of next year, if they are also of large magnitude and irreversible, we cannot in good conscience discount them.

The outline of the report is as follows. In this Synthesis chapter we summarize the outlook for CO_2-induced climatic change and its effects, try to estimate how serious an issue CO_2 is, and make recommendations for improving our understanding of the issue and our societal stance in regard to it. In subsequent chapters, individual authors and groups of authors treat the same topics in greater depth and for more specialized audiences. Both the Synthesis and the volume as a whole examine this sequence of questions: How much CO_2 will be emitted? How much will remain in the air? How much will CO_2 and other greenhouse gases change the climate? Are CO_2-induced climatic changes already identifiable? What would be the effects of substantial warming induced by increased atmospheric concentrations of CO_2 and other greenhouse gases on agriculture, water supply, and polar regions and sea level? And, finally, what are the implications of the CO_2 issue for societal welfare and policy? Figure 1.3 offers an overview of the CO_2 issue as treated in this report.

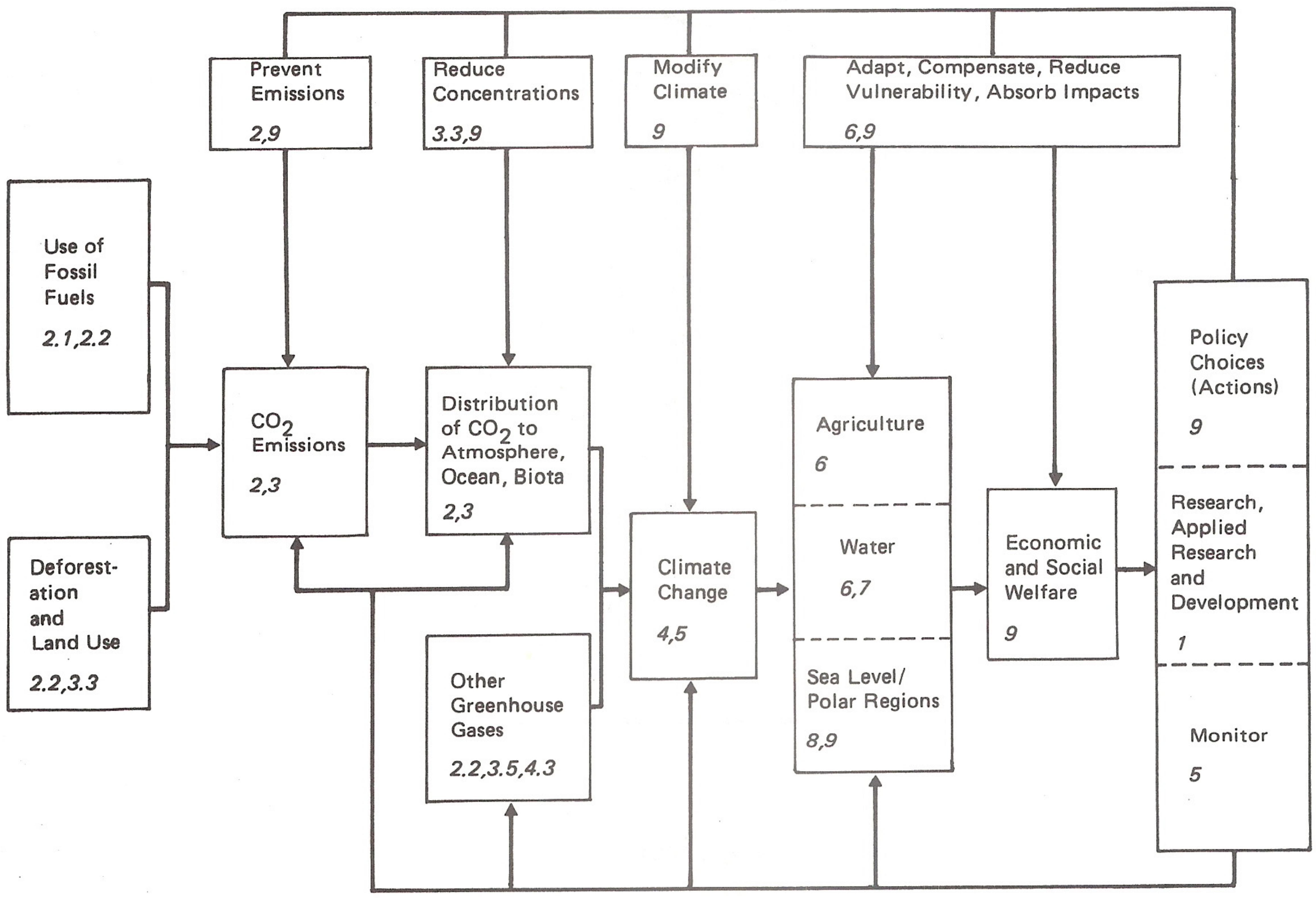

FIGURE 1.3 An overview of the CO_2 issue. Numbers refer to chapters or sections that focus on topic in box.

1.2 THE OUTLOOK

1.2.1 Future CO_2 Emissions

By far the largest potential sources of man-made CO_2 emissions are the fossil fuels, especially the abundant supplies of coal. Current annual fossil fuel emissions are estimated at about 5 x 10^9 tons of carbon (Gt of C) ± 10% (Marland and Rotty, 1983). In 1981, emissions came about 44% from oil, 38% from coal, and 17% from gas. The United States accounts for about one quarter of worldwide fossil fuel emissions, as do Western Europe and Japan, the Soviet Union and Eastern Europe, and developing countries.

To estimate future emissions of CO_2 from fossil fuels, Nordhaus and his co-authors adopted two approaches. One was to review previous global, long-range energy studies and use the range of projections as a guide to the uncertainty of scientific judgment (Ausubel and Nordhaus, this volume, Chapter 2, Section 2.2). The second approach (Nordhaus and Yohe, this volume, Chapter 2, Section 2.1), developed for this assessment, explicitly allows estimation of future emissions and their uncertainty based on a range of values for key parameters.

Review of previous energy studies shows that almost all studies applicable to estimation of CO_2 emissions project a continued marked growth of energy demand. For example, projections of energy demand in the year 2030 generally range from about 2-1/2 to 5 times the recent rate of energy use of 8 terawatt (TW, 10^{12} W) years per year. The studies vary so widely in quality, approach, level of detail, time horizon, data base, and geographic aggregation that strict comparisons are generally inappropriate. However, some generalizations may be ventured. Most studies looking beyond the year 2000 project average energy growth between about 2% and slightly above 3% per year, rates reasonably consistent with the 2.2% global annual average increase in primary energy consumption* that has prevailed over the past 120 years. Of course, the absolute range of projections spreads as the time horizon is extended, as a result of compounding the varied annual rates of increase. To illustrate, the range embracing almost all of the more detailed projections increases from 14-21 TW yr/yr in A.D. 2000 to 20-40 TW yr/yr a generation later. There are no strong signs of convergence toward a single, widely accepted projection or set of assumptions, although generally estimates have been lower in the last few years than in the 1970s. Figure 1.4 summarizes past global energy consumption and most of the long-range projections.

Combining estimates of energy demand and the mix of fuels leads to projections of CO_2 emissions. When the mix includes a large share of fossil energy, the projections show relatively high levels of CO_2 emissions. Figure 1.5 shows paths of CO_2 emissions derived from about a dozen long-range energy projections. Average annual rates of

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*The 2.2%/yr figure includes wood and noncommercial energy sources (Marchetti and Nakicenovic, 1979; Nakicenovic, 1979).

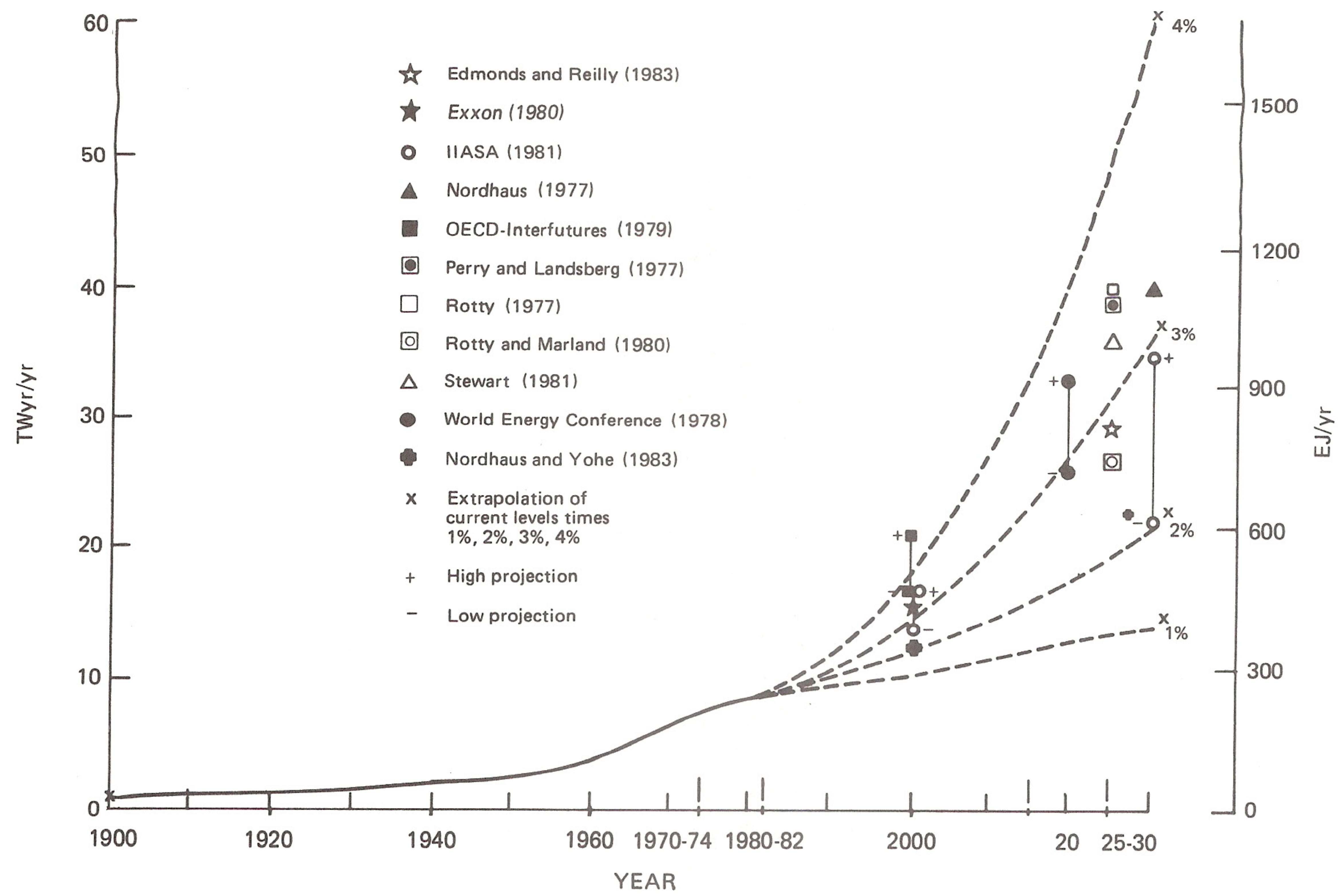


FIGURE 1.4 Past and projected global energy consumption. See Chapter 2, Section 2.2 for discussion of projections included here.

increase in CO_2 emissions to 2030 generally range from about 1 to 3.5%.* Estimated annual emissions range between about 7 and 13 Gt of C in the year 2000 and, with a few exceptions, between about 10 and 30 Gt of C in 2030. Thus, based on a review of past efforts, one might infer that energy consumption 50 years hence could differ by at least a factor of 2 and associated CO_2 emissions by a factor of 3 or more.

For purposes of understanding future outcomes and weighing policy choices, the past efforts reviewed leave open important questions. They generally do not allow a judgment as to the accuracy with which a forecast is made. It is of central importance in many policy problems to know not only the best judgment about an event (such as the time when atmospheric CO_2 will pass a certain level) but also to be able to estimate the degree of precision or approximation about that judgment. Some studies have approached the difficulties of forecasting by

*This range contrasts with the 4.3% figure for past and projected growth in CO_2 emissions that prevailed for several years in the literature on the CO_2 issue. The mean growth rate of fossil fuel CO_2 emissions over the past 120 years has more recently been estimated at about 3.5% per year (Elliott, 1983).

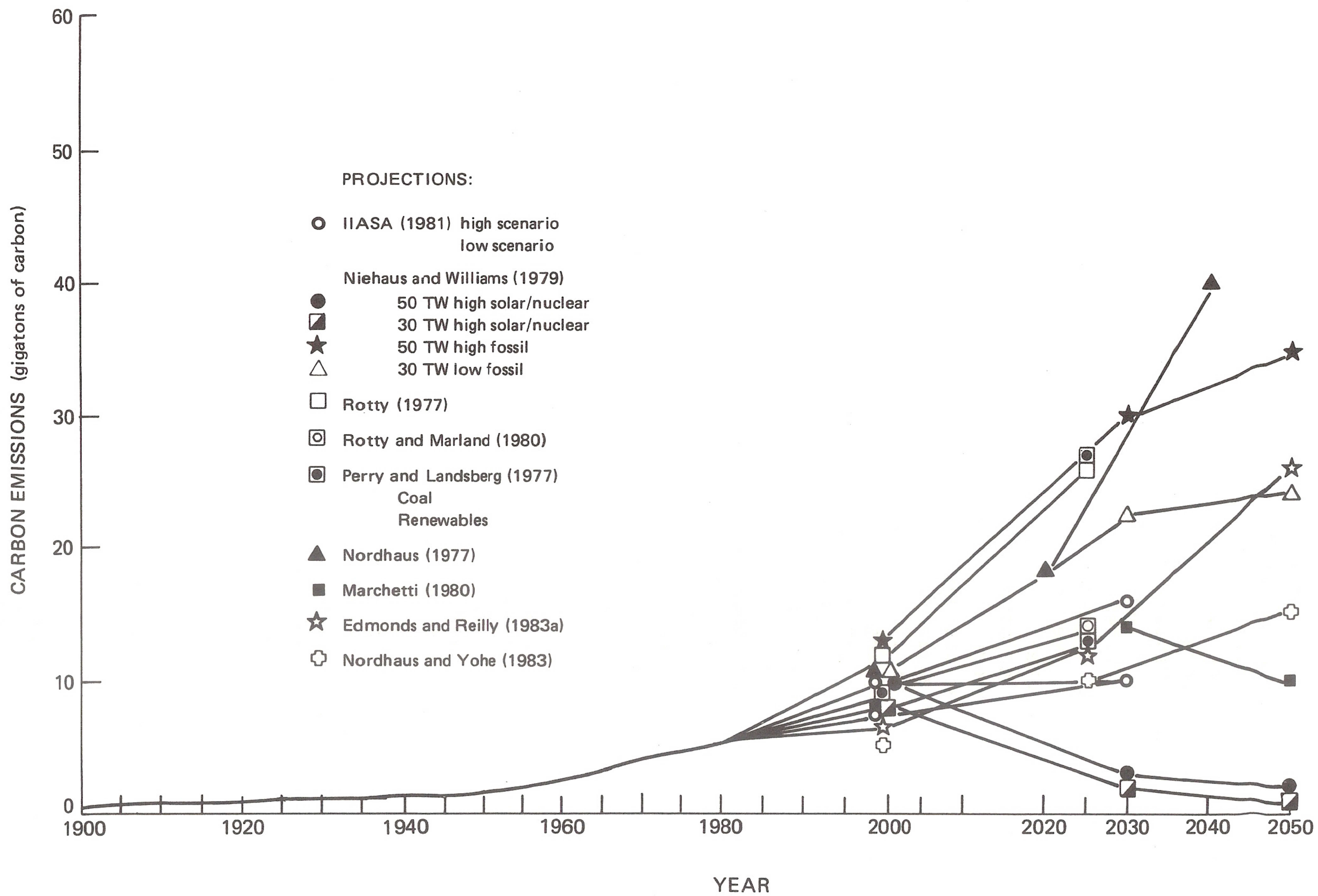


FIGURE 1.5 CO_2 emissions derived from long-range energy projections and historic production from fossil fuels. See Chapter 2, Section 2.2 for discussion of projections included here.

use of "scenario" analysis. The scenario approach involves tracing out time paths for important parameters under assumptions that are thought to be "interesting," usually without assigning measures of probability to the parameters or outcomes. These studies provide answers to hypothetical questions of the "what if?" type. For example, What might be the evolution of the energy system if there is a moratorium on building nuclear power plants? Usually scenario studies examine only a very few possibilities, and they do not attempt to assess the actual likelihood of the scenarios investigated.

To address these shortcomings, Nordhaus and Yohe employed modern developments in aggregative energy and economic modeling to construct a simple model of the global economy and carbon dioxide emissions. Particular care was given to assure that the energy and production sectors of the economy were integrated (most CO_2 emission projections are based on examination of the energy sector taken in isolation) and to respect the cost and availability of fossil fuels. The analysis attempts to recognize explicitly the intrinsic uncertainty about future developments by identifying the most important uncertain parameters of the model, by examining current knowledge and disagreement about these parameters, and then by specifying a range of possible values for each uncertain parameter. The emphasis was not to resolve uncertainties but to represent current uncertainties as realistically as possible. A use of the range of paths and uncertainties for the major economic, energy, and carbon dioxide variables allows not only a "best guess" of the future path of carbon dioxide emissions but also alternative trajectories that represent a reasonable range of possible outcomes given the current state of knowledge. The data employed were gathered from diverse sources and are of quite different levels of precision; judgments as to the uncertainties about the parameters are rough. Political conditions are not treated explicitly, but they may be regarded as included implicitly, for example, as a possible cause of a low value for the parameter representing growth in productivity.

The central tendency in the results of the Nordhaus-Yohe approach is a lower emissions rate than that of most earlier studies, in which the annual emissions increase generally ranged from about 1 to 3.5%. The "best guess" of Nordhaus and Yohe is that CO_2 emissions will grow at about 1.6% annually to 2025, then slow their growth to slightly under 1% annually after 2025. The major reasons for the lower rate are a slower estimated growth of the global economy than had earlier been the general assumption, further conservation as a result of the energy price increases of the past deacde, and a tendency to substitute nonfossil for fossil fuels as a result of the increasing cost of fossil fuels relative to other fuels. Figure 1.6 presents five paths that represent the 5th, 25th, 50th ("best guess"), 75th, and 95th percentiles of annual CO_2 emissions. The percentiles are indexed in terms of the cumulative CO_2 emissions by the year 2050 (see this volume, Chapter 2, Section 2.1).

In addition to burning of fossil fuels, human activities release CO_2 through deforestation and land clearing. Estimates of future biospheric emissions have generally been based on extrapolation of estimates of recent biotic emissions and rough guesses about what

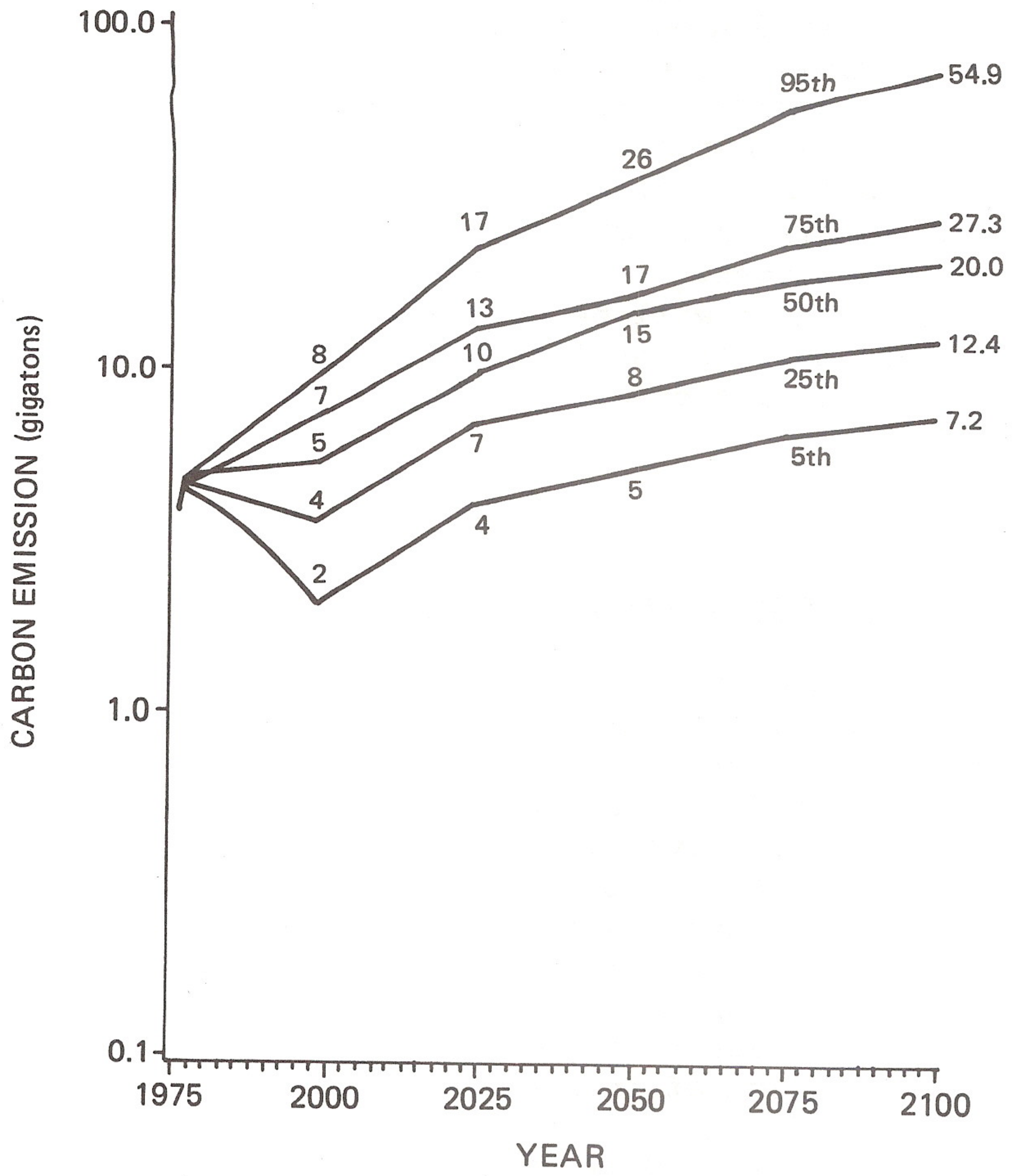


FIGURE 1.6 Carbon dioxide emissions from a sample of 100 randomly chosen runs. The 5th, 25th, 50th, 75th, and 95th percentile runs for yearly emissions, with emissions for years 2000, 2025, 2050, and 2100 indicated. See Chapter 2, Section 2.1, and Figure 2.17 for further detail.

proportion of carbon in the biosphere might be subject to human influence. Models of the carbon in forests and soils are now being developed that might provide projections with a stronger theoretical basis. An estimate for the maximum possible future addition from all biospheric sources is 240 Gt of C (Revelle and Munk, 1977), and Woodwell (this volume, Chapter 3, Section 3.3) offers a similar projection. Baumgartner (1979) estimates that clearing of all tropical forests might contribute about 140 Gt of C. The total carbon content of the Amazon forest is estimated at about 120 Gt of C (Sioli, 1973). Chan et al. (1980) develop a high deforestation scenario in which total additional transfer of carbon from the biosphere to the atmosphere by the year 2100 is about 100 Gt of C. The World Climate Programme (1981) group of experts adopted a range of 50 to 150 Gt of C for biospheric emissions in the 1980 to 2025 period. Projections of future atmospheric CO_2

concentrations embracing both burning of fossil fuels and terrestrial sources have all been dominated by growth rates in fossil fuel emissions, except in cases where fossil fuel emissions are extremely low. Over a period of a decade or two, biospheric emissions could rival fossil fuel emissions, but over a century biospheric emissions from human activities are most unlikely to average higher than 1 to 3 Gt of C per year, and fossil fuel emissions are typically projected to be an order of magnitude larger. It is also possible, as discussed in the next section, that there will be no significant net release of carbon from the biosphere over the next century, depending on which human activities and physical processes are dominant.

1.2.2 Future Atmospheric CO_2 Concentrations

We now turn to the question of translating CO_2 emissions into atmospheric CO_2 concentrations. Projecting CO_2 concentrations requires a determination of how emissions will be partitioned among the atmosphere, the oceans, and the biosphere. Carbon circulates naturally among these reservoirs driven by physical and biological forces; we term this circulation the carbon cycle, and the injection of carbon dioxide into the atmosphere by human activities may be viewed as a perturbation of this cycle (see Figure 1.7). Before the substantial release of CO_2 from human activities began, one part of the carbon cycle involved production of organic matter from atmospheric CO_2 and water and transportation of this material to the ocean where it was buried in marine sediments. Anthropogenic emissions have reversed this part of the carbon cycle. Some of the carbon stored over 500 million years in marine sediments is now returning to the atmosphere in a few short generations.

By means of quantitative models of the carbon cycle, we can estimate the effects of postulated rates of carbon dioxide injections on the pools and fluxes of carbon, in particular on the concentration of carbon in the atmosphere. Moreover, we can also assess the degree to which uncertainties in our understanding of one or another factor influence our forecasts of future atmospheric CO_2 levels.

The atmosphere forms a thin film over the Earth. Its composition is in large part the result of biological activity, and it is powerfully shaped by interaction with the oceans that cover some 70% of the globe. The concentration of CO_2 in the atmosphere has varied over the ages; for example, there is evidence that it may have been about 200 ppm during the last ice age 18,000 years ago. Reliable instrumental records are available only since 1957. Since then, the concentration has increased from about 315 ppm to slightly above 340 ppm and at an average rate of about 0.4% per year over the last decade (Figure 1.2). As discussed by Machta (this volume, Chapter 3, Section 3.4), carbon dioxide is well mixed in the atmosphere; measurements from the global network of sampling sites show relatively small spatial and temporal variations that are explainable largely in terms of fossil fuel sources

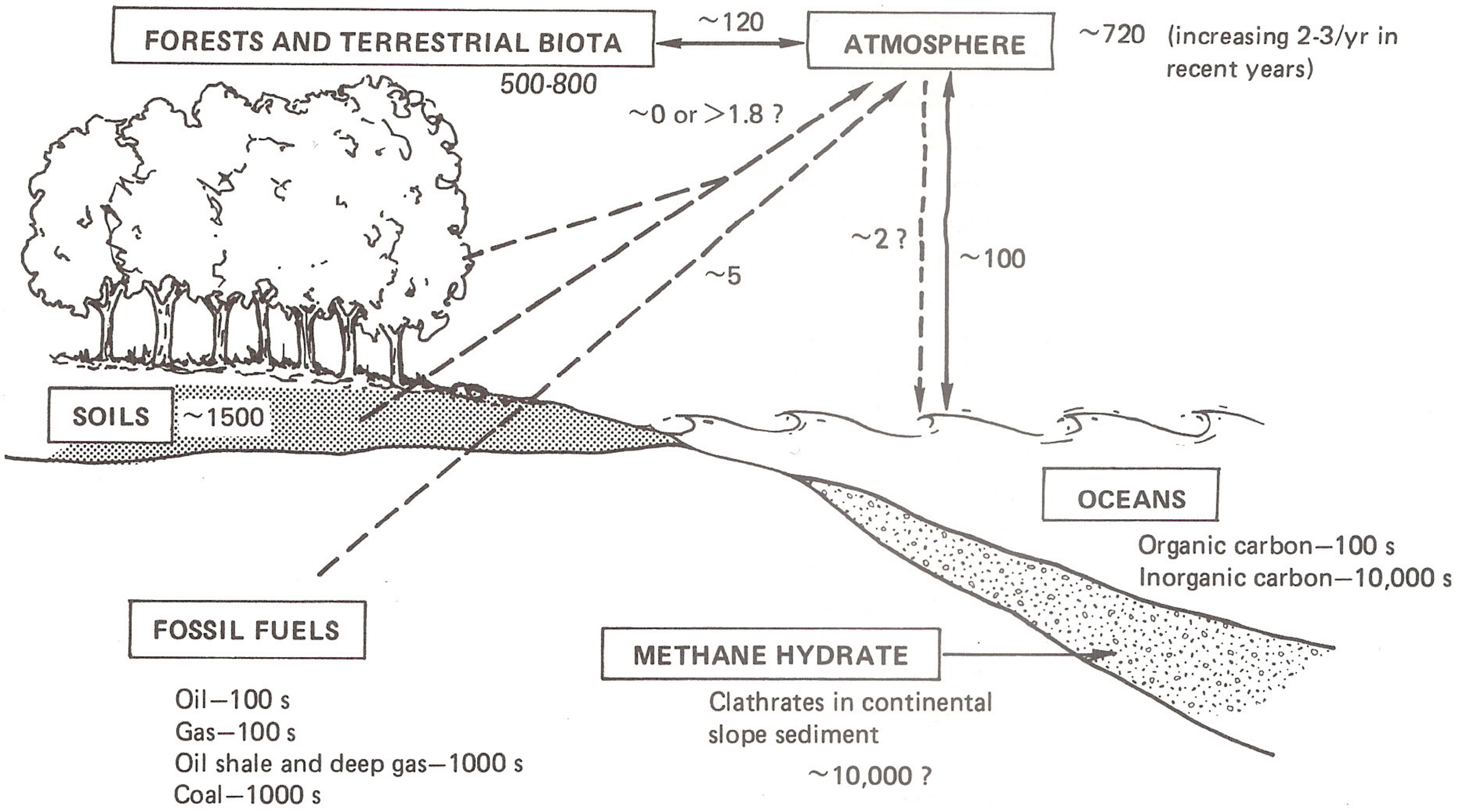


FIGURE 1.7 Some global carbon pools and annual fluxes. Estimated sizes of pools and fluxes are in gigatons of carbon. Estimates are rounded from figures given in Chapters 2 and 3 and from Clark, 1982. Pools that are only broadly measured are assessed here in order of magnitude, e.g., hundreds (100s). Dashed arrows represent additional fluxes due to human activities.

and biological, atmospheric, and oceanic processes, such as the annual cycle of the terrestrial biota and the quasi-periodic Southern Oscillation. Recently noted increases in the amplitude of the annual cycle may be related to changes in the cycling of CO_2 through photosynthesis and respiration. The year-to-year increases in atmospheric concentrations are generally becoming larger with time, roughly in step with emissions of CO_2 from fossil fuel combustion. Indeed, according to Machta (this volume, Chapter 3, Section 3.4), most of the atmospheric variations during the past 20 years are more easily accounted for when we consider a growing fossil fuel source alone than when we consider any significant additional source, such as deforestation.

Comparison of fossil fuel CO_2 releases and growth in atmospheric concentrations shows that a quantity somewhat larger than half the fossil fuel CO_2 has remained in the atmosphere. The rest must have been transferred to some other reservoir, primarily to the ocean. As described by Brewer (this volume, Chapter 3, Section 3.2), the capacity of the ocean as a sink for CO_2 is a function of its chemistry and biology, and the rate at which its capacity can be brought into play is a function of its physics. The low- and mid-latitude oceans are stably stratified, capped by a warm surface layer that is approximately in equilibrium with atmospheric CO_2. The deep waters of the world's oceans are formed in polar seas and slowly circulate through the ocean basins, with an abyssal (deep ocean) circulation time estimated at about 500 years. In the surface waters, CO_2 is fixed by photosynthetic activity and rapidly cycled by grazing organisms, with slow sedimentation of carbon into deeper layers where oxidation or deposition takes place. The absorption of CO_2 by the ocean is buffered by reactions with dissolved carbonate and bicarbonate ions. In the surface mixed layer, the "buffer factor" increases with growing CO_2 concentrations, and the capacity of the ocean to absorb CO_2 added to the atmosphere will decrease unless additional factors change. Measurements of ocean CO_2 at the surface and at depth are consistent with our understanding of the processes involved and confirm the observed atmospheric increases in concentration. Figure 1.8 shows the increase in CO_2 in the atmosphere and in surface ocean waters since 1957.

Mathematical models of ocean CO_2 uptake have been able to reproduce the records of CO_2 and related observations that we have, although complex processes of vertical transport have been modeled as simple diffusion. Radionuclides injected into the atmosphere by bomb tests have served as effective tracers of ocean circulation and essential empirical calibrators of these ocean models. However, the expression of all oceanic physics as a single unrealistic process hardly inspires confidence in the models' ability to deal with altered climatic regimes in the future. Moreover, potentially significant processes, such as changing riverine fluxes of terrestrial carbon and nutrients to the sea, may not yet have been adequately evaluated and represented. Nevertheless, at least for the short run, present-day models appear satisfactory to answer the question of how much anthropogenic CO_2 is taken up by the ocean. Brewer (this volume, Chapter 3, Section 3.2) reports several estimates that give a value at the present time of about 2 Gt of C/yr, or 40% of fossil fuel emissions.

The terrestrial biota and soils contain about three times as much carbon as the atmosphere, and their changes could influence the atmospheric burden. The most active and vulnerable portion of the biota is in forests, which probably contain between about 260 and 500 Gt of C (Olson and Watts, 1982). As discussed by Woodwell (see Figure 1.9 and Chapter 3, Section 3.3), the net flux of carbon between the atmosphere and any ecosystem depends on the balance between photosynthetic production by green plants and respiration by both plants and other organisms. Woodwell observes that on land photosynthesis is more susceptible to disturbance than respiration, so disturbance of the biota tends to release carbon into the atmosphere in the period following disturbance. Subsequently, over a period of years to decades or longer, the balance may shift through recovery due to succession and the slow migration of plants in response to a new, stable environment. Increased CO_2 enhances photosynthesis but does not necessarily lead to increased storage of carbon; on the other hand, increased temperature tends to increase respiration. Extension of growing seasons and extension or reduction of biomes with climate change can also affect the terrestrial carbon balance, particularly on longer time scales. It is thus

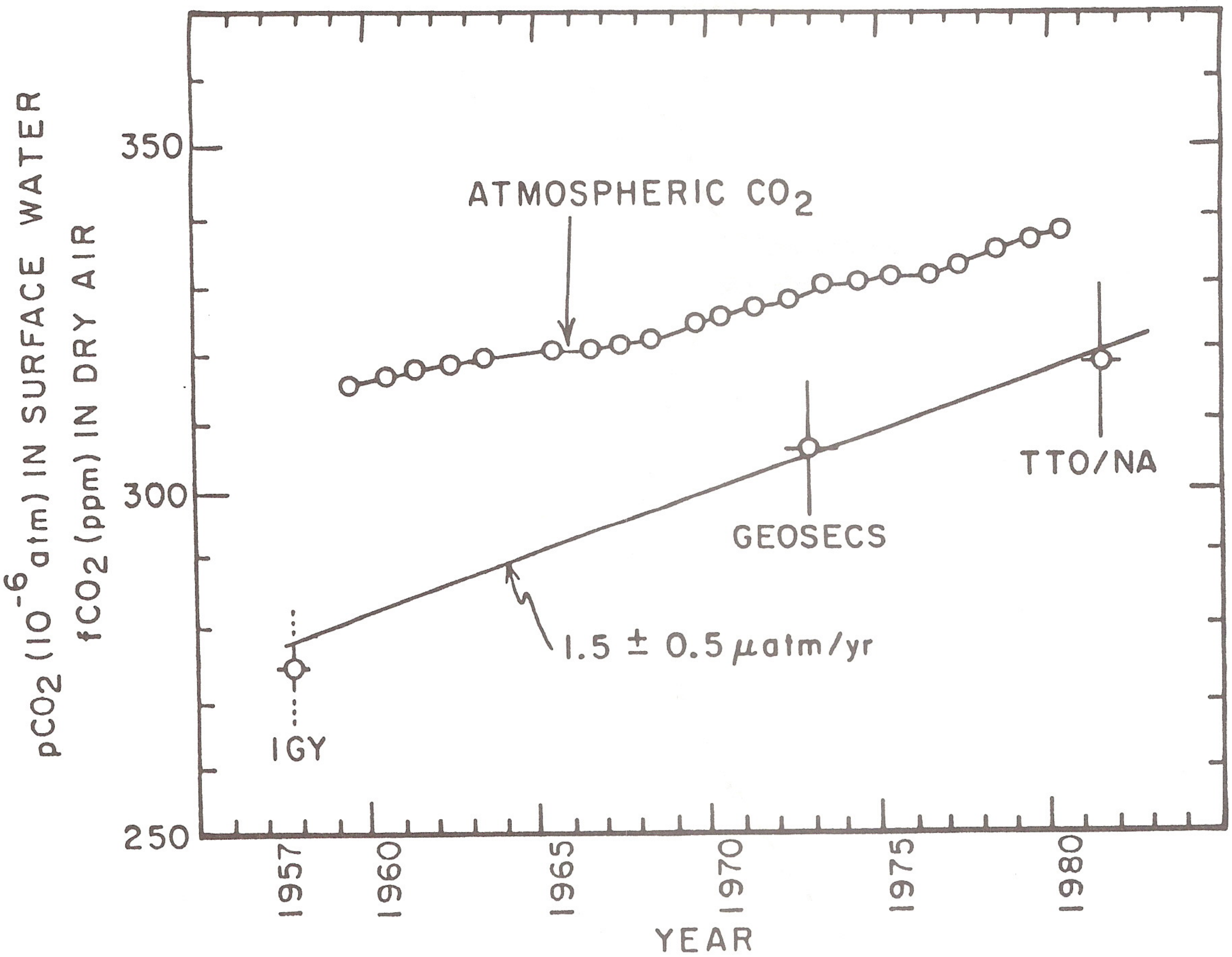


FIGURE 1.8 Mean Sargasso gyre surface water pCO_2 versus time. The atmospheric CO_2 concentration is expressed in mole fraction CO_2 in dry air at Mauna Loa, Hawaii. The IGY was the International Geophysical Year; GEOSECS is the Geochemical Ocean Sections Study; TTO/NA refers to the program of observation of transient tracers in the North Atlantic. (Source: Takahashi et al., 1983.) See Brewer, Chapter 3, Section 3.2 for further explanation.

plausible that future changes in the atmosphere could lead to a significantly increased net biotic flux of carbon to or from the atmosphere.

The possible sources of biotic CO_2 emissions--deforestation and land disturbance--are poorly documented. There are several indirect approaches to estimating what this biotic contribution may have been, largely based on correlation between growth in human population and the rate of conversion of forest for agriculture. The main direct data sources on deforestation have been the production yearbooks of the Food and Agriculture Organization (FAO) of the United Nations, published since 1949, and these may be inaccurate. All examinations of the biota conclude that there has been a marked reduction in storage of carbon over the past century or so; however, the timing and amount are the

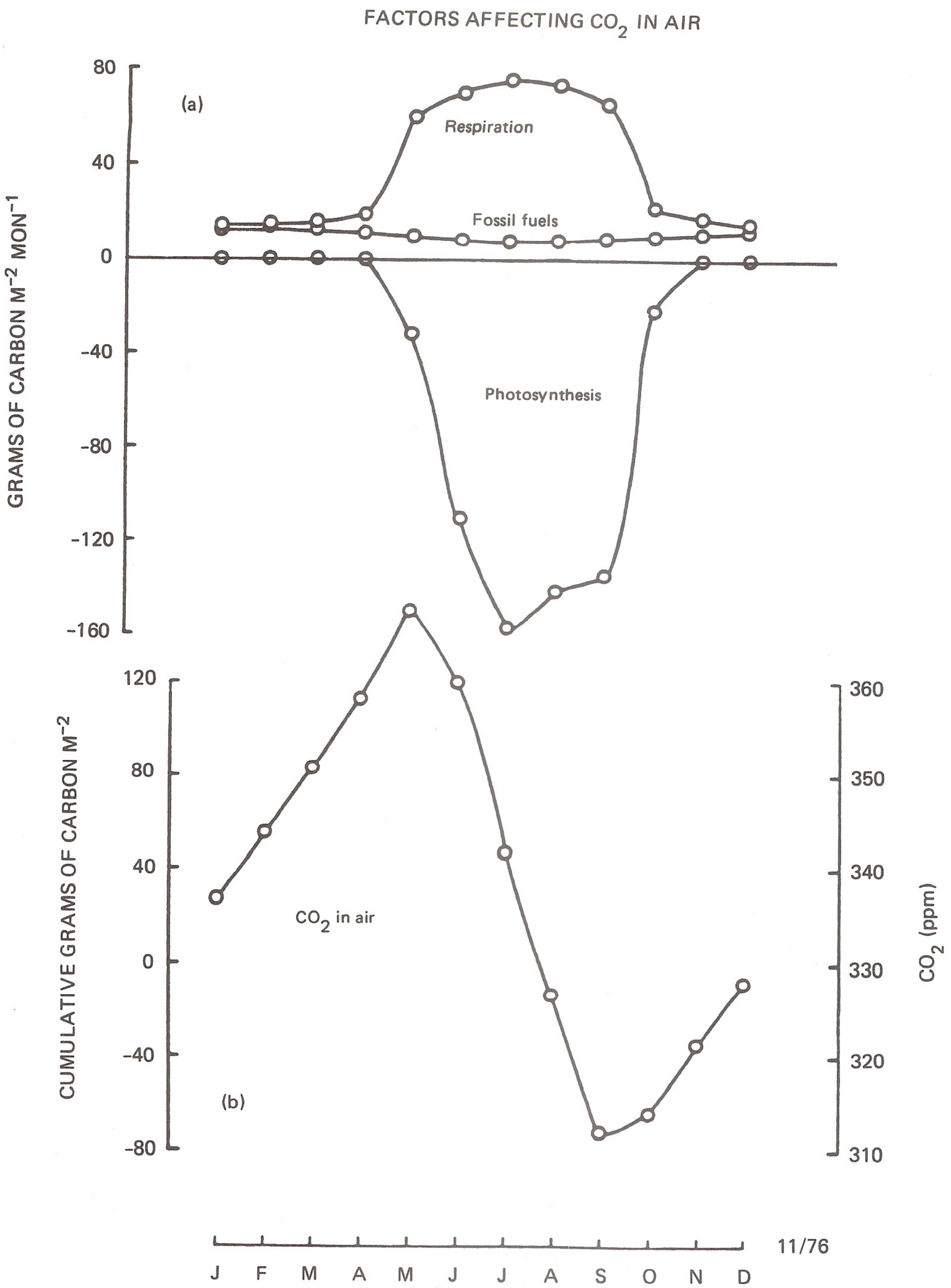


FIGURE 1.9 The upper graph shows the course of total respiration and gross photosynthesis of an oak-pine forest in central Long Island, New York. Integration of these two curves produced the prediction of the annual change in local atmospheric CO_2 shown in the lower graph. The amplitude predicted in this way was considerably greater than observed (Woodwell et al., 1973), apparently because of mixing with air from over the oceans. Fossil fuel emissions are included for comparison.

subject of substantial dispute. Based on a model of the terrestrial carbon cycle, Woodwell (this volume, Chapter 3, Section 3.3) reports a range of 1.8 to 4.7 Gt of C per year at present. Other researchers have suggested lower figures (see Table 3.3). All but the lowest values in Woodwell's range are impossible to reconcile with atmospheric observations and present-day ocean models. A net biotic carbon source of about 2 Gt/yr suggests that about 40% of all (fossil fuel plus biotic) CO_2 emissions have been remaining in the atmosphere, whereas a net biotic source near zero suggests about 60% of all anthropogenic CO_2 emissions remain airborne.

There is also disagreement about whether significant regrowth of forests in some areas and stimulation of plant growth ("fertilization") by increased atmospheric CO_2 are taking place, perhaps countering losses from deforestation. While the increasing amplitude of the seasonal cycle may be interpreted as an indication of regrowth and stimulation, there is as yet no direct evidence of regrowth and stimulation of net ecosystem storage of carbon sufficient to balance the apparent effects of deforestation. At the plant level, there are arguments for increased growth; but at the community level, especially in forests, the relevant mechanisms may be limited by other factors (see Chapter 3, Section 3.3, and Chapter 6). Growth of much biomass may be limited by availability of land, solar radiation, water, and nutrients other than carbon. Inventories of biota and other measurements (e.g., width of tree rings) are not sufficient at present to resolve the debate.

Finally, there is dispute about the level of CO_2 in the atmosphere in the last century before anthropogenic sources began to raise it. The preindustrial (circa 1850) concentration probably lay in the range 250-295 ppm, with 260-280 ppm a preferred interval (see Machta, this volume, Chapter 3, Section 3.4). Backward extrapolation of contemporary observations based solely on estimated fossil fuel CO_2 injections and a constant airborne fraction leads to an estimate of about 290 ppm at the turn of the century. Chemical and other measurements made at that time span a range about the same value. Inferences from air trapped in glacial ice and from deep-ocean measurements indicate concentrations in the vicinity of 265 ppm in the middle of the last century. The discrepancy between mid- and late-nineteenth century data, if real, might partly be accounted for by emissions from the terrestrial biosphere.

For the period since about 1950, we have records of CO_2 emissions from fossil fuels that are reliable within 10-15%. For the period before this, the record of fossil fuel emissions is less reliable.

In view of the uncertainty and conflicting evidence about the preindustrial concentration, fossil fuel emissions, the biotic contribution, and ocean uptake, one reasonable approach is to use models to project different outcomes based on different assumptions about the various reservoirs and mechanisms (see Machta, this volume, Chapter 3, Section 3.6). In the last few years, carbon cycle models, like energy models and climate models, have become more sophisticated. There are now several dynamic, process-oriented models that are making progress in representing, for example, accumulation and decay of dead vegetation; processing of carbon in soils and humus; and the biology, chemistry, and physics of the oceans. Published models have been calibrated to agree well with what is known about recent CO_2 trends, but no model has been properly validated against all trends and all data on emission rates.

The uncertainty of future projections may be examined by comparing different models or by varying parameters within a single model. Study of a group of models, each individually plausible, shows substantial agreement in projections for a fixed scenario of CO_2 input to the atmosphere. Maximum deviation of the lowest and highest concentration from the average among five models is less than 10%. Variation of parameters within plausible ranges in a single model shows at most about 30% variation from the mean (see Table 1.1). Thus, if current carbon-cycle models are accepted as valid representations of reality, reasonable variations in their parameters do not significantly affect predictions of future concentrations of CO_2; research simply to refine these parameters may not be effective in reducing uncertainties.

On the other hand, if net releases of CO_2 from the biosphere comparable to those from fossil fuels are now in progress and have been for the past several decades, the question of carbon-cycle modeling is different. If, for example, CO_2 released annually from deforestation were in the upper part of the range that Woodwell suggests, the current models would fail to reproduce the observed atmospheric CO_2 growth

TABLE 1.1 Sensitivity Study Using a Box Model of the Carbon Cycle (Keeling and Bacastow, 1977) and the Nordhaus-Yohe 50th Percentile CO_2 Emissions Estimate

Variation in Parameter	Range[a] (ppmv)	Range[b] (%)
Rate of exchange between air and sea		
2X and 0.5X standard rate of exchange	2	0.3
Rate of exchange between mixed layer of the ocean and the deep ocean		
2X and 0.5X standard rate of exchange	70	9
Both of above taken together	74	10
Biospheric uptake due enhanced atmospheric CO_2[c]		
No uptake and a β value of 0.266	229	29
Buffer factor		
Constant (10) and variable according to predicted oceanic chemistry change	61	8

[a]The Range is the higher minus the lower predicted by the changes in arithmetic number used for the parameter in the year 2100.
[b]Range divided by 784 ppmv, the predicted value for the year 2100, times 100.
[c]This is the CO_2 fertilization effect. 0.26 is the standard value for the so-called β-factor.

after 1958. The models would most likely have to be modified, since no reasonable adjustment of the parameters will allow a good fit of predictions to observations after 1958. The airborne fraction--the ratio of atmospheric increase in a year to the net (fossil and biotic) amount added to the atmosphere--would drop to about 0.3 from the value of almost 0.6 that is consistent with a net CO_2 release from the biosphere near zero. Increases of predicted concentration would be accordingly slower.

While the sophistication of carbon-cycle models has been increasing, their predictive capability may diminish markedly as we depart from current CO_2 concentrations, reservoir sizes, and climate conditions. For example, the terrestrial biotic reservoir of carbon may increase or decrease in response to climate change as a result of warming, longer growing seasons, and change in rainfall patterns, for example. No model contains a satisfactory long-term treatment of climate feedbacks to the biosphere. For a decade, most carbon-cycle models in estimating biotic response have depended on the so-called Beta (β) factor, a measure of how much plant growth increases as a result of increase in atmospheric CO_2 concentration. The use of the β factor needs to be replaced by separate analyses of effects of changes in the area of forests and potential changes in net ecosystem production caused by both increased atmospheric CO_2 and changes in climate. In sum, the current generation of carbon-cycle models appears to be satisfactory for forecasting concentrations in the next few decades, but credibility of the models fades as concentrations rise.

Keeping in mind the state of the art of projecting CO_2 emissions and their partitioning among different reservoirs, we now report the estimates of Nordhaus and Yohe (this volume, Chapter 2, Section 2.1) and Machta (this volume, Chapter 3, Section 3.6) on possible future atmospheric concentrations and factors that affect them. Perhaps the most useful graph to study is Figure 1.10, which shows the percentiles of CO_2 concentrations for the different Nordhaus-Yohe emission trajectories. To calculate concentrations, Nordhaus and Yohe use an estimate of 0.47 as the fraction of current emissions that remains airborne during the first year after emission. (This amount is consistent with a historic average annual contribution of CO_2 from the biosphere of about 1 Gt of C.) For a quarter or half century, the inertia built into the world economy and carbon cycle leaves an impression of relative certainty about outcomes. After the early part of the next century, however, the degree of uncertainty becomes extremely large. The time at which CO_2 concentrations are assumed to pass 600 ppm, the conventional "doubling" of the concentration representative of the beginning of the twentieth century, can be shown as follows:

Percentile	Doubling Time
5	After 2100
25	2100
50	2065
75	2050
95	2035

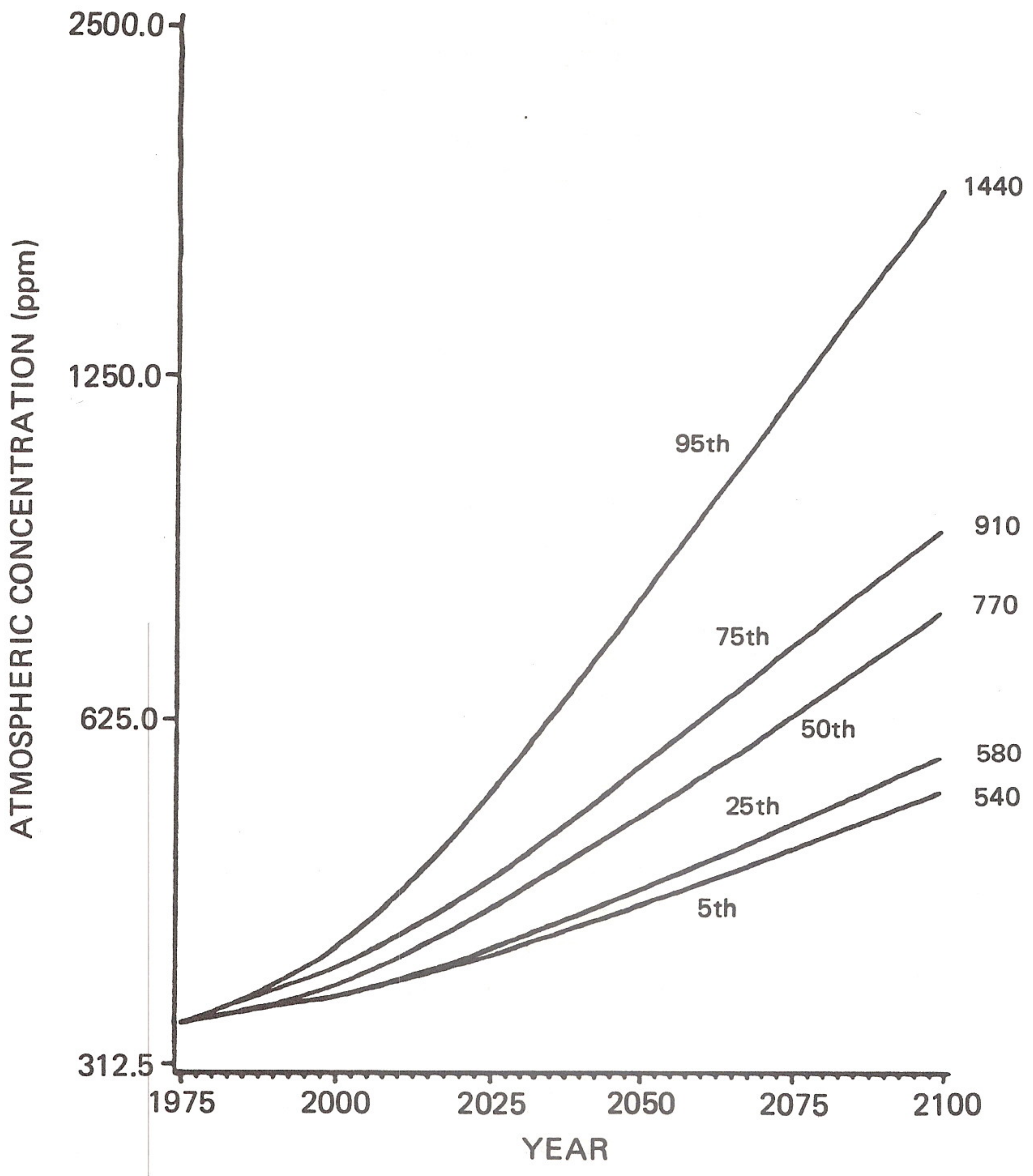


FIGURE 1.10 Atmospheric concentration of carbon dioxide in parts per million. The indicated percentile runs for concentrations; the numbers on the right-hand side indicate concentrations in the year 2100 for each run. See Nordhaus and Yohe, Chapter 2, Section 2.1, and Figure 2.18 for further detail.

On this result, Nordhaus and Yohe base a central conclusion: Given current knowledge, odds are even whether the doubling of carbon dioxide will occur in the period 2050-2100 or outside that period. It is a 1-in-4 possibility that doubling will occur before 2050 and a 1-in-20 possibility that doubling will occur before 2035. The median estimate for passing 600 ppm is 2065. For the year 2000, the most likely concentration is 370 ppm, with an upper limit of about 400 ppm.

Nordhaus and Yohe also address the question of the relative importance of different uncertainties in making concentration projections. Table 1.2 displays the contribution to overall uncertainty made by individual variables or parameters, calculated as the uncertainty induced when a parameter takes its full range of uncertainty and all other parameters are set equal to their most likely values.

TABLE 1.2 Indices of Sensitivity of Atmospheric Concentration in 2100 to Uncertainty about Key Parameters[a] (100 = Level of Effect of Most Important Parameter[b])

	Marginal Variance from Most Likely Outcome
Ease of substitution between fossil and nonfossil fuels	100
General productivity growth	79
Trends in real costs of producing energy	73
Ease of substitution between energy and labor	70
Airborne fraction for CO_2 emission	62
Extraction costs for fossil fuels	56
Population growth	36
Fuel mix among fossil fuels	24
Trends in relative costs of fossil and nonfossil fuels	21
Total resources of fossil fuels	5

[a]For full explanation of parameters see Chapter 2, Section 2.1.2.
[b]Value of sensitivity is scaled at 100 for the parameter that has the highest marginal variance.

The ranking of the importance of uncertainties shown in Table 1.2 contains several surprises. The most important parameters are those relating to future production trends, and the ease with which it is possible to substitute nonfossil sources of energy (e.g., uranium) for fossil sources (e.g., coal) is at the top of the list; several of these parameters have rarely been noted as factors affecting future CO_2 trends. Another surprise concerns two parameters that have been extensively discussed in the CO_2 literature: the extent of world resources of fossil fuels and the carbon cycle (based on a range for the airborne fraction of between 0.38-0.59).* The Nordhaus-Yohe estimates indicate that in projecting future CO_2 concentrations uncertainty about resource inventories is trivial. Uncertainty about the airborne fraction is of intermediate significance.

*The airborne fraction for the last 25 years may have been less than 0.38 if the higher figures reported by Woodwell in Chapter 3, Section 3.3, are accepted, and it could be greater than 0.59 in the future if the figures Woodwell reports are significant overestimates and the buffering capacity of the ocean declines; however, this range is a treatment of uncertainty roughly comparable with that used in Nordhaus-Yohe for the other parameters, which could also have values outside the range employed (see Chapter 2, Section 2.1).

Machta (this volume, Chapter 3, Section 3.6) employs a carbon-cycle model to consider CO_2 from deforestation as a possible real and important source of atmospheric CO_2. If some reasonable amounts of future CO_2 from deforestation are added to CO_2 from future fossil fuel combustion, the error that would be introduced by the omission of the future deforestation CO_2 would be small in the year 2100 assuming, say, a 2% per year growth rate in fossil fuel CO_2 after 1980. To give an extreme example, oxidizing 300 Gt of C, or about half the terrestrial biota, would result in an increase of perhaps 75 ppmv in a predicted value of about 1,000 ppmv in the year 2100 or about 12% of the total increase. If the rate of emissions from fossil fuels is slower, then biotic emissions could account for a somewhat more significant share of overall increase.

Nordhaus and Yohe have also made extremely tentative estimates of the effect of energy-sector policies designed to reduce the burning of fossil fuels, in particular the imposition of fossil fuel taxes, set for illustrative purposes at $10 per ton of coal equivalent. The taxes lower emissions noticeably during the period in which they are in place, but their effect on concentrations at the end of the twenty-first century is small. These examples suggest that use of carbon dioxide taxes (or their regulatory equivalents) will have to be very forceful to have a marked effect on carbon dioxide concentrations.

A review of several studies (Chapter 2, Section 2.4), all quite tentative, shows that if fossil fuel growth rates are 1 or 2%/yr and concentrations of 400-450 ppm are judged acceptable, there is little urgency for reductions in CO_2 emissions below an uncontrolled path before A.D. 1990. The review suggests that if a limit in the vicinity of 450-500 ppm is desirable steps to reduce emissions below an uncontrolled path would need to be initiated around A.D. 2000.

Along with considering the climatic implications of increased CO_2, it is important also to take into account other possible man-made changes in atmospheric composition (see Machta, this volume, Chapter 4, Section 4.3). Reliable measurements have now shown that background concentrations of several radiatively active gases besides CO_2 have increased worldwide in the 1970s. These include the chlorofluorocarbons CF_2Cl_2 and $CFCl_3$, N_2O (nitrous oxide), CH_4 (methane), and ozone (in the troposphere). Since these gases also absorb and emit thermal radiation, their effects on climate may add to those of CO_2.

Chlorofluorocarbons. This class of gases originates from industrial activities and has been emitted to the atmosphere during the past 50 years. These gases are increasing in the atmosphere approximately as expected from their growth in emissions. CFC-11, CFC-12, and CFC-22, the three most abundant ones, all have long residence times in the air (tens of years) so that they can accumulate. Both the sources and sinks of the chlorofluorocarbons are believed to be known. The emissions from industrial production and products (such as aerosol propellants) represent the only source of any consequence. Photochemical destruction, mainly in the stratosphere, and very slow uptake by the oceans are the only known significant sinks. Theoretically, chlorofluorocarbons are implicated as potential destroyers of stratospheric ozone, the destruction of which in turn could result in damage to human health and the environment from increased ultraviolet radiation. Since emissions of these gases may be increasingly restricted, an extrapolation of current or past growth rates of chlorofluorocarbons to predict future atmospheric concentrations may be misleading at this time.

Nitrous oxide. It is likely that most nitrous oxide in the air has come from denitrification in the natural or cultivated biosphere. One would therefore expect to find the largest part of atmospheric nitrous oxide to be derived from nature, unrelated to human activity. Recent, careful measurements have suggested a small growth rate of the concentration of nitrous oxide in ground-level air at remote locations. The source of the small increase is unknown, but prime candidates are the continued expanded use of nitrogen fertilizers around the world to improve agricultural productivity and high temperature combustion in which atmospheric nitrogen is oxidized. If such fertilizers are the source, the current slow increase is likely to continue into the foreseeable future because the demand for food will grow with population size.

Methane. The most abundant hydrocarbon, methane, often called natural gas, is increasing in the atmosphere. It is thought to be a natural constituent of the air arising as it does from many biological processes and from seepage out of the Earth. Measurements in the 1950s and 1960s were imprecise, and there were spatial differences so that the observed temporal variability was not viewed as an upward trend. However, in the late 1970s several investigators using gas chromatography have unequivocally demonstrated an upward trend.

Increase in the number of ruminant farm animals and expansion of rice production might well explain, at least qualitatively, the atmospheric methane growth. Other biological activities, such as termite destruction of wood, and possible leakage from man's mining and use of fossil methane might also contribute to methane in the air, but their contribution to its increase is less clear. The higher concentrations far north of the equatorial region suggest that the termite source may be minor. The relatively rapid recent increase with time, about as fast as for CO_2, combined with the uncertainty as to its origin, are both intriguing features of the methane growth in air.

There is no reason to expect the upward trend in atmospheric methane concentration to stop soon since the most likely sources of methane are related to population size. In the long run, those sources that are dependent on the size of a biospheric feature (e.g., cows or rice paddies) will ultimately be limited by space. Thus, the growth in atmospheric concentration from these sources might continue for many decades but perhaps not for many centuries.

Methane also forms another link in the question of future atmospheric composition. As discussed by Revelle (this volume, Chapter 3, Section 3.5), large amounts of methane are believed to be stored in methane hydrates in continental slope sediments. Methane hydrate is a type of clathrate in which methane and smaller amounts of ethane and other higher hydrocarbons are trapped within a cage of water molecules in the form of ice. Methane hydrates are stable at low temperatures and relatively high pressures. With a rise in ocean-bottom temperatures, the uppermost layers of ocean sediments would also become warmer; and methane hydrates would become unstable in the upper limit of their depth range, that is, about 300 m in the Arctic and about 600 m at low latitudes. The quantity of clathrates that will be released from sediments under the seafloor as a result of ocean warming depends on the distribution of clathrates with depth and on their abundance in the sediments. Estimates of total amount by different authors differ by a factor of 500, from 10^3 to 5×10^5 Gt of C. Revelle, assuming a warming induced by CO_2 and other trace gases released by human activities and a stock of about 10^4 Gt of C, estimates that the resulting increase in atmospheric methane toward the latter part of the twenty-first century could be two thirds to four thirds of the current amount; the uncertainties in the series of methane calculations are so great that the result cannot be thought of as a projection for the future, but it is equally obvious that we must be attentive to the possibility of new, important feedbacks affecting the chemical composition of the atmosphere.

Tropospheric ozone. Tropospheric ozone was originally believed to be primarily a consequence of transport from stratospheric ozone by air motions. It can also be created within the troposphere by man and nature. Locally, as in the Los Angeles Basin, large amounts of ozone are derived from reactions among oxides of nitrogen, hydrocarbons, and sunlight. Few scientists believe that these local sources of pollution can increase the upper-tropospheric concentrations of ozone, because ozone is so reactive that its lifetime in the lower atmosphere is no more than a few days. Nevertheless, an analysis of a limited number of measurements suggests an upward trend. It has been suggested that increase of mid- and upper-troposphere ozone concentration in the northern hemisphere may result from photochemical reactions of the oxides of nitrogen and hydrocarbons emitted by high-flying jet aircraft. Since the lifetime of an ozone molecule in the upper troposphere is also relatively short, little accumulation takes place. An increase in concentration must therefore reflect a continual increase in aircraft emissions, if they are the source.

Some other gases. Several other gases being measured show upward trends and may have absorption lines in the infrared window of the electromagnetic spectrum, making them potential greenhouse gases, for example, carbon tetrachloride ($CC1_4$) and methyl chloroform (CH_3CCl_3). Very likely both of these gases have both natural and man-made sources. On the other hand, measurements at the Mauna Loa Observatory exhibit no or insignificant increases in carbon monoxide (CO). It is likely that the list of atmospheric gases studied for their trends and potential greenhouse effects will grow in years to come: the study of greenhouse gases other than CO_2 is still in its infancy.

The atmospheric concentrations of these trace gases are not all independent of one another. Complicated chemical reactions among them, as well as with other gases not particularly radiatively active, can affect their concentrations. In addition to chemical reactions among today's atmospheric components, there are likely to be new climate-chemistry interactions in the future. As the atmospheric composition changes, the expected higher atmospheric water-vapor content will further affect the atmospheric chemistry.

Unlike CO_2, which generally does not undergo chemical changes in the air, these trace gases frequently do. Not only can the mean concentration be affected by other chemicals and sunlight, but distribution particularly in the vertical can be influenced (ozone is a prime example). To estimate future concentrations will require more than estimates of natural and man-made emission rates, fundamental though those rates will be.

1.2.3 Changing Climate with Changing CO_2

With projections given of rising atmospheric concentration of CO_2 and other greenhouse gases, the next question to be addressed is that of possible effects on climate. The main tools for evaluating the possible role of greenhouse gases are numerical models of the climate system. Simplified models permit economically feasible analyses over a wide range of conditions, but they are limited in the information they can provide, for example, on regional climate change. More detailed inferences may be obtained primarily from three-dimensional general circulation models (GCMs), which represent the global atmospheric circulation, as well as the oceans, the land, and ice (Figure 1.11). Comparisons of simulated time means of a number of climatic variables with observations show that modern climate models provide a reasonably satisfactory simulation of the present large-scale global climate and its average seasonal changes. However, the capabilities of even the most advanced current models remain severely limited; for example, the three-dimensional GCMs are generally deficient in the treatment of ocean heat transport and dynamics and feedback between the ocean and the atmosphere.

The adequacy and results of climate model studies in the CO_2 context were examined in 1979 by an NRC panel chaired by the late Jule Charney, and again in connection with the present study by a panel led by Joseph Smagorinsky. Comprehensive reviews of modeling methods and results have been carried out by Schneider and Dickinson (1974) and international groups (Gates, 1979). The Smagorinsky panel also evaluated empirical approaches to assessing climate sensitivity. The earlier NRC panel reports form one basis of our assessment of the climatic implications of increasing CO_2. A second basis is the search for a "CO_2 signal" in the recent climatic record; this detection approach is discussed below in Section 1.2.4 and by Weller et al. in Chapter 5.

The Carbon Dioxide Assessment Committee did not extend the systematic treatment of uncertainty adopted in several sections of this report to its analysis of climate modeling results. However, Smagorinsky (this volume, Chapter 4, Section 4.2) notes that such approaches are now being initiated by climate researchers.

The primary effect of an increase of CO_2 is to cause more absorption and re-radiation of thermal radiation from and to the Earth's surface and thus to increase the air temperature in the lower troposphere. A strong positive feedback mechanism is the likely accompanying increase of moisture, which is an even more powerful

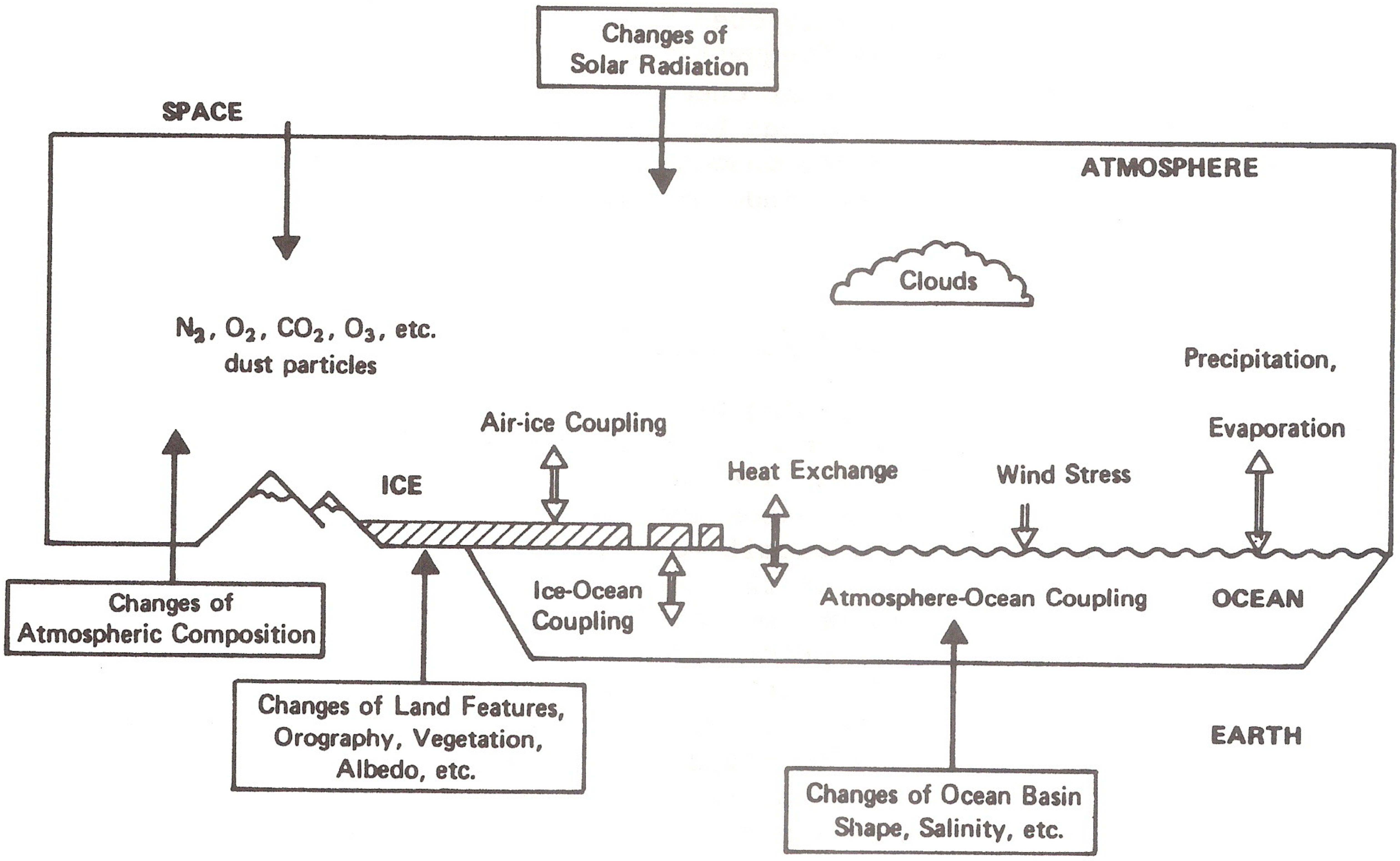


FIGURE 1.11 Schematic illustration of the components of the coupled atmosphere-ocean-ice-earth climatic system. The solid arrows are examples of external processes, and the open arrows are examples of internal processes in climatic change. Source: U.S. Committee for the Global Atmospheric Research Program (1975).

absorber of terrestrial radiation. None of the known potential negative feedback mechanisms, such as increase in the areal extent of low or middle cloud amount, can be expected to vitiate the principal conclusion that there will be appreciable warming, since they do not appear in most current models to be as strong as the positive moisture feedback. There is, however, always the possibility of some overlooked or underestimated factor.

When it is assumed that the CO_2 content of the atmosphere is doubled and statistical thermal equilibrium is achieved, all models predict a global surface warming. None of the calculations with more physically comprehensive models predicts negligible warming. Calculations with the three-dimensional, time-dependent models of the global atmospheric circulation indicate global warming due to a doubling of CO_2 from 300 ppm to 600 ppm to be in the range between about 1.5 and 4.5°C, as suggested in 1979 by the Charney panel. Simpler models that appear to contain the main physical factors give similar results.

Dissenting inferences suggesting negligible CO_2-induced climate change have been drawn in recent years, but careful review shows these studies to be based on incomplete and misleading analysis (National

Research Council, 1982; Luther and MacCracken, 1983). Investigations with a variety of climate models continue to show a broad range of estimates of appreciable warming.

A major uncertainty has to do with the transfer of increased heat into the oceans, which serve as a thermal regulator for the planet. The heat capacity of the oceans is potentially great enough to slow down the response of climate to increasing CO_2 by several decades and to cause important regional differences in response. The influences of clouds, aerosols, and land-surface processes on sensitivity of climate to increased CO_2 also remain poorly understood. Table 1.3 indicates the possible contribution of various processes to the sensitivity of simple climate models. For example, including the feedback provided by reduction in the extent of snow and ice (Model 5) increases the equilibrium surface temperature rise for doubled CO_2 in the model by a factor of 1.3-1.4.

TABLE 1.3 Equilibrium Surface Temperature Increase Due to Doubled CO_2 (300 ppm → 600 ppm) in One-Dimensional Radiative-Convective Models[a,b,c]

Model	Description[d]	ΔT_s (°C)	f	F (W m^{-2})
1	FAH, 6.5LR, FCA	1.2	1	4.0
2	FRH, 6.5LF, FCA	1.9	1.6	3.9
3	Same as 2, except MALR replaces 6.5LR	1.4	0.7	4.0
4	Same as 2, except FCT replaces FCA	2.8	1.4	3.9
5	Same as 2, except SAF included[e]	2.5-2.8	1.3-1.4	
6	Same as 2, except VAF included[f]	3.5	1.8	

[a]Source: National Research Council (1982).
[b]Data from Hansen et al. (1981).
[c]Model 1 has no feedbacks affecting the atmosphere's radiative properties. The feedback factor f specifies the impact of each added process on model sensitivity to doubled CO_2. F is the equilibrium thermal flux into the planetary surface if the ocean temperature is held fixed (infinite heat capacity) when CO_2 is doubled; this is the flux after the atmosphere has adjusted to the radiative perturbation within the model constraints indicated but before the surface temperature has increased.
[d]FRH, fixed relative humidity; FAH, fixed absolute humidity; 6.5LR, 6.5°C km^{-1} limiting lapse rate; MALR, moist adiabatic limiting lapse rate; FCA, fixed cloud altitude; FCT, fixed cloud temperature; SAF, snow-ice albedo feedback; VAF, vegetation albedo feedback.
[e]Based on Wang and Stone (1980).
[f]Based on Cess (1978).

Warming of the lower troposphere will be accompanied by regional shifts in the geographical distribution of the various climatic elements, such as temperature, rainfall, evaporation, and soil moisture. Indeed, variations with latitude, longitude, and season are likely in many cases to be more striking than globally averaged changes. Unfortunately, we cannot at present predict the magnitude and locations of regional climate changes with much precision or confidence. Although current models are not sufficiently realistic to provide reliable predictions in the detail desired, they do suggest scales and ranges of temporal and spatial variations. Along with global warming, the main conclusions of the model studies, discussed in greater detail in the report of the Smagorinsky panel (National Research Council, 1982) and in Chapter 4 of this report, may be summarized as follows:

- A cooling of the stratosphere with relatively small latitudinal variation is expected.
- Global-mean rates of both evaporation and precipitation are projected to increase.

With less confidence it is concluded that:

- Increases in surface air temperature would vary significantly with latitude and over the seasons:
  - (a) Warming at equilibrium would be 2-3 times as great over the polar regions as over the tropics; warming would probably be significantly greater over the Arctic than over the Antarctic.
  - (b) Temperature increases would have large seasonal variations over the Arctic, with minimum warming in summer and maximum warming in winter. In lower latitudes (equatorward of 45° latitude) the warming has smaller seasonal variation.
- Some qualitative inferences on hydrological changes averaged around latitude circles may be drawn from model simulations of large, fixed CO_2 increase in equilibrium:
  - (a) Annual-mean runoff increases over polar and surrounding regions.
  - (b) Snowmelt arrives earlier and snowfall begins later.
  - (c) Summer soil moisture decreases in large regions in middle and high latitudes of the northern hemisphere.
  - (d) The coverage and thickness of sea ice over the Arctic and circum-Antarctic oceans decrease.

As CO_2 slowly increases, land and ocean will both warm but at different rates. Eventually, with a steady CO_2 concentration, a new equilibrium would be reached with a climate different from today's. However, we should not expect that the detailed distribution and timing of changes during the intervening years can be obtained solely by interpolation. The differences between rapidly heated land and slowly warming water, coupled with the irregular distribution of continents and oceans and continually changing CO_2 concentrations, may bring varying "transient" patterns of climate change.

While the climatic effects of CO_2 have been explored with a wide variety of climate models, most of the estimates of the climate effects of other greenhouse gases have been based on simple one-dimensional radiative-convective models. Typically the calculation involves doubling a reference concentration of the gas (for the chlorofluorocarbons, increases from 0 to 1 or 2 ppb are used) while other constituents are held constant. Table 1.4 gives some estimates of the change in surface temperature due to either a doubling of their concentration or an increase from 0 to 1 ppb for the halocarbons. The table was adapted from Table 2a in the report of the World Meteorological Organization (1983). There are other published values, but they generally do not disagree by more than about ±30% with the figures given here.

The models used to obtain these results generally gave a sensitivity to doubled CO_2 between 2 and 3°C. None of the changes of individual gases by itself approaches CO_2, but it is clear that the summation of all of these potential changes could be of the same magnitude as CO_2. It is worth noting that because the concentration of each of these gases is small enough for their radiative effect to be treated as optically thin, the temperature effect is linearly proportional to

TABLE 1.4 Some Estimates of Surface Temperature Change Due to Changes in Atmospheric Constituents Other Than CO_2

Constituent	Mixing Ratio Change (ppb) From	To	Surface Temperature Change (°C)	Source[a]
Nitrous oxide (N_2O)	300	600	0.3-0.4	1,3
Methane (CH_4)	1500	3000	0.3	3,4
CFC-11 ($CFCl_3$)	0	1	0.15	1,5
CFC-12 (CF_2Cl_2)	0	1	0.13	1,5
CFC-22 (CF_2HCl)	0	1	0.04	7
Carbon tetrachloride (CCl_4)	0	1	0.14	1,5
Carbon tetrafluoride (CF_4)	0	1	0.07	2
Methyl chloride (CH_3Cl_3)	0	1	0.013	1,5
Methylene chloride (CH_2Cl_2)	0	1	0.05	1,5
Chloroform ($CHCl_3$)	0	1	0.1	1,5
Methyl chloroform (CH_3CCl_3)	0	1	0.02	7
Ethylene (C_2H_4)	0.2	0.4	0.01	1
Sulfur dioxide (SO_2)	2	4	0.02	1
Ammonia (NH_3)	6	12	0.09	1
Tropospheric ozone (O_3)	F(Lat,ht)	2 F(Lat,ht)	0.9	4,6
Stratospheric water vapor (H_2O)	3000	6000	0.6	1

[a]Sources: 1, Wang et al. (1976); 2, Wang et al. (1980); 3, Donner and Ramanathan (1980); 4, Hameed et al. (1980); 5, Ramanathan (1975); 6, Fishman et al. (1979); 7, Hummel and Reck (1981).

their concentration, whereas the CO_2 effect depends logarithmically on the concentration.

The implication of the prospective increases in trace gases is that climatic changes of the character expected for elevated CO_2 concentrations may be encountered sooner than if CO_2 were the only cause of change, or, alternatively, that estimates solely of a CO_2 effect may be conservative.

At present little or nothing can be estimated about changes in extreme conditions that might accompany changes in mean climatic conditions and more generally about the weather of future climate. We do not know, for example, whether the climate will show more or less year-to-year variability under generally warmer planetary conditions. Variability of climate is one of its most important features. Food production, human settlements, and numerous aspects of the environment are strongly influenced by occasional extreme episodes. An area of particular interest is that of severe storms. The frequency, severity, and track of hurricanes and other severe storms are likely to be affected by CO_2-induced climatic changes, such as warming of ocean waters. Neither our current knowledge of storm genesis nor the current capabilities of climate models are great enough to allow convincing linkages at this time.

Besides numerical modeling approaches, past climates and recent climate fluctuations have been studied empirically to discern possible regional patterns of climatic variation associated with elevated CO_2 levels or warmer mean temperatures. These studies can be useful in exploring the sensitivity of climate to various factors, in evaluating how well climate models perform, and in exploring the kinds of regional patterns of change that are possible. However, the search for a historical analogue to CO_2-induced climatic change is hampered by inadequacies in data and by the absence of close parallels of cause and effect. Maps of a warmer earth derived from analogue approaches should not be viewed as predictions of regional effects of CO_2-induced changes.

1.2.4 Detection of CO_2-Induced Changes

Given the historic increase in atmospheric CO_2 and the results of climate models concerning the effects of increasing CO_2, it is appropriate to ask whether climatic records tend to confirm model estimates. Weller et al. examine this question at length in Chapter 5 of this report. Observational verification of model-based predictions is also important in calibrating climate models so that we can attach more confidence to their predictions of future changes.

The most clearly defined change expected from increasing atmospheric CO_2 is a large-scale warming of the Earth's surface and lower atmosphere. Thus, a number of investigators have examined trends in globally or hemispherically averaged surface temperature for evidence of CO_2-induced changes. Although differing in detail because of varying data sources and analysis methods, the records of large-scale average temperatures reconstructed by a number of investigators are in general agreement for the period of instrumental records, i.e., about the last 100 years. Northern hemisphere temperatures, mostly measured over land in the 20-70° latitude zone, increased from the late nineteenth century to the 1940s, decreased until the mid-1970s, and have apparently increased again in recent years (Figure 1.12). If one selects the 1970s to compare with the 1880s, one finds that the mean temperature of the recent decade was about 0.5°C warmer; other selective examinations of the time series of northern hemisphere temperatures could show different results. To the extent that one can judge from scanty data, southern hemisphere temperatures have increased more steadily than in the north by about the same total amount. In view of the relatively large and inadequately explained fluctuations over the last century, we do not believe that the overall pattern of variations in hemispheric-mean or global-mean temperature or associated changes in other climatic variables either confirms or contradicts model projections of temperature changes attributable to increasing atmospheric CO_2 concentration.

Factors other than CO_2--such as atmospheric turbidity, solar radiation, and albedo--also influence climate. Attempts have been made to account for such influences on the temperature record and thereby make the sought-for CO_2 signal stand out more clearly. Unfortunately, only indirect sources of historical data are available. For example, stratospheric turbidity has been inferred primarily from volcanic activity, and solar radiance from phenomena such as sunspots. The quantitative reliability of these inferences is unknown.

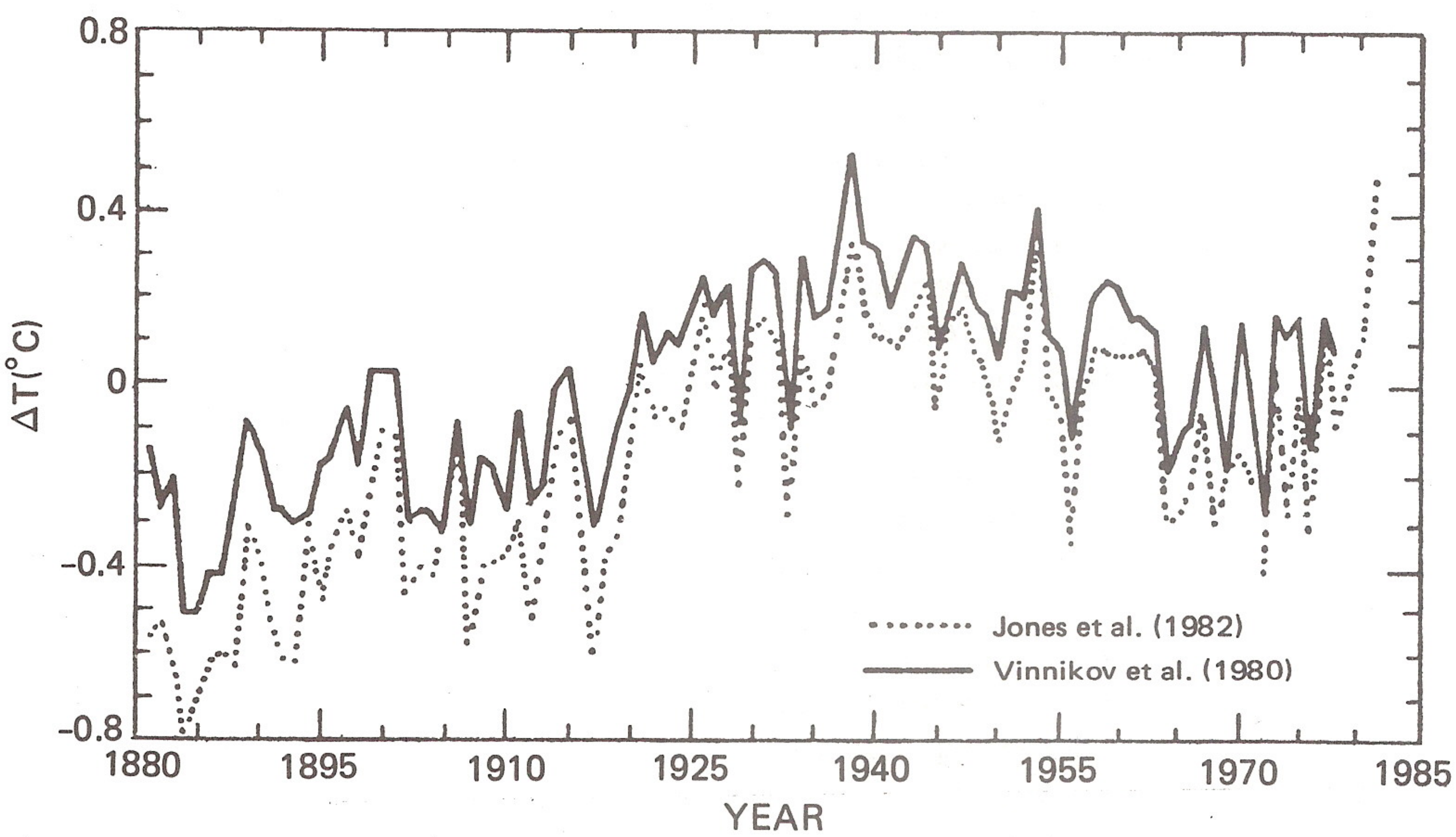


FIGURE 1.12 Comparison of the reconstructions of annual surface air temperature anomalies for the northern hemisphere from Jones and Wigley (1980) and Vinnikov et al. (1980). Figure from Clark (1982), but data for 1981 added to Jones and Wigley (Jones, 1981). See Weller et al., Chapter 5, for further discussion.

Despite these difficulties, a number of investigators, employing various combinations of data and methodology, have related the global or hemispheric mean temperature record to indices of turbidity and solar radiance and to estimates of the effect of increasing CO_2. Although good agreement between modeled and observed variations has been obtained in some of these studies, it is clear that considerable uncertainties remain. When attempts are made to account for climatic influences of such other factors as volcanic and solar variations, an apparent temperature trend consistent with the trend in CO_2 concentrations and simulations with climate models becomes more evident. However, uncertainties preclude acceptance of such analyses as more than suggestive. The studies done to date have been most helpful in raising questions, suggesting relationships, and identifying gaps in data and observations.

In essence, the problem of detection is to determine the existence and magnitude of a hypothesized CO_2 effect against the background of quasi-random climatic variability, which may be in part due to internal processes in the atmosphere and ocean and in part explainable in terms of fluctuations in other external factors. A reasonable approach is to assume that the record of some climatic parameter, e.g., temperature, is the sum of a hypothesized "natural" value, a perturbation due to CO_2, and a random component. The "natural" value may be taken as a constant long-run preindustrial mean or perhaps that mean corrected for the factors discussed above. The random component will have statistical characteristics different from simple "white noise" and will be difficult to model. It is clear that the magnitude of the derived CO_2 signal will depend markedly on the hypothesis chosen for the unperturbed underlying climatic trend and the change in CO_2 assumed between the poorly known preindustrial value and the accurately measured current concentrations. The success achieved by several workers in explaining the temperature record in diverse ways demonstrates that a number of hypotheses can fit the poorly defined historical data and estimated preindustrial concentrations.

The available data on trends in globally or hemispherically averaged temperatures over the last century, together with estimates of CO_2 changes over the period, do not preclude the possibility that slow climatic changes due to increasing atmospheric CO_2 projections might already be under way. If the climate has warmed about 0.5°C and the preindustrial CO_2 concentration was near 300 ppm, the sensitivity of climate to CO_2 (expressed as projected increase of equilibrium global temperature for a doubling of CO_2 concentration) might be as large as suggested by the upper half of the range indicated earlier, i.e., up to perhaps 4.5°C; if the preindustrial CO_2 concentration was well below 300 ppm and if other forcing factors did not intervene, however, the sensitivity must be below 3°C if we are to avoid inconsistency with the available record (see Figure 1.13).

If, as expected, the CO_2 signal gradually increases in the future, then the likelihood of perceiving it with an appropriate degree of statistical significance will increase. Given the inertia created by the ocean thermal capacity and the level of natural fluctuations, achieving statistical confirmation of the CO_2-induced contribution to

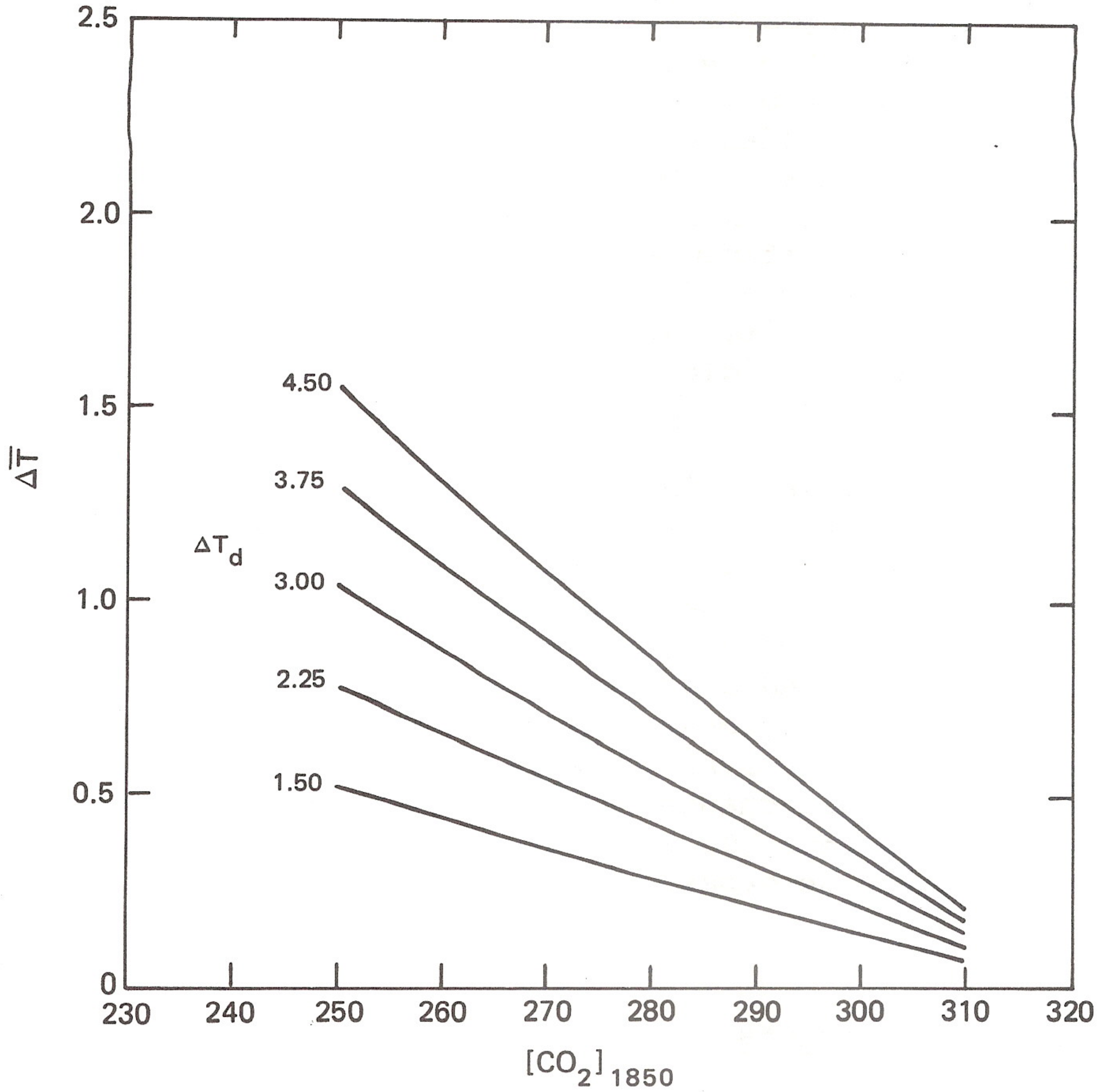


FIGURE 1.13 Relationship between CO_2 change, temperature change, and climate sensitivity assuming no other factors intervene. The abscissa represents a range of values for the preindustrial (1850) concentration of CO_2. The ordinate represents the increase ($\Delta\bar{T}$) in global mean equilibrium surface temperature between 1850 and the period 1961-1980. The response is calculated for a range of values of ΔT_d, the change of global mean equilibrium temperature for a doubling of CO_2 concentration (assumed independent of initial CO_2 concentration), and assumes that the temperature range is logarithmically related to the change in CO_2 concentration (Augustsson and Ramanathan, 1977). An ocean response time (mean thermal lag) of 15 years is used. The concentration of CO_2 was assumed in each case to increase linearly from the indicated value in 1850 to 310 ppm in 1950, and then linearly from 1950 to 340 ppm in 1980. Note that if the temperature increase from 1850 to the interval 1961-1980 is taken to be 0.5°C, then for consistency, ΔT_d may be as large as 4.5°C only if nineteenth century CO_2 concentrations were about 300 ppm, whereas ΔT_d may be as small as about 1.5°C if nineteenth century CO_2 concentrations were as low as 250 ppm. For ocean response times shorter than 15 years, the isolines slide upward and move in the opposite direction for longer ocean lag time. Varying the time of the start of the increase in CO_2 concentrations from 1850 to 1920 has little effect. See Weller et al., Chapter 5, for further discussion.

global temperature changes so as to narrow substantially the range of acceptable model estimates may require an extended period. Improvements in climatic monitoring and modeling and in our historic data bases for changes in CO_2, solar radiance, atmospheric turbidity, and other factors may, however, make it possible to account for climatic effects with less uncertainty and thus to detect a CO_2 signal at an earlier time and with greater confidence. A complicating factor of increasing importance will be the role of rising concentrations of greenhouse gases other than CO_2. While the role of these gases in altering climate may have been negligible up to the present, their significance is likely to grow, and their effects may be indistinguishable from the effects of CO_2.

For purposes of analysis, in the next three sections we accept the estimates from models for CO_2 emissions, concentrations, and climate change and examine their implications for agriculture, water resources, and sea level and polar regions. For examination of agriculture, Waggoner looks ahead about 20 years and adopts maximum assumptions of change: about 400 ppm and a 1°C warming. For examination of water resources, Revelle and Waggoner assume a 2°C warming in midlatitudes; such a change could occur a few decades into the next century. For examination of sea-level change, a global average warming of about 3-4°C over about the next 100 years is assumed from a combination of CO_2 and other greenhouse gases. Our perspective is predominantly American.

1.2.5 Agricultural Impacts

Virtually all the food for the people of the United States and the feed for our animals grow on a third of a billion acres (1.35×10^{12} m^2) of cropland and vast rangelands and pastures, exposed to the annual lottery of the weather and climate. Rather than seek to examine all aspects of agriculture that might be affected by CO_2-induced climatic changes, we concentrate on a critical, susceptible, and illustrative aspect of agriculture: American crop production. These crops are critical to Americans because they feed us and bring $40 billion of our foreign exchange. They are also critical to others. For example, in 1979 the United States provided 42% of the wheat and 19% of the rice traded between the nations of the world, and fully 43% of the world's corn crop is American. These crops may be susceptible and illustrative because most are grown in latitudes from 35 to 49°, within a zone that climate researchers expect will experience a substantial change in weather and climate as CO_2 increases. Waggoner, in the detailed analysis in Chapter 6, concentrates particularly on wheat, corn, and soybeans, which outdistance in value any other American crop.

From past experience we know that:

- Farmers fit husbandry and crops to weather and climate.
- Rapid environmental change disrupts agriculture.
- Colder as well as warmer and wetter as well as drier conditions can damage crops.

- Pests can amplify effects of bad weather.
- The very soil can be changed by atmospheric conditions.
- Farm and range animals are affected by weather and climate.
- Occasional extremes destroy agriculture.
- Impact of changed weather is sharp in marginal climates.

Against this background it is possible to calculate or speculate on the changes in crops that would follow hypothetical changes in the atmosphere. The hypothetical change that Waggoner considers is at the high end of the range estimated for the year 2000: an increase in CO_2 to about 400 ppmv, a mean warming of about 1°C in the northern United States with a growing season about 10 days longer, and more frequent drought in the United States caused by somewhat less rain and slightly more evaporation. Regional studies in other areas or for other times might well begin by assuming different changes.

Carbon dioxide is a major substrate for photosynthesis and, therefore, can directly affect plant growth if a lack of CO_2 rather than a shortage of water or some other nutrient is the limiting factor. Since the current 340 ppmv appears to be limiting in many cases, a rise in atmospheric CO_2 should increase photosynthesis. However, most effects of CO_2 on photosynthesis and plant growth have been studied and measured during short periods when other factors such as light, water, temperature, and nutrients were adjusted to an optimal level. In addition, growth habits and adaptations to different environments might alter the effects of changing CO_2 concentration.

Increased CO_2 affects photosynthetic rate and duration, as well as the fate and partitioning of photosynthate. Increased CO_2 may also improve the hydration of plants, because it influences the opening of the stomates, the pores through which plants gain CO_2 and transpire water. Increased production of photosynthates may improve the availability of nutrients by encouraging growth of nitrogen-fixing symbionts, enlarging the pool of soil organic matter and increasing soil nitrogen levels. Changed environment not only affects crops but also weeds, pests, and their interrelationships, sometimes benefiting the crop, sometimes its competitors and predators.

Although it is difficult to predict the changes in yield in real crops that might follow a rise in atmospheric CO_2, a survey of experiments in growth chambers and greenhouses leads to the conclusion that CO_2 enrichment to 400 ppmv by A.D. 2000 may increase yields of well-tended crops by, say, 5% (see Table 1.5). In comparison, yield of Illinois corn has quadrupled in about half a century. Although the quantitative evidence for changes in yield under growing conditions in which factors other than CO_2 are limiting is equivocal, some increase in yield--even in poor circumstances--is indicated.

Two orderly means are at hand to calculate how the yields of corn, soybeans, and wheat will change if rising CO_2 makes the climate warmer and drier. In one method, statistical regression, history is distilled to obtain the change in yield for a specified change in weather, such as the decrease in wheat yield in Kansas after a 10% decrease in March precipitation. In the other method, the physiology of, e.g., wheat and the physics of evaporation are assembled in a computer program or

TABLE 1.5 Changes in Yields of Crops in Optimum and Stressful Environments Anticipated from Atmospheric Enrichment to 400 ppmv of CO_2

Crop	Change in Yield (%)	Component Harvested	Yield Increment/ CO_2 Increment (%/ppmv of CO_2)	Yield Change by Enrichment (%/60 ppmv of CO_2)	Reference
Optimum Environments					
Barley	0.9[a]	Grain	0.18	11	Gifford et al. (1973)
Corn	0.28	Young shoots	0.03	1.9	Wong (1979)
Cotton	0.6	Lint	0.34	20	Mauney et al. (1978)
Soybean	0.4[a]	Grain	0.04	2	Hardman and Brun (1971)
Wheat	0.4	Grain	0.13	8	Gifford (1979)
Wheat	0.3	Grain	0.07	4	Sionit et al. (1980)
Wheat	0.6	Grain	0.13	8	Sionit et al. (1981)
Stressful Environments					
Corn (1/3 normal N)	0.28	Young shoots	0.03	1.9	Wong (1979)
Wheat (water limited)	0.6	Grain	0.44	26	Gifford (1979)
Wheat (one H_2O stress cycle)	0.5	Grain	0.10	6	Sionit et al. (1980)
Wheat (two H_2O stress cycles)	0.2	Grain	0.05	3	Sionit et al. (1980)
Wheat (1/8 normal nutrient)	0.1	Grain	0.02	1	Sionit et al. (1981)

[a]Calculated from shoots only.

"simulator" of wheat to calculate the change in wheat yields per change in environment. Waggoner employs both these methods, comparing and verifying them as well as making predictions. Despite a long list of qualifications and warnings, a clear conclusion is obtained (see Table 1.6). If we assume no significant adaptation of inputs and limited geographic mobility, the warmer and drier climate assumed to accompany the increased CO_2 will decrease yields of the three great American food crops over the entire grain belt by 5 to 10%, tempering any direct advantage of CO_2 enhancement of photosynthesis.

Sometimes a change in the weather that has only a modest direct effect on a crop is amplified into a disaster by a third party, a pest. Although pests will change, we cannot predict how.

Turning briefly to other countries and longer times, one can make some extrapolations. The direct benefit of more CO_2 to photosynthesis is universal and will continue for a long time. Crops in northern nations will benefit from warming, and tropical crops will be less

TABLE 1.6 Climate Change and Agricultural Productivity[a]

Crop and Region/State	Present Yield (quintals/hectare)	Estimated Change for 1°C Temperature Increase and 10% Precipitation Decrease: Amount (quintals/hectare)	Percentage Change (%)
Spring Wheat			
Red River Valley	18.2	-1.32	-7
North Dakota	14.9	-1.77	-12
South Dakota	12.0	-1.36	-11
Winter Wheat			
Nebraska	21.3	-1.04	-5
Kansas	21.3	-1.04	-5
Oklahoma	19.7	-0.37	-2
Soybeans			
Iowa	23.6	-1.55	-7
Illinois	21.9	-0.82	-4
Indiana	22.0	-1.25	-6
Corn			
Iowa	72.7	-2.36	-3
Illinois	68.8	-1.72	-3
Indiana	65.3	-2.80	-4

[a]Examples of the effect of a hypothetical climate change on crop yields, if we assume no significant adaptation of inputs and limited geographic mobility. Results shown are based on statistical multiple regression analysis of observed crop and weather data and are calculated for a nominal 1°C increase in temperature and 10% decrease in precipitation for each season or monthly period used as input to the analysis (see Chapter 6).

affected, if, as indicated by climate models, temperatures change little there. Where rainfall is now meager, an increase will have great benefit and a decrease can be tragic. Adaptation will be easier in countries that span several climatic zones and have sufficient wealth, ingenious farmers, and capable scientists with a practical outlook. Although adaptation will continue if the rise in CO_2 continues for generations, an accompanying and continuing desiccation could pass the ability to adapt.

Returning to American crops, one sees in the end that the effects on plants of the changes in CO_2 and climate foreseen for A.D. 2000 are modest, some positive and some negative. The best forecast of yield for the next few decades in the United States, therefore, seems a continuation of the incremental increases in production accomplished in the past generation as scientists and farmers adapt crops and husbandry to an environment that is slowly changing with the usual annual fluctuations around the trend.

1.2.6 Water Supplies

As discussed above in connection with agriculture, CO_2-induced climate changes would involve changes in precipitation, temperature, and their seasonal characteristics. Such changes must be expected to have consequences for rivers and thus for the availability of water for personal use, industry, inland navigation, and irrigation. Of the rain that falls on a given watershed, a large part is eventually evaporated and transpired; the remaining runoff feeds the streams, rivers, and aquifers that drain the region. Despite the current imprecision in predictions of climate changes, it thus seems useful to consider their implications for runoff available for cities and irrigation.

To assess the effects on the water resources of the United States of probable climate change, Revelle and Waggoner (Chapter 7) use the empirical relationships found by Langbein et al. (1949) among mean annual precipitation, temperature, and runoff. The catchments studied by Langbein and his colleagues were distributed over climates from warm to cold and from humid to arid, but Revelle and Waggoner focus on the relations among runoff, temperature, and precipitation only for relatively arid areas. From Langbein's data, they observe that for any given annual precipitation, runoff diminishes rapidly with increasing temperature. Similarly, for any given temperature, the proportion of runoff to precipitation increases rapidly with increasing precipitation.

For any particular region, the relations derived are rather crude approximations because many physical factors, including geology, topography, size of drainage basin, and vegetation, may alter the effect of climate on runoff. Revelle and Waggoner believe, nevertheless, that these relations can be used without serious error to describe the effects of relatively small changes in average temperature and precipitation on mean annual runoff. Table 1.7 shows the approximate percentage decrease in runoff to be expected for a 2°C increase in temperature. Table 1.8 shows the approximate percentage decreases in runoff for a 10% decrease in precipitation. From these exploratory investigations it is evident that in arid and semiarid lands relatively small changes in temperature or precipitation can produce amplified changes in runoff, river flow, and hence the availability of water for irrigation.

1.2.7 Sea Level, Antarctic, and Arctic

Many processes can cause an apparent change in sea level at any particular location. They include local or regional uplift or subsidence of the land; changes of atmospheric pressure, winds, or ocean currents; changes in the volume of the ocean basins owing to volcanic activity, marine sediment deposition, isostatic adjustment of the Earth's crust under the sea, or changes in the rate of seafloor spreading; changes in the mass of ocean water brought about by melting or accumulation of ice in ice sheets and alpine glaciers; and thermal expansion or contraction of ocean waters when these become warmer or colder. Only the last two processes are of primary interest in con-

TABLE 1.7 Approximate Percentage Decrease in Runoff for a 2°C Increase in Temperature[a]

Initial Temperature (°C)	Precipitation (mm yr-1) 200	300	400	500	600	700
- 2	26	20	19	17	17	14
0	30	23	23	19	17	16
2	39	30	24	19	17	16
4	47	35	25	20	17	16
6	100	35	30	21	17	16
8		53	31	22	20	16
10		100	34	22	22	16
12			47	32	22	19
14			100	38	23	19

[a]Source: Revelle and Waggoner, Chapter 7. Computed from data on runoff as a function of precipitation and temperature (Table 7.1) taken from Langbein et al. (1949).

sidering worldwide changes in sea level resulting from climate change, such as the warming that may be induced by increasing greenhouse gases in the atmosphere. (Melting or formation of sea ice and floating ice shelves have no effect on sea level--a glass of ice water filled to the brim does not overflow while the ice melts.) But the other processes contribute to the "noise" that afflicts all sea-level records and may make their interpretation over periods of a few decades difficult or impossible.

For orientation, it is useful to keep in mind that sea level has risen 150 m in the 150 centuries since the peak of the last glacial period. Hence, the present rate of 10-20 cm per century is small compared with the average rate of 1 m per century over the past 15 millennia and very much smaller than the inferred maximum rise of perhaps 5 m per century immediately following the glacial period. Indeed, the present is a time of quiet sea level compared with the violent oscillations that occurred during most of the last 100,000 years.

The projected climatic warming from increasing atmospheric CO_2 and other greenhouse gases will lead to an increased transfer of water mass to the sea from continental (Greenland and Antarctic) and alpine glaciers. As shown by Revelle in Chapter 8, the resulting rise in sea level could be about 40 cm over the next century. Increased downward infrared radiation will also lead to a warming and, therefore, expansion of the upper ocean waters, which can contribute another 30 cm for a total of 70 cm. Assuming the correctness of the figure of 4 W m^{-2} for the increased downward infrared flux with a doubling of CO_2

TABLE 1.8 Approximate Percentage Decrease in Runoff for a 10% Decrease in Precipitation[a]

Temperature (°C)	Initial Precipitation (mm yr-1)				
	300	400	500	600	700
- 2	12	16	17	18	18
0	14	16	17	19	19
2	15	16	19	19	20
4	17	19	19	21	21
6	23	23	21	21	21
8	30	24	24	22	22
10		24	27	23	23
12		40	30	25	25
14			34	30	27
16			50	36	29

[a]Source: Revelle and Waggoner, Chapter 7. Computed from data on runoff as a function of precipitation and temperature (Table 7.1) taken from Langbein et al. (1949).

(higher concentrations of other infrared absorbing gases might further increase this flux), the estimates for both ice melting and ocean thermal expansion still have large uncertainty--at least ±25%. These are due to our uncertainty over the causes of the current rise in sea level, our inability to predict whether changes in atmospheric circulation will cause more or less snow to fall on the ice caps, our ignorance of the conditions for advance or retreat of alpine glaciers, and our lack of understanding of the physical processes associated with the flux of heat to the ocean.

Of even greater uncertainty is the potential disintegration of the West Antarctic Ice Sheet, most of which now rests on bedrock below sea level. This could cause a further sea-level rise of 5 to 6 m in the next several hundred years.

West of the Transantarctic Mountains (approximately from the Meridian of Greenwich, across the Antarctic Peninsula to 180° W), most of the Antarctic Ice Sheet rests on bedrock below sea level, some of it more than 1000 m beneath the sea surface. In its present configuration, this "marine ice sheet" is believed to be inherently unstable; it may be subject to rapid shrinkage and disintegration under the impact of a CO_2-induced climatic change (Mercer, 1978). Events in the fairly recent geologic past suggest that rapid disappearance of West Antarctic ice has occurred before. However, evidence from radar soundings of flow lines extending across the Ross Ice Shelf indicates that the remaining West Antarctic Ice Sheet has been relatively stable for the last 1000-2000 years. Indeed, various lines of evidence suggest that the mass balance of the entire Antarctic Ice Sheet may be positive, i.e., ice may be accumulating.

If the West Antarctic Ice Sheet were to "collapse" (slide into the sea), it would release about 2 million cubic kilometers of ice before the remaining half of the ice sheet began to float.

The rate at which the West Antarctic Ice Sheet could disappear under the impact of a CO_2-induced warming has recently been examined by Bentley (1983). He concluded that rates of discharges and removal of icebergs might make disappearance barely possible, although unlikely, in 200 years, but only after removal of the ice shelves.

If the time required for the ice shelves to disappear is 100 years, Bentley's analysis would not be incompatible with a minimum time of 300 years for disintegration of the West Antarctic Ice Sheet. The corresponding average rate of rise of sea level would be slightly less than 2 m/100 years, beginning about the middle of the next century. Bentley's "preferred" minimum time of about 500 years would give a rate of sea-level rise of 1.1 m/100 years, which is, as pointed out earlier, about the mean rate for the last 15,000 years. To either of these figures we must add a rise of 70 $\pm$ 18 cm between 1980 and 2080, which Revelle has shown is likely to result from ocean warming and ice ablation in Greenland and Antarctica, plus a possible retreat of alpine glaciers. These processes may well continue in later centuries.

Like the Antarctic ice, Arctic ice has been a stable climate feature (see Annex 1). There is quite good evidence for persistence of the ice cover all year round for the last 700,000 years and perhaps for the past 3,000,000 years, although there is debate about whether the Arctic may have been open in summer from 700,000 to 3,000,000 years ago. The existence of glacial marine sediments in the Arctic basin shows that ice rafting occurred during the past 5,000,000 years. Longer ago than 5,000,000-15,000,000 years, the Arctic may have been open year round. Global cooling patterns are such that an initial freeze-up of the Arctic may have occurred 15,000,000 years before the present, although there is no direct evidence. The physical reasons for the persistence of the Arctic ice are not well understood; but they may reflect both dynamic and thermodynamic processes, such that when little (excess) ice exists, correspondingly more (less) ice is produced the next winter.

Studies on whether the Arctic sea ice will completely melt in summer, and if so, whether the ice will remain melted in winter, as suggested by Flohn (1983), have produced ambiguous results. Given the apparent long-term stability of Arctic ice, one must be cautious in projecting a melting due to prospective warming from increasing CO_2 concentrations. A number of climate and ice models suggest that the Arctic ice may melt in summer with a warming of about the magnitude that may be induced by a doubling of CO_2 and increase of other greenhouse gases, but this conclusion must be viewed as still tentative. The representations of the Arctic in energy balance and most climate models that have melted Arctic ice with a CO_2 warming usually do not include changes in cloud cover, ice dynamics, or the effects of open leads and salinity stratification.

Owing to dynamic and thermodynamic processes, thickness of ice may respond more readily to temperature increases than extent of ice. However, verification of ice extent and thickness estimates from climate models is not yet adequate.

Oceanographic studies are also quite limited for the case of an open Arctic. There is now a very strong, salinity-induced, density stratification, the causes of which are not fully understood. If this stratification can be broken and does not reform, then the Arctic might be able to remain open through the winter. This possibility is not considered likely.

Finally, there have been few studies of the effect of less ice or no ice in summer on atmospheric circulation. While atmospheric effects of reduction in Arctic ice remain highly speculative, some poleward shift of storm tracks seems likely and most significant climatic effects may occur during transition seasons.

1.3 SERIOUSNESS OF PROJECTED CHANGES

In assessing the seriousness of the changes projected in the preceding sections, there are two enormous sources of uncertainty. One source is the contents of the above outlook itself: uncertainties about sources and uses of energy, which in turn embody uncertainties about population, per capita income, energy-using and energy-producing technologies, density and geographic distribution of populations, and the distribution of income; a multitude of uncertainties about the carbon cycle; uncertainties in translating a growth curve for CO_2 in the atmosphere into appropriately time-phased changes in climate in all the regions of the globe; uncertainties about whether human activities other than release of CO_2 will be affecting the climate and what "natural" climatic trends will be; and, finally, uncertainties about effects on plant growth, water supplies, sea level, and other factors.

The second source is uncertainty about the kind of world the human race will be inhabiting as the decades go by, through the coming century, and beyond. This source overlaps the uncertainties just mentioned; per capita income both influences the use of fossil fuels and affects how readily the world's population can afford, or can adapt to, changes in climate. And for both purposes the distribution of income--the income disparities among different parts of the world, within countries as well as between countries--affects the calculations. Similarly, the structures people inhabit, the ways people and goods are transported, the foods people eat, the ways countries defend themselves, and the geographical distributions of populations within and among countries, all affect land use and the kinds and amounts of energy used and hence the production of CO_2; but they also affect the ways that climate impinges on living and earning, even on what climates are preferred. The mobility of people, capital, and goods--the readiness with which people can migrate, goods can be traded, and capital for infrastructure and productive capacity can flow among regions and countries--would also determine how much difference the changes in climate would make. The location and significance of national boundaries and various international and supranational institutions would have much to do with whether adverse climatic effects in parts of the world could be offset, in a welfare assessment, by improvements in other places. Different individuals and groups will interpret these uncertainties in different ways, depending on their culture, training, societal vantage point, and other factors.

While emphasizing that the uncertainties just described must be kept in mind, we now discuss the areas of concern we have been able to identify in our discussions of the CO_2 issue. First we address areas of specifiable concern, then of more speculative concern, and, finally, of poorly defined but potentially serious concern.

1.3.1 Specifiable Concerns

1.3.1.1 Agriculture and Water Resources

The outlook for American agriculture over the next couple of decades based on a foundation of physiology and history (summarized above and presented in detail by Waggoner in Chapter 6) tells how a CO_2-induced change in climate would change the yields of crops if farmers, ignoring the weather, persisted in planting the same varieties of the same species in the same way in the same place. The safest prediction of any made by Waggoner is that farmers will adapt to a change in climate, exploiting it and, probably, proving our predictions to be pessimistic. If the climate changes, farmers will move themselves, change the crops, modify varieties, and alter husbandry. The loss of acreage to the margin of the desert, for example, may be replaced by yield and acres at the cold margin. Seeking higher yields and more profit, farmers will correct their course annually, and they may even adapt to a slowly changing climate unconsciously and successfully. Thus, we do not regard the hypothesized CO_2-induced climate changes as a major direct threat to American agriculture over the next few decades. Of course, shifts at the margins may be easy for the nation but not for those involved.

While the effects of increased CO_2 plus climatic warming on agriculture might be relatively small in the United States, such effects might be much larger in countries that do not have or build a good agricultural research infrastructure or the agricultural flexibility that come from relatively large capital investments in agriculture, rural transportation, farm credit and crop insurance, and marketing systems. Through trade linkages and political and social awareness, climate-induced agricultural problems in other parts of the world will become America's concern. Longer-term agricultural impacts, as global climatic conditions continue to shift, perhaps at an increasing rate, might also conceivably be much more serious. Will these be offset by the benefits of CO_2 for photosynthesis and water-use efficiency? At present we lack tools with which to evaluate in a credible way the very long-run prospects.

While on balance U.S. agriculture as a whole may not suffer significantly, irrigated agriculture is both important and susceptible. Its importance derives from its expanse and the value of its crops. Fully 50 million acres, or about 1 in 7 American acres, of cropland are irrigated. The quarter trillion cubic meters of irrigation water withdrawn from American streams and groundwater represent about half of all withdrawals of this natural resource. Averaging wheat yields over all American fields, humid as well as arid, one sees an average of 1.9 tons/ha on unirrigated versus 3.7 tons/ha on irrigated land. Valuable crops are grown on irrigated fields because irrigation reduces variability of water and produces consistently high yields. Thus, most of the irrigated cropland (44 million acres) occurs on only 12% of the farms, but these farms produce fully 40% of the market value of the crops from all American cropland (Jensen, 1982).

Irrigation is susceptible, because it is such a heavy user of water. In seven U.S. water regions examined by Revelle and Waggoner (Chapter 7), the share of total water withdrawals for irrigation ranged from 68% to 95%. For these regions, Revelle and Waggoner draw on the efforts of Stockton and Boggess (1979) and perform a corroborating study of the Colorado River to estimate the effects of a climatic change on water.

Revelle and Waggoner (Chapter 7) show that the effect of climatic change on water must be considered separately for different regions. Following Stockton and Boggess (1979), they make several simplifying assumptions, the most important of which are: 1) variations in annual runoff are predominantly influenced by climate, although other factors, such as geology, topography, and vegetation, have effects, and 2) that evapotranspiration is controlled only by temperature. A warmer and drier climate would severely affect the seven water regions: the Missouri, Texas Gulf, Rio Grande, Arkansas-White-Red, Upper Colorado, Lower Colorado, and California. All are in the western United States; and although they cover about half the country, they have less than 15% of the runoff. A 10% decrease in precipitation, combined with a 2°C warming, would decrease runoff in these regions between 40 and 76% (see Table 1.9). The impact would be especially severe in the Missouri, Rio Grande, Upper Colorado, and Lower Colorado regions where even current water requirements would exceed the supplies after climatic change by between 20 and 270%. Local shortages and a general deterioration of water quality would occur in the Arkansas-White-Red, Texas Gulf, and California regions. Much of the irrigated area might have to be abandoned unless water could be imported from other regions with more abundant supplies, such as the Pacific Northwest or the Upper and Lower Mississippi. Major additions to reservoirs would be required in several regions to maintain a safe yield of water during drought, even after a reduction of irrigated area and the maximum practicable rise in the efficiency of the use of water in irrigation.

Except for the Rio Grande, the Colorado River is more intensively used than any other major stream in the United States. Half the estimated "normal" river flow of 18 billion cubic meters per year has been allocated by interstate compact, confirmed by federal law, to the "lower basin" states of Arizona and California, with minor amounts going to Nevada, although nearly all of the runoff originates from snow in the high mountains of western Colorado, southwestern Wyoming, and eastern Utah. Revelle and Waggoner examined mean annual precipitation, temperature, and river flow for 1931 to 1976 and found a high correlation between variations in precipitation and temperature, on the one hand, and runoff on the other. A rise of 2°C in average temperature from 4.2 to 6.2°C would reduce runoff by 29 $\pm$ 6%, and a 10% decrease in precipitation would cause a further reduction of about 11 $\pm$ 1.4% in

TABLE 1.9 Comparison of Water Requirements and Supplies for Present Climatic State and for a 2°C Increase in Temperature and 10% Reduction in Precipitation in Seven Western U.S. Water Regions[a]

	Present Climate						Warmer and Drier Climate		
Water Region[b]	Area ($10^{10}/m^2$)	Mean Annual Runoff (10^{10} m^3 yr^{-1})	Mean Annual Runoff (mm)	Mean Annual Supply (10^{10} m^3 yr^{-1})	Mean Annual Requirements[c] (10^{10} m^3 yr^{-1})	Ratio of Requirement to Supply	Mean Annual Supply (10^{10} m^3 yr^{-1})	Percent Change in Supply	Ratio of Requirement[d] to Supply
Missouri	132.4	8.50	64	8.50	3.63	0.43	3.07	-63.9	1.18
Arkansas-White-Red	63.2	9.35	148	9.35	1.67	0.18	4.32	-53.8	0.39
Texas Gulf	44.9	4.92	110	4.92	1.74	0.35	2.47	-49.8	0.70
Rio Grande	35.2	0.74	21	0.74	0.67	0.91	0.18	-75.7	3.72
Upper Colorado	29.6	1.64[e]	55	1.64	1.63[f]	0.99	0.99	-39.6	1.65
Lower Colorado	40.1	0.38	10	1.15[g]	1.37	1.19	0.50[g]	-56.5	2.68
California	42.9	9.56	222	10.18[g]	4.22	0.41	5.71[g]	-43.9	0.74
For the 7 regions together	388.3	35.09	90.4	35.09[h]	14.93	0.43	16.53[h]	-53	0.90

[a]Source: Stockton and Boggess (1979) and calculations from Revelle and Waggoner, this volume, Chapter 7.
[b]As defined by the U.S. Water Resources Council (1978).
[c]Projected through A.D. 2000.
[d]Assuming no increase in requirement because of increased evapotranspiration from irrigated farms or reservoirs.
[e]Average "virgin flow" of the Colorado River at Lee Ferry from 1931 to 1976.
[f]Includes allocation to Lower Basin states, California included, of 0.93×10^{10} m^3 yr^{-1}.
[g]Includes water received from Upper Colorado Basin, but not mined groundwater.
[h]Total is less than sum of the column because of flow of Lower Colorado derived from Upper Colorado (g).

runoff. A rise in temperature--even without a decrease in precipitation--would seriously affect entire states.

A 2°C warming and a 10% reduction in precipitation would probably not have serious effects on water supplies in the humid regions east of the 100th meridian. Neither would effects be severe in the water-rich Pacific Northwest and the Great Basin (parts of Nevada, Utah, and Idaho), where demand is relatively small and groundwater reserves are large.

Loss in irrigated yield accompanying a change in climate can be envisaged in two ways. For grain, one might simply and roughly say that some areas can no longer be irrigated, and on those acres the yield will be reduced by at least 50% because the subsequent dryland crops will be grown in alternate years. For produce, a decrease in water and irrigated area for truck croplands could reduce yields to zero on many acres and thus decrease the supply of fresh vegetables in the supermarkets, especially in the winter. Of course, decline of irrigation systems, often caused by increasing salinity and rising water table when drainage facilities are inadequate, is not a new experience for mankind.

1.3.1.2 Rising Sea Level

If one accepts the projections of warming, then certain physical consequences seem inescapable. One of these is the slow rise in global sea level. As explained by Revelle, melting of land ice and thermal expansion of the ocean may lead to a rise of about 70 cm in global sea level over the next 100 years, continuing thereafter. Many shoreline problems (for example, coastal erosion, storm surges, and salinity of groundwater) are sensitive to sea-level changes on the order of decimeters, and 70 cm, though modest-sounding on a calm day at the seashore, could effect a variety of unwelcome changes. We discuss the question of larger and continuing sea-level rise in the section that follows.

1.3.2 More Speculative Concerns

Our more speculative concerns center on the West Antarctic Ice Sheet (WAIS) and sea-level rise, the Arctic, and human health. These concerns are more speculative in that both the scientific uncertainties are greater and the potential effects are more distant.

Resuming the question of sea level, we concluded above that with a postulated warming of about 3 or 4°C from CO_2 and other greenhouse gases a gradual rise is probable over the next 100 years as a result of thermal expansion of the ocean, ablation of the Greenland and Antarctic ice caps, and retreat of alpine glaciers. We have also mentioned that, because of events in Antarctica, a much larger rate of rise is not unlikely during the following several centuries. Rates of sea-level rise could reach 1-2 m per 100 years. A complete collapse of the WAIS would produce a worldwide rise in sea level of between 5 and 6 m.

How serious would such rates and levels of sea-level rise be? As Schelling discusses in Chapter 9, there are three principal ways that human populations can adapt to a rising sea level: retreat and abandonment, construction of dams and dikes, or building on piers and landfill. The basic division is between abandonment and defense.

Defense against sea-level rise has received little attention in this country. It is therefore worth emphasizing that there are ways to defend against rising sea levels. For built-up and densely populated areas, defenses could be cost effective for a rise of as much as 5 or 6 m. Even where defending against 5 m would not be cost effective, defending against a meter or two could make sense for a century or two. Defense is not an empty hypothetical or purely speculative option.

The economics of dikes and levees depends on the availability of materials (sand, clay, rock); on the configuration of the area to be protected; on the differential elevation of sea level and internal water table; on the depth of the dike where it encloses a harbor or estuary; on the tide, currents, storm surges, and wave action that it must withstand; and on the level of security demanded for contingencies such as extreme ocean storms, extreme internal flooding, earthquakes, military action, sabotage, and uncertainties in the construction itself. On the economics of diking, it is worth remembering that the Dutch for centuries have found it economical to reclaim the bottom of the sea, at depths of several meters, for agricultural, industrial, and residential purposes.

The situation is totally different for an area like the coast of Bangladesh. Defense would be extremely costly for a region with a huge coastal area subject to inundation, rather than a concentration of capital assets that could be enclosed by a few miles of dikes. Such an area would be so susceptible to internal flooding with freshwater that levees required to protect the country would be many times greater than the length of the shoreline.

Where defense is not practicable, retreat is inevitable, at least selectively. In urban concentrations, where buildings may last a century, good 100-year predictions of sea-level change (including likely erosion and storm damage) might permit the orderly evacuation and demolition of buildings without excessive write-off of undepreciated assets.

Changes in Arctic weather and climate would have both practical and noneconomic implications. Open seas and easier ice conditions would have bearing on long-term strategies of use for northern seas and channels with respect to both navigation and seafloor development. Oil and gas exploration, drilling, production, and transportation could become easier and less expensive. The old dream of a "Northwest Passage" might become a reality. An ice-free Arctic Ocean in summer and a less hostile environment in North American, Russian, and Scandinavian Arctic regions would also have implications for military strategy and tactics, if technology does not shift military issues to other spheres entirely. For example, surface and aircraft-carrying fleets could operate in the Arctic during the summer months, as they do now in other oceans. One effect of warming should be a change in the stability and distribution of permafrost. This change would, in turn, suggest design changes for overland vehicles, construction equipment, pipelines, and buildings. On a different plane, concern arises about possible loss of habitats and the conservation of nature; polar regions are among the wilder and more pristine environments remaining.

In contrast to polar and sea-level change, not much consideration has been given by those who study increasing CO_2 and climate change to any possible direct effect on human health or the animal population from CO_2 in the air we breathe. The natural a priori concern with the health effects of a doubling or quadrupling of an important gas in the air we breathe--the substance that actually regulates our breathing rate--is relieved by the observation that for as long as people have been living indoors, not to mention burning fuel to heat themselves, they have been spending large parts of their lives--virtually entire lives in the case of people who work indoors and travel in enclosed vehicles--in an atmosphere of elevated CO_2. Doubling or even quadrupling CO_2 would still present a school child with a lesser concentration during outdoor recess than the child faces in today's average classroom.

There is, furthermore, no documented evidence that CO_2 concentrations of five or ten times the normal outdoor concentration damage human or animal tissue, affect metabolism, or interfere with the nervous system. Nor is there a theoretical basis for expecting direct effects on health from the kinds of CO_2 concentrations anticipated.

But even though this answer is reassuring, the question has to be faced. It will occur to people who hear about changes in the atmosphere that their grandchildren are going to breathe. And experiments have not been carried out with either people or large animals whose whole lives, including prenatal life, were spent in an environment that never contained less than, say, 700 ppmv of CO_2. So the question deserves attention, even though there is no known cause for alarm.

Probably more serious is the effect of elevated temperatures on health and welfare. If a 3 or 4°C increase in average temperatures occurs, as might be expected in different parts of the United States with a CO_2 doubling, extreme summer temperatures in warm years might rise by an equal amount. Excess human death and illness are already characteristic of summer "hot spells," and these might be worsened by much higher extreme summer temperatures. And, climatic shifts may change the habitats of disease vectors or the hosts for such vectors.

1.3.3 The Problem of Unease about Changes of This Magnitude

Enveloping our specific and more speculative concerns about impacts of climatic change on water resources, sea level, and other areas discussed is a profound uneasiness about inducing environmental changes of the magnitude envisaged with major increases in atmospheric CO_2 and other greenhouse gases.

To establish a context, consider, for example, the most frequently quoted index--change in global average surface temperature. This crude measure of climate tells us little about what temperature change to expect for specific regions and nothing about the type of climate that would be experienced. Global average surface temperature has come to such prominence in large part because it represents a relative measure of CO_2 effects among climate models. Indeed, for many models it is the only result with much scientific validity. Nevertheless, changes in average surface temperature may suggest well the nature of our unease.

Increasing CO_2 is expected to produce changes in global mean temperature that, in both magnitude and rate of change, have few or no precedents in the Earth's recent history. Consider the ranges of temperature experienced in various periods in the past (Figure 1.14). A range of less than a degree was experienced in the last century, less than 2°C in the last thousand years, and only 6 or 7°C in the last million years. The development of civilization since the retreat of the last glaciation has taken place in a global climate never more than 1°C warmer or colder than today's. Despite the modest decline of time-averaged global-mean temperatures since the 1940s, we are still in an unusually warm period in the Earth's history. Indeed, according to one source (Jones, 1981), 1981 was the warmest year on record. Thus, the temperature increases of a couple of degrees or so projected for the next century are not only large in historical terms but also carry our planet into largely unknown territory. Increasing CO_2 promises to impose a warming of unusual magnitude on a global climate that is already unusually warm.

Furthermore, the question of threshold responses arises. It is possible that a change in the central tendency of climate will come about smoothly and gradually. It is also possible that discontinuities will occur. For example, Lorenz (1968) and others have suggested the possibility of more than one climatic equilibrium.

As Schelling (Chapter 9) points out, our calm assessment of the CO_2 issue rests essentially on the "foreseeable" consequences of climatic change. Less well-seen aspects remain troubling. We have mentioned the possible release of methane clathrates from ocean sediments. We have also mentioned melting of the central Arctic sea ice. Disappearance of the permanent Arctic ice would result in a marked increase in the thermal asymmetry of the planet, with only one pole still glaciated. Such asymmetric conditions could produce further, unanticipated climatic changes (Flohn, 1982). Warming amplified at high-latitude regions could also affect major features of the oceanic circulation, and these too could lead to unexpectedly different climatic conditions, as well as changes in the capacity of the oceans to absorb CO_2. At the level of ecosystems, surprising changes may also result from climatic shifts.

We are not complacent about global-average temperature changes that sound small; very serious shifts in the environment could well be implied. There is probably some positive association between what we can predict and what we can accommodate. To predict requires some understanding, and that same understanding may help us to overcome the problem. What we have not predicted, what we have overlooked, may be what we least understand. And when it finally forces itself on our attention, it may appear harder to adapt to, precisely because it is not familiar and well understood. There may yet be surprises. Antici-

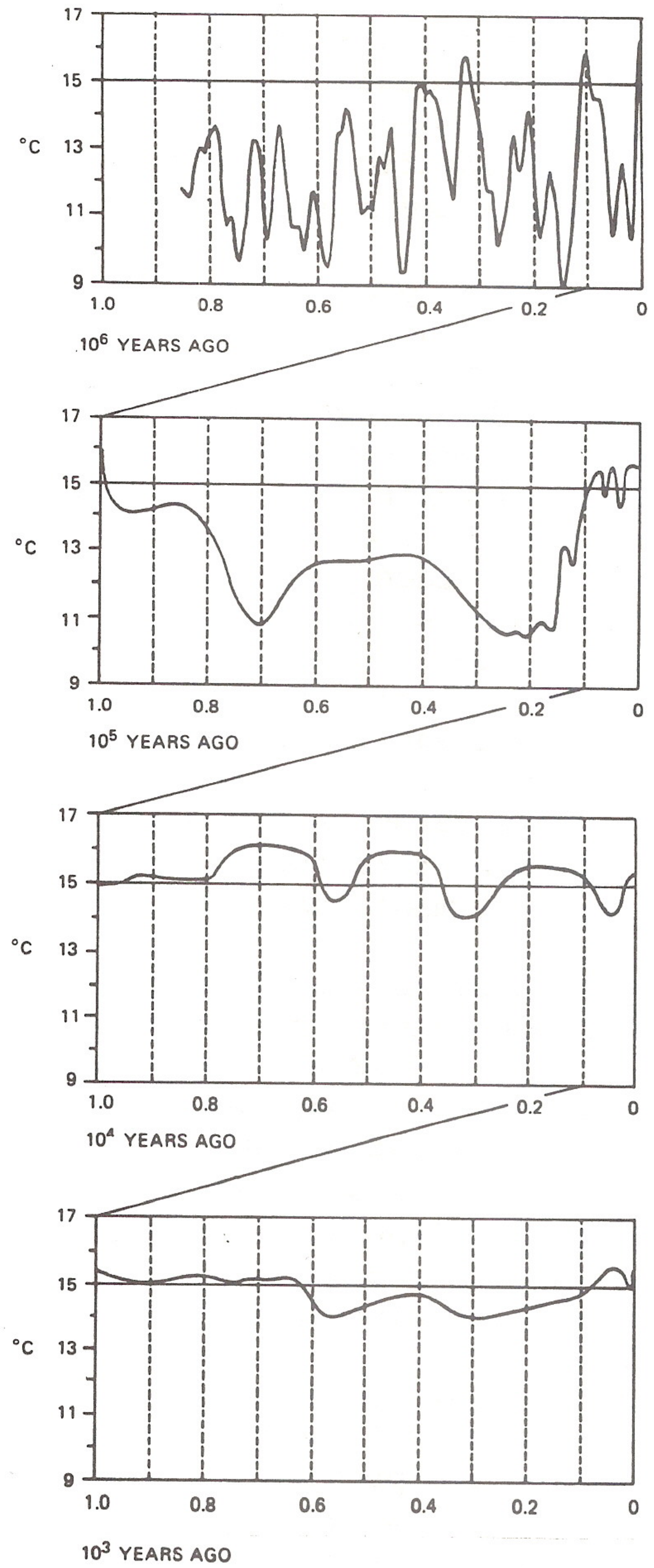


FIGURE 1.14 An approximate temperature history of the northern hemisphere for the last 850,000 years. The panels are at the same vertical scale. The top panel shows the past million years, the second panel amplifies the past 100,000 years, the third panel the past 10,000 years, and the bottom panel the past 1000 years. The horizontal line at 15°C is included simply for reference. Considerable uncertainty attaches to the record in each panel, and the temperature records are derived from a variety of sources, for example, ice volume, as well as more direct data. Spatial and temporal (e.g., seasonal) variation of data sources is also considerable. From Clark (1982). Original data from Matthews (1976), Mitchell (1979), and National Research Council (1975).

pating climate change is a new art. In our calm assessment we may be overlooking things that should alarm us.

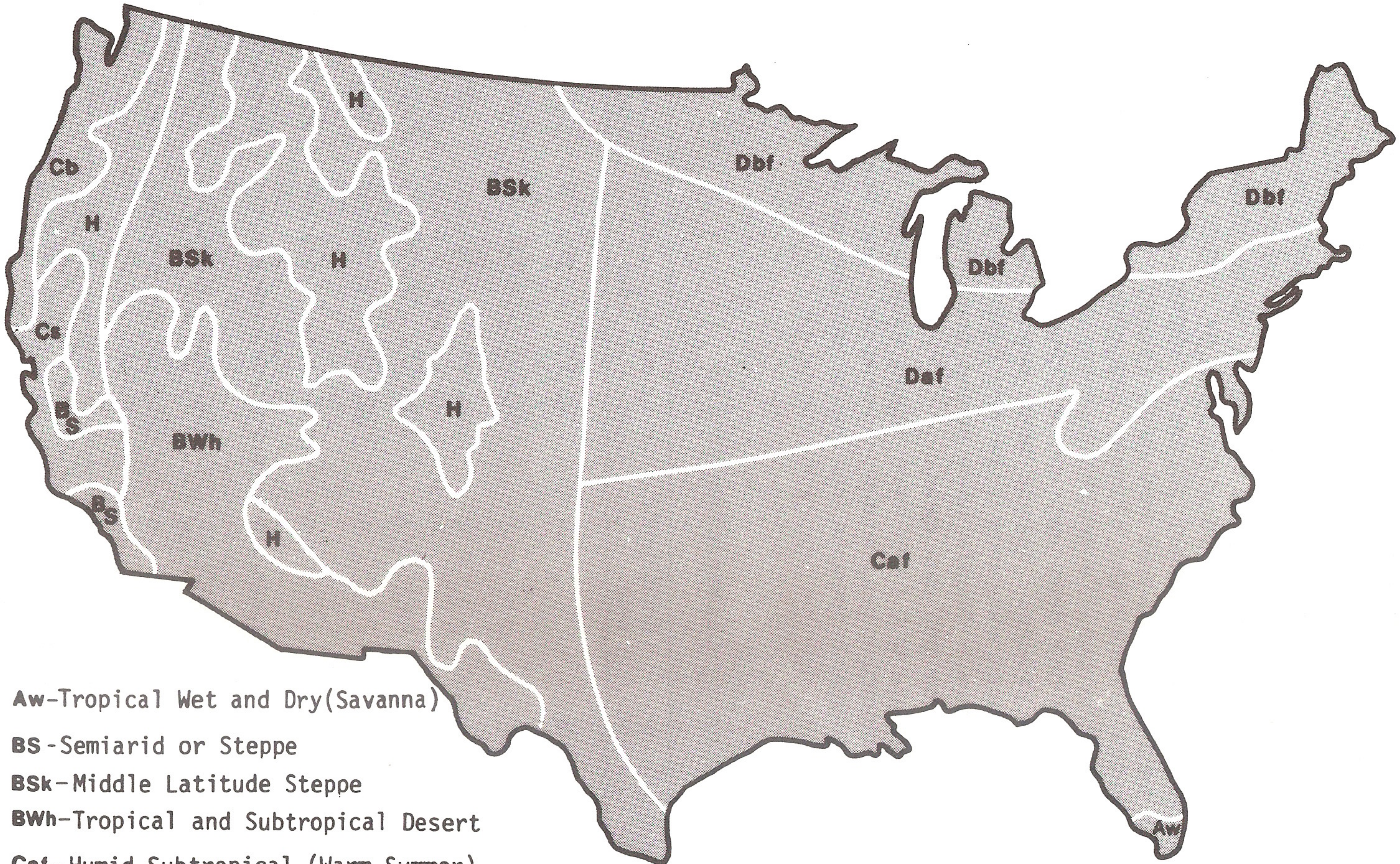
At the same time, one might observe that--barring the kind of surprises mentioned above--the climate changes under consideration are not large in comparison with the climate changes individuals and social groups have undergone historically as a result of migration. Table 1.10 shows U.S. population for 1800, 1860, 1920, and 1980, distributed according to the climatic zones in Figure 1.15. These data have been transformed into a series of maps of the United States in which the areas of our various climatic zones are drawn so as to be proportionate to their populations at various times (see Chapter 9). The maps seemingly depict massive climate change; formerly empty, thus small, climatic zones become heavily populated and grow large. But it is not that deserts have expanded or that the climate has changed from permafrost to rain forest, or from prairie to Mediterranean west coast, or to places where it gets cold but does not quite freeze from where it got a little colder and did freeze. People have moved, and to all climates, to places of enormous extremes like the Dakotas and places of little change like Puerto Rico. People have moved from the seacoast to the prairie, from the snows to the Sun Belt.

Not only have people moved, but they have taken with them their horses, dogs, children, technologies, crops, livestock, and hobbies. It is extraordinary how adaptable people can be in moving to drastically

TABLE 1.10 U.S. Population by Climatic Zone[a,b,c]

Climatic Zone[c]	Description	Population 1800	1860	1920	1980
Aw	Tropical wet and dry (Savannah)	0	2,996 (1)	129,741 (1)	2,793,140 (1)
BS and BS_k	Semiarid and steppe	0	64,018 (1)	4,291,664 (4)	21,000,465 (9)
BW_h	Tropical and subtropical desert	0	28,029 (1)	743,263 (1)	4,955,742 (2)
Caf	Humid subtropical (warm summer)	2,034,536 (42)	9,426,517 (32)	32,360,561 (29)	71,932,014 (32)
Cb	Marine (cool summer)	0	39,246 (1)	1,795,406 (2)	4,447,811 (2)
Cs	Dry-summer subtropical (Mediterranean)	0	202,420 (1)	1,636,597 (2)	8,675,763 (4)
Daf	Humid continental (warm summer)	2,348,030 (49)	16,074,866 (54)	59,811,474 (54)	90,882,262 (40)
Dbf	Humid continental (cool summer)	435,665 (9)	3,586,555 (12)	9,394,792 (8)	13,710,636 (6)
H	Undifferentiated highlands	0	184,896 (1)	1,559,963 (1)	9;147,733 (4)

[a]Source: U.S. Census Bureau, 1800, 1860, 1920, 1980. Data compiled by Clark University Cartographic Service.
[b]Figures in parentheses are percentage of total population in that climate zone.
[c]Climatic zones shown in Figure 1.15.



Aw-Tropical Wet and Dry(Savanna)
BS-Semiarid or Steppe
BSk-Middle Latitude Steppe
BWh-Tropical and Subtropical Desert
Caf-Humid Subtropical (Warm Summer)
Cb-Marine (Cool Summer)
Cs-Dry Summer Subtropical (Mediterranean)
Daf-Humid Continental (Warm Summer)
Dbf-Humid Continental (Cool Summer)
H-Undifferentiated Highlands

Source: Trewartha "The Earth's Problem Climates", 1961.

FIGURE 1.15 Climatic zones of the United States. Prepared by Clark University Cartographic Service.

different climates. That adaptability may suggest that if climates change only by shifting familiar climates around the world, it is not altogether different from leaving the climates alone and moving the people around. Of course, when people moved from England to Massachusetts or from the East Coast to the Great Plains, there were substantial difficulties in adapting; and if the climate changes and people stay, they may also have substantial difficulties. But it appears that a change in the climates where people live may not be altogether different from people moving to another climate. It may be that what we have to look forward to is not quite so historically unusual as a human experience as the descriptions from the paleoclimatic record would suggest. We have really become accustomed to marked climate change. For the individual, in contrast to the environment, the idea of climate change in a generation or two is far from novel.

While people may be able to adapt readily to climatic change, they may be unwilling to accept climatic changes imposed on them involuntarily by the decisions of others. Thus, in trying to clarify our unease about CO_2-induced climatic change, it is necessary to point out the potentially divisive nature of the issue. It is important to recognize the distribution of incentives for, and effects of, human-induced climatic changes. Although it might be in the interest of the world economy to restrict, at some cost, the use of fossil fuels, it is probably not in the interest of any single region or nation to incur on its own the cost of reduction in global CO_2. For example, countries that view heavy rains as disasters and countries that view them as water for their crops would have different preferences about which, if any, rains to avoid or restore and whether they or another country should forgo (or burn) fossil fuels to help effect the change. The marginal effects of climatic change on the distribution of wealth may range from quite positive to quite negative. In short, CO_2-induced climatic changes, and more generally weather and climate modification, may be a potent source of international conflict.

1.4 POSSIBLE RESPONSES

So far we have developed an outlook for CO_2-induced climate change and made some tentative evaluations of the seriousness of possible changes in prospect. In the preceding discussions we have occasionally referred to potential societal responses, for example, taxes on CO_2 emissions, agricultural adjustments, and migration. Now we discuss possible responses in a more systematic fashion and offer two sets of comments. One set relates to flexibility in defining the issue, the other to specific categories of response.

1.4.1 Defining the Problem

As Schelling points out in Chapter 9, how one defines a problem or issue often governs or biases the search for solutions and sometimes in a way that puts emphasis on more difficult or less attractive solutions.

The protagonist of this study has been CO_2. Recent research reflected in this report has been largely motivated, first, by the observation that atmospheric CO_2 is increasing as the use of fossil fuels expands and, second, by the known potential for a "greenhouse effect" that could generate quantitatively significant changes in climate worldwide. The members of the group responsible for the report are known as the Carbon Dioxide Assessment Committee, the work was authorized by an Act of Congress concerned with carbon-intensive fossil fuels, and the agency principally charged with managing the research is the Department of Energy. The topic is generally referred to as "the carbon dioxide problem," a global challenge to the management of energy resources.

However, there are good reasons for taking climate change itself as the main perspective rather than CO_2 or energy. One reason is that over the span of time that this report has to cover there could be changes and fluctuations in climate not due to human activity. A second reason is that CO_2 is not the only climate-affecting substance that society releases to the atmosphere. Not only must the impact of CO_2 be assessed in conjunction with other climate-changing activities, but any policy response needs a focus broader than CO_2. A third reason is that there is a natural tendency to define a problem by reference to the agent of change and to seek solutions in the domain suggested by the naming of the problem, e.g., "fossil fuels" or "CO_2."

There is a legitimate presumption that where the Earth's biosphere is concerned any drastic change may produce mischief. There is also a widespread methodological preference for preventive over alleviating programs, and for dealing with causes rather than symptoms. But it may be wrong to commit ourselves to the principle that, if fossil fuels and CO_2 are where the problem lies, they must also be where the solution lies. Although a precautionary attitude toward any drastic changes in world climates would be prudent, definition of the problem requires investigation not only of what changes in climates may occur but also of what damages or blessings the changes may bring.

To illustrate the point, while for any expected adverse consequences of CO_2, conserving fossil fuel is an obvious policy option at the outset, the parallel importance of water supply and conservation emerges only later. Defining the issue as "the CO_2 problem" can focus attention too exclusively on energy and fossil fuels and divert it from rainfall or irrigation or, more even-handedly, the broad issue of climate change.

Something else is illustrated about the character of the issue. If the solution has to be reduced CO_2 emissions, both the problem and the solution are global in a severe sense. A ton of CO_2 produced anywhere in the world has the same effects, for good or ill, as a ton produced anywhere else. Any nation or locality that attempts to mitigate prospective changes in climate through a unilateral program of conservation, fuel switching, biomass enhancement, or scrubbing of CO_2 from smokestacks, in the absence of some global fuel rationing or compensation arrangement, pays alone the cost of its program while sharing the consequences with the rest of the world. In contrast, water resources are usually regional or local. Worldwide agreements involving some of the main consumers or producers of fossil fuels would be essential to programs for reducing CO_2 emissions; in contrast, water development and conservation are national in scope or involve a few neighboring countries.

1.4.2 The Organizing Framework

If we accept that the issue is climate, then it follows that the organizing framework for welfare and policy implications of atmospheric CO_2 should also be built around climate change, not around CO_2.

As Schelling argues, the framework ought to be comprehensive. It should include theoretical possibilities that may be of no contemporary significance, because we have to think about choices as they evolve through the next century. The framework should make room for imagination, not just for options that currently look cost effective.

The framework should lend itself to different levels of universality. While atmospheric CO_2 is a global condition, its consequences and many of its policy implications will be regional and local. Governments will assess consequences and choose policies according to the climatic impacts on their own populations and territory. At the same time, some national governments, including ours, will need a framework for assessing worldwide consequences and policy options that are international in scope.

Just as governments will assess differently the implications of climate change for their own countries, some perceiving gains and others losses, so will interests be divided within countries. Not only are some countries, like our own, large enough to have diverse climates subject to different kinds of change, but people in the same climate are affected differently according to how they live and earn their living, their age and health, what they eat, and how they take their recreation. Our framework has to be susceptible of disaggregation.

The framework should be construed as moving through time. The changes take time; the uncertainties unfold over time; policies and their effects have lead times, lag times, and growth rates. Governments and people will attach different discounts to events and conditions at different distances in the future. And a country that appears to be victim or beneficiary of a climate-change forecast for the next 75 years would not be helped or hurt the same amount, or necessarily even in the same direction, by an additional 75 years of the same scenario.

1.4.3 Categories of Response

Schelling (Table 1.11) develops a framework consisting of four categories of response, arrayed against background climate and trends. Category 1 is prevention, containing options for affecting the production of CO_2. Category 2 is removal: if you cannot help producing too much CO_2, can you remove some? Category 3 consists of policies deliberately intended to modify climate and weather: if too much CO_2 is produced and not enough can be removed, so that concentration is

TABLE 1.11 CO_2-Induced Climatic Change: Framework for Policy Choices

Possibly Changing Background Factors	Policy Choices for Response[a]: (1) Reduce CO_2 Production	(2) Remove CO_2 from Effluents or Atmosphere	(3) Make Countervailing Modifications in Climate, Weather, Hydrology	(4) Adapt to Increasing CO_2 and Changing Climate
Natural warming, cooling, variability			Weather Enhance precipitation Modify, steer hurricanes and tornadoes	Environmental controls heating/cooling of buildings, area enclosures Other adaptations habitation, health, construction, transport, military
Population global, distribution: nation, climate zone, elevation (sea level), density				Migrate--internationally, intranationally
Income global average distribution				Compensate losers--intranationally, internationally

Governments				
Industrial emissions non-CO_2 greenhouse gases particulates			Climate Change production of gases, particulates Change albedo ice, land, ocean Change cloud cover	
Energy per capita demand fossil versus nonfossil	Energy management Reduce energy use Reduce role of fossil energy Increase role of low-carbon fuels	Remove CO_2 from effluents Dispose in ocean, land Dispose of byproducts in land, ocean		
Agriculture, forestry, land use, erosion Farming and other dust Agricultural emissions (N_2O, CH_4)	Land use Reduce rate of deforestation Preserve undisturbed carbon-rich landscapes	Reforest Increase standing stock, fossilize trees		Change agricultural practices: cultivation, plant genetics Change demand for agricultural products, diet Direct CO_2 effects Change crop mix Alter genetics
Water supply, demand, technology, transport, conservation, exotic sources (icebergs, desalinization)			Hydrology Build dams, canals Change river courses	Improve water-use efficiency

[a]Responses may be considered at individual, local, national, and international levels.

going to increase and climate is going to change in systematic fashion, can we do something about climate? Finally, Category 4 is adaptation, consisting of all the policies or actions taken in consequence of anticipated or experienced climate change.

In Category 1, production of CO_2, there are two main subdivisions: energy and land use. Energy breaks down into three main subdivisions: reduction in total energy use, reduction in the fossil fuel component, and switching to less carbon-intensive fossil fuels. Land use cuts across categories 1 and 2. There is no way to "unuse" fuel that has been burned, but forests can be grown or cut, and the net effect can go either way. Preserving a growing forest rather than cutting it can be thought of as producing less CO_2 or removing it from the atmosphere. The relevant land use encompasses more than forests and other living biomass. What happens to forests affects the release of carbon from the exposed soil, and so does what happens to unforested land through cultivation, erosion, and other disturbances or changes.

Category 2, removal of CO_2, shares with production the characteristic that it affects the global carbon inventory. Removal can be subdivided into processes that take CO_2 out of the atmosphere at large and those that "scrub" the CO_2 or otherwise remove it directly from the products of combustion, i.e., from stack gases and other exhausts. With respect to using photosynthesis and reforestation to reduce atmospheric CO_2 one conclusion is inescapable, irrespective of a hundred years' technological change: increasing the standing stock of trees can be no great part of any solution to the growing CO_2 problem. That does not mean that a strategy for the use of lands and forests should ignore CO_2, only that the role of trees, standing or fossilized, will be modest. "Scrubbing" from stacks and "washing" by the oceans offer the possibility of yielding to technological advance.

Category 3, modification of climate and weather, can be summarized in four points. (1) From study of CO_2 we know that, in principle, modification of climate and weather is feasible; the question is what kinds of advances in climate and weather modification will emerge over the coming century? (2) Interest in CO_2 may generate or reinforce a lasting interest in national and international means of climate and weather modification; once generated, that interest may flourish independently of whatever is done about CO_2. (3) Climate and weather modification may be more a source of international tension than a relief. (4) CO_2 may not dominate the subject of anthropogenic climate change as it does now; emission of, or reduction of emission of, non-CO_2 greenhouse gases may become increasingly important to policy on climate change.

Category 4, adaptation, policies, or actions taken in consequence of anticipated or experienced climatic change, will consist of a multitude of largely decentralized, unconnected actions. Adaptation can be undertaken by units of all sizes, families, firms, ministries and departments, cities, states, nations, and international organizations. Impacts of climatic change could, of course, be numerous and diverse, affecting agriculture and water supply, ecosystems, and location of industry, for example, and adaptive response could thus take numerous forms, from writing assessment reports (studying the problem), to developing markets for water and incentives for water conservation, to enlarging buffer stocks, to strengthening financial institutions (e.g., insurance), air conditioning and central heating, and educational and training activity. Qualitatively, the basic adaptive responses would seem to be learning new skills and relocation or migration (Meyer-Abich, 1980).

1.4.4 Reprise

Overall, we find in the CO_2 issue reason for concern, but not panic. Although the prospect of historically unprecedented climatic changes is troubling, the problems that may be associated with it are of quite uncertain magnitude, and both climate change and increased CO_2 may also bring benefits. There are theory and evidence for each link in the chain of causal inference that we have described, but it could be that emissions will be low, or that concentrations will rise slowly, or that climatic effects will be small, or that environmental and societal impacts will be mild. Thus, we make some tentative suggestions about actual and near-term changes of policies, firmer recommendations about applied research and development with regard to the possibility of a CO_2-induced climatic change, and strong recommendations about acquiring more knowledge of various aspects of the CO_2 question. In our judgment, the knowledge we can gain in coming years should be more beneficial than a lack of action will be damaging; a program of action without a program for learning could be costly and ineffective. In the words of one reviewer of the manuscript of this report, our recommendations call for "research, monitoring, vigilance, and an open mind."

1.5 RECOMMENDATIONS

1.5.1 Can CO_2 Be Addressed as an Isolated Issue?

Before discussing actions and policies, we raise the question of whether CO_2 should be treated jointly with other issues or as a separable, isolated issue.

If one chooses to isolate the CO_2 issue, it can be judged in basically two ways. One is the approach of welfare economics: to measure the potential costs of a CO_2 buildup against the potential costs of controlling CO_2 emissions (or other societal reponses). For example, Nordhaus (1980) has proposed an optimal control strategy for concentrations, in which strategies are judged by the effects they generate on paths of consumption. "Consumption" here is interpreted in a broad way, including not only conventional items, such as food, clothing, and shelter, but also intangibles, such as enjoying the environment. The purpose of economic policy--and CO_2 control--is to enhance total consumption to the greatest extent. The central result of an analysis along these lines at present is that, given current knowledge, we are highly uncertain about the appropriate direction and stringency of CO_2 controls. The key uncertainties in the analysis are (1) the economic and social impact of elevation of CO_2 concentrations, (2) the economic costs of controlling CO_2 emissions, and (3) the relevant value judgments (e.g., discount rates) that we should apply in weighing alternative paths. In this approach the best single investment strategy for coping with the CO_2 issue is more research.

A second approach that treats the CO_2 issue in isolation compares it with other areas in which societal investments might be made. Is CO_2 more or less important than nuclear war, or economic depression, or population growth, or drug addiction? If CO_2 comes out far down the agenda, the implication is that little or no investment, even of research, need be made in it. Meyer-Abich (1980) has argued that CO_2 is "chalk on a white wall" or a "particular darkness in the night." He proposes that the world already faces such serious problems of energy, agriculture, water, and land use that additional problems from climatic change will be trivial; CO_2 will be a marginal, probably negligible, factor.

If the significance of CO_2 is not isolated as an issue, the approach is to stress its ties to other social, economic, and environmental problems. For example, use of fossil fuels generates not only CO_2 but other problems for air and water quality. Deforestation creates not only CO_2 but problems of soil erosion. And, similarly, responses that might be useful with respect to CO_2-induced climatic changes--such as reducing water demand or increasing water supply in the Great Plains of the United States--might be appropriate responses to other problems, like depletion of the Ogallala Aquifer. Attitudes toward CO_2 may be different if one treats it jointly with other issues; policies judged expensive for one issue might seem more affordable as responses to a combination of issues. Advocates of action deriving from potential CO_2 problems generally rely on this argument. A single problem, like CO_2 or acid rain or soil erosion, may not weigh heavily in the cost-benefit calculus, but combinations of problems may weigh heavily indeed. It is the essence of the political process to come to terms with arrays of problems.

1.5.2 Actual and Near-Term Change of Policies

We recommend caution in undertaking any major changes in current behavior and policies solely on account of CO_2. It is probably wiser not to act aggressively to "solve the CO_2 problem" right now when we really do not know the future consequences or context of CO_2 increase. In trying to consider the world of 50 or 100 years from now, we cannot be sure that we can tell the difference between solutions and problems. It is instructive to look back at, say, 1905 to see if even the best guesses made at that time about accumulating world problems and their solutions were actually valid or useful as planning guides for the twentieth century. Life has changed since then in many unexpected ways; penicillin and air transport are vivid examples.

It is not easy to anticipate now what will appear as correct decisions with respect to CO_2 50 or 100 years hence. For example, we might anticipate that climatic warming in the north would permit seaborne commerce through the Northwest Passage. However, it is quite possible that transport will be so different in generations hence that surface ice cover in the Arctic will be largely irrelevant, and expenditures to develop Arctic transport as we can currently envision it would be wasteful.

Allowing for this general caution, we nevertheless recommend that activities and planning that involve long time scales (i.e., on the order of decades or more)--particularly concerning agriculture and water resources--explicitly incorporate the assumption that the climate of the future is unlikely to resemble the climate of the recent past. In fact, because of trace gases besides CO_2, future climate is likely to diverge increasingly from our recent climate whether we control CO_2 or not. Planners of hydroelectric or irrigation systems, agricultural infrastructure, forestry, hazardous-waste disposal, nature conservation, and other areas might ask whether current policies are vulnerable to climatic change and whether alternative policies can be designed that will both serve our needs and be robust in the face of climatic change.

The need to design and manage on the basis of likely future climates as well as past climates is probably greatest in the area of water resources. Experience has shown that the planning and construction of water-resource developments in major river basins can take several decades. It is not too soon to begin to think of ways in which the planned use of water could alleviate potential effects of climatic changes or even take advantage of them. Several possible measures come to mind: changes in legislation that would allow water to be transferred from one river basin to another; improved efficiency in the use of water for irrigation; conservation of waste water and of municipal water supplies; limitations on the size of irrigated areas; increases in crop yields per unit volume of applied water; and enhancement of the recharge of aquifers (Revelle, 1982).

In fact, greater efficiency in water use is a prudent goal to pursue even if we neglect CO_2 concerns. Opportunities for conservation of agricultural water through improved conveyance and farm distribution systems, application methods, scheduling, crop selection, and cropping practices are great. So, too, are the opportunities to halt and reverse the degradation of irrigated lands beset by waterlogging and salinization (White, 1983).

In fact, as Waggoner (this volume, Chapter 6) shows, we already know how to reduce greatly the harm of drought by storing more precipitation and getting more yield from the stored water. Fewer weeds and tillages decrease the loss of soil moisture, while more stubble captures more precipitation. Other means of increasing storage include barriers that catch snow, leveling and terracing to decrease runoff, and harvesting water from nearby acreage. Matching irrigation to need can decrease pumping; but if most of the former excess was returned to the groundwater supply, the saving of water will not be great. Getting more yield per acre increases the yield of marketable product per unit of water consumed. Changing to shorter growing-season crops can also increase water-use efficiency.

Concern about climatic changes may foster readjustments in agriculture and water management that will be beneficial in any event. For example, some of the same measures that would help us to prepare for a permanently drier average climate--such as encouragement of water conservation or provision of additional carry-over water storage--would make current agriculture and water use more resistant to passing droughts.

1.5.3 Energy Research and Policy

The major impetus to this report was concern about the projected impact on atmospheric CO_2 of fossil fuel combustion, coal conversion, and related synthetic fuels activities authorized in the Energy Security Act of 1980 (PL-96-294, Title VII, subtitle B, appended). During 1979 many scientists expressed concern that U.S. energy policy and its changing emphasis would exacerbate the CO_2 problem. They recommended, in part, conservation of fossil fuels and choice among fossil fuels and conversion processes based on CO_2 emissions, implying a bias against coal and carbon-based synthetic fuels.

Our study does not support the extent of concern expressed about the importance of decisions planned at that time about synthetic fuels in relation to the CO_2 issue (see the following section for more detail). Analysis of the contribution of various factors to uncertainty about future emissions of CO_2 shows that other factors besides the choice among fossil fuels are much more important in determining future emissions. If one wishes to reduce emissions through decisions relating to energy policy, placing a moratorium or limitation on development of synthetic fuels, especially in one country, even a large one like the United States, is likely to be a poor choice. By itself, shifting the fuel mix within fossil fuels is highly unlikely to achieve a reduction of CO_2 concentrations by more than a few parts per million by the year 2100, even if accomplished globally. A global policy banning carbon-based synfuels might lead to a reduction in CO_2 concentration of only 10-20 ppm by the year 2100, because of the large alternative supply of coal available. Suggestions that a near-term shift to carbon-based synfuels could advance the time of CO_2 doubling by decades are much exaggerated. Our study does, however, suggest that considerations of the ease of substitution between fossil and nonfossil fuels and between energy and labor inputs in the economy, along with extraction costs of fossil fuels, and the bias of technological change in the energy sector are of great importance in determining future emissions, which will account for considerable variance in atmospheric concentration over the next century.

Thus, we conclude that

1. The possibilities that concerns about the CO_2 issue will become more serious provide strong arguments for stimulating research on nonfossil energy sources. We may find that emissions are rising rapidly, that the fraction remaining airborne is high, that climate is very sensitive to CO_2 increase, or that the impacts of climate change are costly and divisive. In such a case, we want to have an enhanced ability to make a transition to nonfossil fuels.

2. The potential disruptions associated with CO_2-induced climatic change are sufficiently serious to make us lean away from fossil fuel energy options, if other things are equal. However, our current assessment of the probability of an alarming scenario justifies primarily increased monitoring and vigilance and not immediate action to curtail fossil fuel use.
3. Analysis of prospective CO_2 emissions does not offer a strong argument for making choices among particular patterns of fossil fuel use at this time.

It should be kept in mind that important uncertainties about future emissions stem from variables such as rates of productivity and population growth, as well as from decisions centered in the energy sector. Several of these variables that affect future emissions, like productivity growth, population growth, or technological change, strongly resist adjustment by policymakers.

1.5.4 Synfuels Policy and CO_2

By synfuels policy we refer to the development and use of new carbon-based fuels derived from fossil sources to replace a portion of the existing fuel mix. Synfuels would include oil and gas from coals and shales. At present, synfuels are a negligible part of world energy supply.

Overall, some skepticism is in order about the relation between the CO_2 issue and encouragement of synfuels. The causal links are complex and numerous; the direction of the effect is ambiguous; the importance of the effect has not been convincingly demonstrated. As suggested above, it would probably be more effective to address the issue of CO_2 emissions through policies other than the highly uncertain mechanism of slowing or speeding synfuels development.

Synfuels policy might be separated into three components:

1. Short-run emergency preparedness (for example, stockpiles or temporary surge capacity).
2. Tax or subsidy arrangements for research and development (R&D) on synfuels or for the use of synfuels.
3. Less specifically focused policies that might have an effect on synfuels and CO_2 emissions (mass transit, hydrogen R&D, nuclear- or solar-power policy).

A range of interactions can be envisaged between the different kinds of policies and CO_2. From short-run policies in one or a few nations, such as strategic stockpiles, there is unlikely to be significant impact on CO_2. More widespread, enduring tax and subsidy arrangements are likely to have more important effects on CO_2, but the impacts are not obvious. Of course, taxes on carbon-based fuels are the most predictable in their emission-reducing impact.

The most likely kind of synfuels policy is to encourage R&D and commercialization of synfuels; this was the major goal of the 1980 Energy

Security Act. An example of such a policy is an interest guarantee, which acts as an implicit subsidy to production and as a subsidy to learning about the technology. The effect of such a subsidy is subtle. If in fact the technology is viable, the subsidy will speed up its introduction, but it is unlikely to have a major impact on CO_2 emissions in the long run. If the technology is not viable, it will, like commercial supersonic transport, tend to disappear even with subsidies.

A second subtlety arises because the impact of early introduction of synfuels on CO_2 emissions is ambiguous and could either speed up or slow down CO_2 emissions. For example, if the price of the synfuel turns out to be high and the availability of other fuels is restricted, demand for energy may fall, and CO_2 emissions may decline. If, on the other hand, the new synfuel is attractive economically, it may lead to greater CO_2 emissions. Another ambiguity arises because the synfuel may replace either a carbon-based or noncarbon-based fuel. In the former case, it might have a small impact on CO_2 emissions; in the latter, a larger one. It is impossible to determine a priori the net effect of such influences, but using energy models might provide a range of answers.

Probably the most important determinant of the role of synfuels will be their interaction with other policies. Thus, a policy that encourages mass transit or solar energy could discourage carbon-based synfuels. A nuclear moratorium or heavy regulation of nuclear power could encourage synfuels. A stringent environmental policy, banning surface mining or growth in emissions of air pollutants, could discourage synfuels. These more subtle influences are probably important in determining CO_2 emissions from synfuels, more important than synfuels policy itself.

1.5.5 Applied Research and Development

The prospect of climate change clearly lends urgency to applied research and development in two areas besides energy: agriculture and water resources. Although no detailed timetable of climatic change is yet available, we have some notion of the general character of the climatic challenges that may be ahead of us. America is fortunate in possessing widespread and effective research networks in both agriculture and water resources. The tasks are to build and to maintain a strong and flexible national capability to adapt to changing climate and indeed to exploit new opportunities that changed climates may offer.

Modern agriculture possesses great flexibility and adaptability to change. For example, changing crops can be swift. And changing the variety of a crop by planting a different strain can be even swifter, because little in the process needs to be altered, from the dealer who supplies chemicals, to the farmer who must finance equipment, to the consumer who may be scarcely aware of the change. The question is whether breeders can develop new varieties to adapt to climate as fast as it changes. A complete breeding cycle is approximately a decade from the beginning of inbreeding to the marketing of a product; the objectives can be shifted during the first 5 years, and new hybrids emerging are those adapted to the final 3 years. Ideally, one would identify the critical environmental changes for a given crop and engineer appropriate genetic changes to cope with the new conditions. This process is as yet beyond our capabilities, but research may bring it within our grasp. In any event, there is ample reason to believe that steady work by plant breeders will continue to produce varieties of the life-sustaining major crops which are adapted to a changing environment.

There are also numerous avenues to pursue if there is less rainfall and runoff. White (1983) emphasized two sets of advanced techniques with potentially great impact and broad application: those relating to groundwater exploration and extraction and those relating to re-use of water. Improved seismic and geological surveys, well drilling, and pumping methods are opening up a huge volume of water previously ignored or inaccessible. Where this water exists in aquifers that are easily rechargable, it represents a potentially permanent addition to water supplies. White pointed out that the techniques have been of major importance in developing countries that can use them to gain access to previously untapped supplies without building elaborate storage and conveyance works. As a result of advances in treatment methods and in system planning, the re-use of water is also beginning to be viewed as a practical measure in both urban and agricultural settings. Other more tested alternatives deserve more widespread appraisal as well; these include water-pricing policies, leak detection, water-conserving devices, canal lining when seepage from the canal enters a saline-water aquifer, water application scheduling, drip irrigation, and choice of water-efficient or salt-tolerant crops.

Water technology needs to be developed complementary to changes in social and economic institutions. Research and activities should not focus exclusively on water control but on the combination of water development, land-use management, and economic and social adjustment.

1.5.6 Basic Research and Monitoring

The CO_2 issue involves virtually every branch of science and impinges on virtually every area of human activity. Whether motivated by concern for CO_2 or some other problem, or simply by scientific interest, research is in progress on nearly every identifiable topic that could contribute to our understanding. Research is funded by several federal agencies and coordinated through the National Climate Program and the lead agency for CO_2-related research, the Department of Energy (DOE). The DOE Carbon Dioxide Research and Assessment Program itself supports a broad program of investigation specifically aimed at the periodic development of detailed and comprehensive technical assessments drawing on the work of a large community. Indeed, in developing some portions of this report, we have worked closely with the DOE program and drawn on its participants, research results, and periodic coordination and review activities.

As we have emphasized throughout this report, the uncertainties regarding the CO_2 issue are numerous. Some areas of uncertainty are unlikely to diminish rapidly. The issue, and research directed at its illumination, will be with us for a long time. While we have tried to carry out some exemplary analyses in this report, we can propose no fresh and efficient route to the knowledge we would like to have. Rather than stress the need to attack any particular link in the CO_2 argument, we stress the need for balanced attention to the major components: emissions, concentrations, climate change, and environmental and social impacts and responses. A plethora of research recommendations exists, and several areas, for example, the carbon cycle and climatic effects, are being pursued with considerable vigor. Other areas may require more concentrated effort. For example, detection of the effects of increasing CO_2 may require better focus and increased interaction among climatologists, statisticians, investigators from several other disciplines, and those responsible for design and operation of monitoring programs. We offer several general comments about research with regard to CO_2 assessment before addressing specific subject areas.

1.5.6.1 General Research Comments

1. A broad, healthy program of basic research in the physical, biological, and social sciences is an indispensable foundation for our efforts to understand the CO_2 issue, which offers vivid evidence of the indivisibility of basic and applied research. The kinds of knowledge that we would like to have for analyzing the CO_2 issue--knowledge, for example, about the role of clouds and the ocean in the climate system or about the behavior of ice sheets--are unlikely to be produced on a procurement schedule defined by contracting agencies. While rates of learning appear to be rapid in most of the areas of concern for the CO_2 issue, fundamental, difficult questions are involved, and in some areas we simply do not know whether or when insights will be forthcoming.

2. The importance of geophysical and biospheric monitoring must be stressed. Over the past decade or so we have seen a series of climate-related issues become prominent and subjected to costly analysis. These include, for example, the Sahelian drought, the impacts of stratospheric flight on the ozone layer, and now CO_2. In each case, data bases are deficient, whether about the variability of climate in the Sahel, or on concentrations of gases in the stratosphere, or of carbon inventories, global temperatures, and CO_2 concentrations. With sound, stably supported, long-term geophysical and biospheric monitoring programs we can have the capability for dealing with such issues and with new ones that will undoubtedly arise in the future.

Certain kinds of routine data collection are both expensive and uninteresting and may not appeal to the most gifted scientists, yet their cumulative significance over time can be important. There is a problem of how to ensure that an adequate investment is made in this kind of data collection and that it is done well with methods that are validated by the most knowledgeable people. Historically, this kind of deficiency has been serious with respect to research programs in many environmental areas (Brooks, 1982).

3. More systematic setting of research priorities based on the relative contributions of various problems to the overall uncertainty of the CO_2 issue should be considered. For example, the sensitivity studies of Nordhaus and Yohe (this volume, Chapter 2, Section 2.1) and Machta (this volume, Chapter 3, Section 3.6) are suggestive about specific research priorities in certain areas. We cannot, it should be emphasized, move directly from estimates of sources of uncertainties to a budget allocation for research funds on CO_2. It may be easier, for example, to reduce uncertainties about the "depletion factor" for carbon fuels than about future "productivity growth," even though the latter appears to be a greater source of uncertainty. The problem is to provide incentives that will induce the most gifted researchers to shift to the most significant problems, i.e., to those areas contributing the most to uncertainties regarding future impact of CO_2. But these researchers must be convinced not only by the social importance of the problem but also by the perception of genuine scientific opportunities to contribute to its resolution.

4. The question of overall program balance in the CO_2 area also needs to be considered. We argued above that the way an issue is defined is fundamental to what research and policies are considered and that the main perspective here should probably be climate change, not simply CO_2. A CO_2 program geared heavily toward estimation of CO_2 concentrations and associated warming will probably be less useful than one with strong interests in, for example, other greenhouse gases, water resources, and sea-level rise, as well. Indeed, it may be wise for the government to anticipate the evolution of concern in this area into a broader program on human activities-greenhouse gases-climate change-adaptation.

5. Human-induced climatic change and the CO_2 issue more generally are not problems for which traditional paradigms of policy analysis and methods of assessment, like those taken from economics, engineering, and decision analysis, have had much success (Glantz et al., 1982). It is naive, indeed mistaken and misleading, to expect a "definitive" assessment of the CO_2 issue here, or from other groups or individuals in the foreseeable future. What is required is a sustained approach, probably no larger than the sum of efforts currently under way, which emphasizes carry over of learning from one effort to the next.

A healthy reaction to CO_2 would be one in which there is a steady production of knowledge, and in which every few years, either in the United States or in another country or in a combination of countries, developed or developing, east or west, some group undertakes a thoughtful synthesis. As we become generally better at global geophysical and biospheric modeling and at thinking one or two or more generations into the future, assessment of the CO_2 issue will deepen and strengthen. Each assessment must be regarded as part of an iterative process, consisting of efforts to assemble relevant knowledge, to assess the problem based on the assembled knowledge, to estimate the marginal value of additional knowledge to reduce uncertainties in the assessment, and to diffuse results to individuals and groups with power to act (Mar, 1982).

6. While the CO_2 issue remains--appropriately so, in our view--largely in the research community, it is important to consider the possibility that the issue may become prominent in political arenas. It is quite possible that, as a result of weather conditions or bad harvests in one part or another of the world, CO_2 will abruptly rise nearer to the top of many national and international agendas, regardless of the scientific basis for concern. How long it might hold such a position one can only speculate; most issues star for only a short while. And it is unlikely that prominence for one session of the United Nations or the United States Congress would bring about policy changes that would be of lasting importance with respect to CO_2. It is important that we fashion perspectives and programs that can be sustained through periods of excessive attention or inattention to the issue.

1.5.6.2 The International Aspect

Should it be desirable to control CO_2 emissions, it would be natural to suppose that they could be controlled in a way similar to conventional pollutants, but this supposition would be optimistic. Most externalities, or side effects of economic activity, are at least internal to nations; thus a government can weigh the costs and benefits of a control program and decide that, on balance, it is in the interests of its citizens. The CO_2 problem is different from conventional pollutants because it is an externality across so much space and time. Thus, just as we as individuals have little reason to curtail our emissions, we as a nation have little incentive to curb CO_2 emissions. By curbing our CO_2 output, we make little contribution to the solution and do not know whether we will receive any benefits. With respect to a CO_2-induced climate change, there is little incentive to act alone. The problem is exacerbated by the long time period over which CO_2 can affect our society and the environment. Although politicians may have one eye on posterity, political systems tend to be myopic and to emphasize short-term rewards.

Given the need for widespread, long-term commitment, a CO_2 control strategy could only work if major nations successfully negotiated a global policy. While such an outcome is possible, there are few examples where a multinational environmental pact has succeeded, the nuclear test ban treaty being the most prominent. Other clearly recognized problems--whale fisheries, acid rain, undersea mining, the ozone layer--emphasize how time on the order of decades is required to achieve even modest progress on international management strategies.

With regard to CO_2 increase, the multilateral bargaining is severely complicated by the likelihood that some major countries will probably <u>benefit</u>, at least from a moderate rise. For example, it is sometimes conjectured that the Soviet Union and Canada would benefit from a warmer climate. Given that these two countries (and the former's allies) burn 25% of world coal and hold a larger share of carbon resources in the ground, it is hard to see how a CO_2 control strategy can succeed without them. Given the unlikelihood that the United States or other western nations will compensate the Soviet Union for participating, it is hard to see why the Soviet Union would participate. If a major nation or group of nations does not participate, it is difficult to envisage others, particularly developing countries, making a major sacrifice. Thus, differences in the experience and expectations of nations pose major obstacles to any international agreement for control of CO_2.

While we may not be optimistic that agreement could ever be reached among nations about a control strategy for CO_2 (should such a control strategy be the desirable response in the first place), it is essential that research and dialogue about the CO_2 issue be carried on internationally. Study of world energy supply and demand inherently necessitates data from many countries, and a variety of national and international views of the energy situation is likely to enrich our analysis substantially. Study of the carbon cycle is also inherently global, and significant capability in this area, moreover, resides outside the United States. The atmosphere and oceans are similarly global, and in many countries there are strong research communities investigating them. Finally, monitoring--of the climate, the biosphere, the oceans--requires international participation. Exchange between nations and international collaboration should therefore be pursued extensively with respect to study of the CO_2 issue.

In addition, no matter how outstanding the analysis coming out of a particular country might be, other countries will always view individual national studies with suspicion. With a potentially divisive issue like CO_2, it is critical that assessments be undertaken independently by several nations, as well as by relatively neutral international groups. We commend the cooperation that has been initiated among the International Council of Scientific Unions, the World Meteorological Organization, and the United Nations Environment Program to prepare a careful assessment of the CO_2 issue during the next few years. The United States should contribute energetically to this effort from both governmental and nongovernmental communities concerned with studying and responding to the prospect of a CO_2-induced climate change.

It is worth noting that on particular issues, like detection of a CO_2-induced climatic change and evaluation of climate model results, there may be considerable efficiency in having an international focal point. Qualified individuals and groups from the United States should participate in support of such centers and assist where possible and appropriate in sharing, comparing, and analyzing findings on important questions. We note that in several areas--for example, biogeochemical cycles, atmospheric monitoring, and climate research--international programs and organizations have been functioning well.

In general, diffusion of sound information and calm, thoughtful anticipation of the future may be the best international insurance against poor decisions about possible control of CO_2 emissions, against possible adverse consequences of climatic change, and against the issue's becoming a source of major conflict. Indeed, if approached in a constructive manner, the CO_2 issue offers an opportunity to strengthen international cooperation and capabilities in many highly desirable respects. Vigorous efforts should be made to prevent CO_2 from becoming politically divisive; instead the nations of the world should seek to benefit from it as a catalyst for learning how to treat common problems effectively.

1.5.6.3 Projecting CO_2 Emissions

The current modeling and knowledge of future CO_2 emissions appears marginally adequate today; we have a general idea of likely future trends and the range of uncertainty. It may be that further effort could increase the accuracy of our forecasts substantially. Given the large uncertainty that future energy growth and energy projections are contributing to the CO_2 issue, this area may well merit more research attention and support than it has received in the past. Future research efforts might be designed with four points in mind.

1. In general, the most detailed and theoretically based projections of CO_2 emissions have been a spillover from work in other areas, particularly energy studies. This fact suggests that continued support of energy modeling efforts will be of importance in pushing out the frontier of knowledge about future CO_2 emissions, as well as the interaction between possible CO_2 controls and the economy.
2. We have identified a serious deficiency in the support of long-run economic and energy models in the United States. There is not one U.S. long-range global energy or economic model that is being developed and constantly maintained, updated with documentation, and made usable to a wide variety of groups. This shortcoming is in contrast to climate or carbon-cycle models, where several models receive long-term support, are periodically updated, and can be used by outside groups. Another contrast is with short-run economic models, which are too plentiful to enumerate.
3. Most CO_2 projections have been primitive from a methodological point of view. Work on projecting CO_2 emissions has not drawn sufficiently on existing work in statistics, econometrics, or decision theory. There has been little attention to uncertainties and probabilities. Also, considerable confusion of normative and positive approaches exists in modeling of CO_2 emissions.
4. Application of models for analysis of policies, where there are, for example, feedbacks to the economy from climatic change or CO_2 control strategies, is just beginning. Efforts to evaluate the effectiveness for CO_2 control of energy policies of particular nations or groups of nations in a globally consistent framework have been lacking.

1.5.6.4 Projecting CO_2 Concentrations

Projecting CO_2 concentrations consists essentially of the application of our knowledge of the carbon cycle to projections of CO_2 emissions.

After more than a decade of intense research, findings on the roles of the different reservoirs of carbon, particularly the biosphere and the oceans, remain in obvious, unresolved conflict. Efforts to improve our understanding of the carbon cycle are desirable for many reasons, and monitoring of carbon in its various forms must be maintained and in some cases expanded. However, examination of uncertainties in the CO_2 issue introduced by different factors suggests that uncertainty about the airborne fraction is of less significance for the overall CO_2 issue than the extensive discussion in the CO_2 literature would suggest. Questions that may merit more attention in the carbon cycle area include the history of CO_2 concentrations and the future behavior of the oceans and biosphere beneath a high-CO_2 atmosphere.

With respect to the biosphere, surveys, field experiments, and dynamic models will be the means to achieve insights into the responses of the biota to increasing CO_2 concentrations and changing climate. To provide a better basis for this work, inventories of carbon in the biosphere should be improved; satellite surveillance may be particularly helpful in strengthening the empirical basis of biospheric research and in assessing biospheric changes on a regular basis. Clarifying the history of the size of the biotic pool over the past century is also useful; it may help corroborate data on the preindustrial concentration, reduce uncertainty about the fraction of emissions remaining airborne, and provide a check on the quality of carbon-cycle models.

Historical and geological data on CO_2 from records of the past such as ice cores have proven to be valuable, and an expanded effort to confirm and refine previous findings should be undertaken. Recent ice-core data have placed new constraints on what the atmospheric CO_2 levels could have been in past centuries. Isotopic studies of tree rings, lake sediments, and current air samples offer the potential to elucidate further the history and fate of atmospheric CO_2.

With respect to the atmosphere, the need to continue high-precision observations cannot be overemphasized. The atmospheric CO_2 data provide information beyond simple evidence that atmospheric CO_2 is increasing. Through careful measurements, one is able to derive valuable information from the temporal and spatial variability of CO_2. For example, the pattern of results so far is suggestive of a minimal contribution from sources of CO_2 other than fossil fuel over the past couple of decades or even that the biota are a net sink for CO_2, although the limited quantity of the data (and the possibility of alternative explanations) prevent any definitive statement today that excludes nonfossil fuel sources.

With respect to the oceans, it now appears to be quite possible to measure the changing CO_2 properties of the ocean over time by using modern techniques, though no ongoing program yet exists to do so. Previous programs have provided regional coverage in different years and seasons. We recommend initiation of a program with more consistency in space and time. Until quite recently, oceanic CO_2 system measurements contained substantial inaccuracies.

Although many oceanographers believe that current methods appear satisfactory to answer approximately the question of how much CO_2 the sea takes up, there is room for improvement. Models of ocean CO_2 uptake have depended greatly on tracer data, particularly natural and bomb-produced ^{14}C, tritium, and, more recently, halogenated hydrocarbons. Typically, these models represent some features of ocean chemistry quite well, even though they represent vertical transport by a simple diffusion coefficient. The models treat only the CO_2 perturbation and do not yet adequately mimic the natural and complex CO_2-oxygen nutrient biogeochemical cycles within the ocean. As our ocean data base grows, the current generation of one-dimensional models will become increasingly inadequate, and incorporation of the CO_2 and tracer data into new models will be required. Warming accompanying atmospheric CO_2 rise will also affect the ocean. Storage of heat in the upper layers will postpone, but not prevent, climate change. Models of this heat storage generally treat it as passive uptake, not affecting water mass formation and vertical circulation. If changes occur in ocean transport and dynamics, they may affect ocean CO_2 uptake in significant ways. For example, changes in formation of oceanic bottom waters in high latitudes may affect the rate of transfer of dissolved CO_2 to the deep ocean. Progress in incorporating such processes and features into more advanced ocean models is anticipated and should be encouraged. Such models will require complex global measurements from ocean research ships, ocean-scanning satellites, and other sources.

With respect to the methane hydrate clathrates, we recommend further consideration of the probable effects of a rise in ocean-bottom temperatures on the stability of the clathrates. We also recommend a sediment sampling program on continental slopes to determine the depth, thickness, and distribution of methane hydrate clathrates, especially where oceanfloor temperatures and depths are such that methane release is possible from ocean warming during the next century.

Finally, more attention should be given to interactions among the biogeochemical cycles of carbon, sulfur, nitrogen, and phosphorus (Bolin et al., 1983). These interactions may offer another example of an area where there are important, as yet unforeseen, feedbacks. To illustrate, lower atmospheric CO_2 concentrations 10,000 to 20,000 years ago may have resulted from changes in oceanic biologic production, perhaps related to larger quantities of ocean nitrogen and phosphate.

1.5.6.5 Climate

The width of the range of projections associated with a given CO_2 increase and the desire for more detailed information on prospective climate change warrant continuing support for climate research. Special attention should be given to the role of the oceans and clouds, model comparison and validation, extremes, and non-CO_2 greenhouse gases.

The heat capacity of the upper ocean is potentially great enough to delay by decades the response of climate to increasing atmospheric CO_2, as modeled without it; and the lagging ocean thermal response may cause important regional differences in climatic response to increasing CO_2. The role of the ocean in time-dependent climatic response deserves special attention in future modeling studies, stressing the regional nature of oceanic thermal inertia and atmospheric energy-transfer mechanisms. Progress in understanding the ocean's role must be based on a broad program of research and ocean monitoring. Particular attention should be paid to improving estimates of mixing time scales in the main thermocline.

Cloud amounts, heights, optical properties, and structure may be influenced by CO_2-induced climatic changes. In view of the uncertainties in our knowledge of cloud parameters and the crudeness of cloud prediction schemes in existing climate models, it is premature to draw conclusions regarding the influence of clouds on climate sensitivity to increased CO_2, particularly on a regional basis. Empirical approaches, including satellite-observed radiation budget data, are an important means of studying the cloudiness-radiation problem, and they should be pursued.

Simplified models permit economically feasible analyses over a wide range of conditions. Although they can provide only limited information on local or regional effects, simplified models are valuable for focusing and interpreting studies performed with more complete and realistic models.

In addition to improvement and validation of models, we recommend more research into the question of statistical properties of a warmer, CO_2-enriched atmosphere. Particular attention should be given to possible changes in the character and frequency of extreme conditions and to severe storms. Variance studies with general circulation models (GCMs) are one potentially useful approach. Insights into the question of extremes may also be obtained from research in other fields, such as hydrology.

With respect to non-CO_2 greenhouse gases, improved, sustained monitoring is called for. Available instrumentation and methods are probably sufficient for high-quality data collection.

Equally important is the goal of obtaining an understanding of the mechanisms by which the gases increase. For the chlorofluorocarbons and several other potentially significant trace gases, only industrial production statistics are needed to establish annual emissions. For CH_4 and N_2O, biological sources probably dominate. Microbial processes in soils, water bodies, and living organisms produce and release these gases and a number of others. (Release of CH_4 and higher hydrocarbons from clathrates may become significant in the future.) Key sites for emissions and processes have been identified, but a variety of field and laboratory measurements requires implementation. Similarly, there is need for more elucidation of the mechanisms that control levels of ozone in the troposphere, where increases of ozone can have a warming effect. Interactions among the gases and with changing climate must be considered.

There is also need to make careful new projections of future emissions of non-CO_2 greenhouse gases. Projections of future emissions of these non-CO_2 gases are generally at a more primitive stage than are CO_2 projections. Projections have typically been derived from simple assumptions of linear increase or exponential growth based on a short segment of recent years. The times in the future vary to which the relevant studies of agricultural production, smelting, industrial use of chemicals, and other activities extend, and the assumptions employed vary as well. It would be desirable to have studies of the greenhouse effect that use assumptions consistently in generating both CO_2 emissions and emissions of other infrared-absorbing trace gases. In human activities--like those relating to emissions of the chlorofluorocarbons--where rapid technological change is occurring and where less inertia is imposed by a large and expensive capital stock than in the energy system, projections for several decades are especially hazardous.

The spectroscopic parameters of several of these gases are not well known, and even the band strengths of some have not been measured. The spectral transmittance and total band absorptions also need to be more closely determined. These improvements will help in developing more accurate radiative-transfer models and in answering questions about band overlap between constituents and with water vapor. Such information is needed for defining more accurate parameters in climate models.

1.5.6.6 Detection and Monitoring

In view of the importance of verifying the theoretical results about climatic effects of CO_2, a careful, well-designed program of monitoring and analysis must proceed. The information obtained will help us not only in detecting CO_2-induced changes as early as possible but in improving, validating, and calibrating the climate models employed for prediction of future changes.

If, as expected, the CO_2 signal gradually increases in the future, then the likelihood of perceiving it with an appropriate degree of statistical significance will increase. Given the inertia created by the ocean thermal capacity and the level of natural fluctuations, we expect that achieving statistical confirmation of the CO_2-induced contribution to global temperature changes so as to narrow substantially the range of acceptable model estimates may require an extended period. Improvements in climatic monitoring and modeling and in our historic data bases for changes in CO_2, solar radiance, atmospheric turbidity, and other factors may, however, make it possible to account for climatic effects with less uncertainty and thus to detect a CO_2 signal at an earlier time and with greater confidence.

A complicating factor of increasing importance will be the role of rising concentrations of greenhouse gases other than CO_2. While the role of these gases in altering climate may have been negligible up to the present, their significance is likely to grow. It will be difficult to distinguish between the climatic effects of CO_2 and those of other radiatively active trace gases. Their expected relative contributions to climatic change will have to be inferred from model calculations and precise monitoring of radiation fluxes.

A monitoring strategy should focus on parameters expected to respond strongly to changes in CO_2 (and other greenhouse gases) and on other factors that may influence climate. Candidate parameters may be identified, their variability estimated, and their evolution through time predicted by means of climate model simulations. Through analysis of past data, continued monitoring, and a combination of careful statistical analysis and physical reasoning, the effects of CO_2 may eventually be discerned.

Monitoring parameters should include not only data on the CO_2 forcing and the expected climate system responses but also data on other external factors that may influence climate and obscure CO_2 influences. Climate modeling and monitoring studies already accomplished provide considerable background for the selection of these parameters. Since fairly distinct climate changes are expected to become evident only over one or more decades, monitoring for both early detection and more rapid model improvement should be carried out for an extended period. Parameters may be selected for early emphasis on the basis of the following criteria:

1. Sensitivity. How do the effects exerted on climate by the variables or the changes experienced by the variables on decadal time scales compare with those associated with corresponding changes in CO_2?
2. Response characteristics. Are changes likely to be rapid enough to be detectable in a few decades?
3. Signal-to-noise ratio. Are the relevant changes sufficiently greater than the statistical variability to be measured accurately?
4. Past data base. Are data on the past behavior of the variable adequate for determining its natural variability?
5. Spatial coverage and resolution of required measurements.
6. Required frequency of measurements.
7. Feasibility of technical systems. Can we make the required measurements?

Initial application of these criteria leads to this list of recommended variables for monitoring:

Monitoring Causal Factors by Measuring Changes in	Monitoring Climatic Effects by Measuring Changes in
CO_2 concentrations	Troposphere/surface temperatures (including sea temperatures)
Volcanic aerosols	Stratospheric temperatures
Solar radiance	Radiation fluxes at the top of the atmosphere
"Greenhouse" gases other than CO_2	Precipitable water content (and clouds)
Stratospheric and tropospheric ozone	Snow and sea-ice covers
	Polar ice-sheet mass balance
	Sea level

In the above list, evaluated more thoroughly in Chapter 5, emphasis has been given to parameters that may contribute, either directly or through model improvements, to detection of CO_2 effects at the earliest possible time. Over the long run, it is important to build up a relatively complete data base of possible causes and effects of climate change and characteristics of climate variability, not simply for detection but to assist in research on and calibration of models of the climate system. Once we become convinced that climate changes are indeed under way, we will seek to predict their future evolution with increasing urgency and with increasing emphasis on parameters of societal importance (e.g., sea level and rainfall). We should thus anticipate that a detection program will gradually evolve into a more comprehensive geophysical monitoring and prediction program. It should be emphasized that the strategy proposed here is a simple tentative step in what must be an iterative process of measurement and study.

Collection of the desired observations will require a healthy global observing system, of which satellites will be a major component. Satellites can provide or contribute to long-term global measurements of radiative fluxes, planetary albedo, snow/ice extent, ocean and atmospheric temperatures, atmospheric water content, polar ice-sheet volume, sea level, aerosols, ozone, and trace atmospheric components; a well-designed and stable program of space-based environmental observation is essential if we are to monitor the state of our climate. Requirements and technical systems for monitoring high-priority CO_2 variables are summarized in Table 5.1.

We will also have to continue to improve climate models to reduce the uncertainties in predictions of climate effects and to validate the models against observations, although we believe that current climate models are sufficiently sound and detailed to enable us to identify a set of variables that could form the basis for an initial monitoring strategy. Statistical techniques for assessing the significance of observed changes may have to be improved so as to deal with the characteristics of the monitored variables. In the end, confidence that we have detected the effect of CO_2 will have to rest on a combination of both statistical testing and physical reasoning.

1.5.6.7 Impacts

1.5.6.7.1 Sea Level and Antarctica

With respect to sea-level rise, we recommend research to confirm the estimate of a possible 70-cm rise over the next century (Revelle, this volume, Chapter 8) and to explore the implications of a variety of other more gradual and more rapid rates of warming for sea-level rise. High priority should also be given to strengthening our understanding of the possibilities of disintegration of the WAIS and the rate at which this might occur. One promising approach to these questions is through examination of the morphology of reef corals at different depths in terraces formed during the last interglacial period about 125,000 years ago, when the ice mass in question may previously have disappeared.

Other studies and monitoring programs should also be undertaken. In doing so, five problems deserve special emphasis: possible changes in the mass balance of the Antarctic Ice Sheet; interaction between the Ross and Filchner-Ronne ice shelves and adjacent ocean waters; ice-stream velocities and mass transport into the Amundsen Sea from Pine Island and Thwaites Glaciers; modeling of the ice-sheet response to CO_2-induced climate change; and deep coring of the West Antarctic Ice Sheet to learn whether it did in fact disappear 125,000 years ago.

1.5.6.7.2 The Arctic Environment

A number of research efforts should bring progress in understanding effects of a greenhouse warming on the Arctic. Specifically, efforts should be made to

1. Improve GCMs and other models (sea ice, Arctic stratus, ocean dynamics, radiation balance, for example) and use them in studies focused on Arctic response. Proper handling of cloud cover in the Arctic merits special attention as do sensitivity studies using improved sea-ice models.
2. Study stability of the Arctic Ocean density stratification and the potential for its destruction.
3. Obtain long central Arctic sediment cores that could improve the record of variations in the Arctic Ocean for the period from 10,000 to 15,000,000 years ago.

1.5.6.7.3 Agriculture

Basic research on agriculture in relation to CO_2 assessment falls into two broad categories: (1) effects of CO_2 on photosynthesis and plant growth and (2) predicting the changes in yield that will follow a change to a warmer, drier (or other forecast) climate. With respect to the first category, research should be pursued in five obviously related areas: rate of photosynthesis, duration of photosynthesis, and fate and partitioning of photosynthate; drought and transpiration; relationship of increasing CO_2 to demand for and availability of nitrogen and other nutrients; phenology; and weeds. With respect to the second category, the relationship of climate to agriculture should be explored through both historical (e.g., regression) studies and through simulation. A difficult area that deserves consideration is the relationship of changing climate to insect pests and pathogens. Finally, attention should be given to analyzing effects of concurrent changes in climate and atmospheric composition on agriculture, as we make progress on the individual aspects. While our assessment is that near-term effects of CO_2 and climate change on U.S. agriculture will be modest, the evaluation needs to be extended to other regions and, if sound methods are available, to more distant times.

1.5.6.7.4 Ecosystem Response

The response of ecosystems to projected atmospheric conditions remains largely unexplored. Research is called for on ecosystem character and net ecosystem production in relation to increasing atmospheric CO_2 and climatic change. While there is accumulating evidence of effects of increasing CO_2 in increasing the growth of well-watered, fertilized plants, there is a question as to whether these effects extend to natural communities. The question arises particularly with respect to forests, where plants live in conditions of extreme competition for light, water, nutrients, space, and, probably, CO_2 during daylight. The question of redistributing forests with respect to climate change also needs to be addressed. Effects of increasing temperature on respiration of plants have received inadequate attention; by comparison, effects of other factors on respiration may be small. Finally, distribution of ecosystems over the globe induced by CO_2 and climate change may also affect global distribution of albedo; this relationship and its feedback to climate should be explored.

1.5.6.7.5 Water Resources

There is need to develop further the conceptual basis of analysis for all river basins; but the relationships between climate and water resources are complex and unique to each river basin, so that basin-by-basin studies are also needed. Priority should be given to regions with large commitments to irrigated agriculture and for basins where scanty or overabundant flow is already a problem. The roles of extreme events and interannual variability should be kept in mind. More specifically research and analysis is needed on

1. Relations among temperature, rainfall, runoff, and groundwater recharge rates; relations during past decadal or longer climatic excursions may be indicative of future possibilities.
2. Regional, seasonal, and interannual characteristics (including extremes) of rainfall and evaporation that might occur with a greenhouse warming.
3. Societal response to variations in water supply of different duration; water management, especially rates of development of water-resource systems and institutional change.
4. Geomorphologic changes during the last 5000 years from the perspective of changes in water regime.

1.5.6.7.6 Human Health

The need for research relating rising CO_2 concentrations to possible effects on human health arises primarily from a lack of biological data from which it would be possible to project thresholds of CO_2 concentrations hazardous over long periods of time. We know that high doses, 5000 ppm, for example, have measurable effects. There is evidence that levels approachable as a result of the activities discussed in this report will never be dangerous (Clark et al., 1982, p. 43, fn. 56). However, the literature and supporting experimentation in the area are scant (U.S. Department of Energy, 1982). Given the continuing difficulty of identifying health effects of much less subtle changes in the atmosphere, we are skeptical about whether meaningful or interpretable results could be available soon in this area and whether the research would be cost effective. However, it does deserve further consideration. The area of heat stress under climatic conditions and the relationship of climate to disease and disease vectors is less difficult and also merits attention.

1.6 CONCLUDING REMARKS

The CO_2 issue has been with us for over a century, and impacts of increasing CO_2 will be experienced in the century to come. Buildup of CO_2 in the atmosphere is one of many issues arising from our growth in numbers and power on a planet of finite size and limited--though large--resources. Indeed, an argument for continuing attention to the CO_2 issue is that it reminds us of the need to solve intellectual and societal problems, which are important to solve for other, perhaps more immediate, reasons. The skills called for to provide better analysis of and response to the CO_2 issue are similar to the skills we would like to have to tackle other problems. With more insight into the long-term evolution of the economy and technology, the carbon cycle, the oceans and the atmosphere and the ice, the responses of agriculture and ecosystems to environmental change, and why systems and societies collapse or adapt well, and with more extensive cooperation among the carbon-rich nations, many other problems besides CO_2 might yield to solution. The CO_2 issue has proven to be a stimulus to communication across academic disciplines and to cooperation among scientists of many nations. While it may be a worrisome issue for mankind, it is in some respects a healthy issue for science and for people. It is conceivable that CO_2 could serve as a stimulus not only for the integration of the sciences but for increasingly effective cooperative treatment of world issues.

REFERENCES

Augustsson, T., and V. Ramanathan (1977). A radiative-convective model study of the CO_2 climate problem. J. Atmos. Sci. 34:448-451.

Baumgartner, A. (1979). Climatic variability and forestry. In Proceedings of the World Climate Conference. World Meteorological Organization, Geneva, Switzerland.

Bentley, C. R. (1983). The West Antarctic Ice Sheet: diagnosis and prognosis. In Carbon Dioxide, Science and Consensus. Proceedings: Carbon Dioxide Research Conference, Sept. 19-23, 1983. Dept. of Energy CONF-820970, NTIS, Springfield, Va.

Bolin, B., P. J. Crutzen, P. M. Vitousek, R. G. Woodmansee, E. D. Goldberg, and R. B. Cook (1983). The Biogeochemical Cycles and Their Interactions. SCOPE 24. Wiley, New York.

Brooks, H. (1982). Science indicators and science priorities. Science, Technology, and Human Values 7:14-31.

Cess, R. D. (1978). Biosphere-albedo feedback and climate modeling. J. Atmos. Sci. 35:1765.

Chan, Y.-H., J. Olson, and W. Emanuel (1980). Land use and energy scenarios affecting the global carbon cycle. Environ. Internat. 4:189-206.

Charney, J. (1979). Carbon Dioxide and Climate: A Scientific Assessment. Report of the Ad Hoc Study Group on Carbon Dioxide and Climate, J. Charney, chairman. National Research Council, National Academy Press, Washington, D.C.

Clark, W. C., ed. (1982). Carbon Dioxide Review: 1982. Oxford U. Press, New York.

Clark, W. C., K. H. Cook, G. Marland, A. M. Weinberg, R. M. Rotty, P. R. Bell, L. J. Allison, and C. L. Cooper (1982). The carbon dioxide question: a perspective for 1982. In Carbon Dioxide Review: 1982, W. C. Clark, ed. Oxford U. Press, New York.

Donner, L., and V. Ramanathan (1980). Methane and nitrous oxide: their effect on the terrestrial climate. J. Atmos. Sci. 37:119-124.

Edmonds, J. A., and J. M. Reilly (1983). Global energy and CO_2 to the year 2050. Institute for Energy Analysis, Oak Ridge, Tenn. Submitted to the Energy Journal.

Elliott, W. P. (1983). A note on the historical industrial production of carbon dioxide. Clim. Change 5:141-144.

Exxon Corporation (1980). World Energy Outlook. Exxon Corp., New York, December.

Fishman, J., V. Ramanathan, P. Crutzen, and S. Liu (1979). Tropospheric ozone and climate. Nature 282:818-820.

Flohn, H. (1982). Climate change and an ice-free Arctic Ocean. In Carbon Dioxide Review: 1982, W. C. Clark, ed. Oxford U. Press, New York, pp. 145-177.

Gates, W. L., ed. (1979). Report of the JOC Study Conference on Climate Models: Performance, Intercomparison and Sensitivity Studies, Vols. I and II. GARP Publ. Ser. No. 22. Joint Planning Staff, Global Atmospheric Research Programme, World Meteorological Organization, Geneva, Switzerland, 1049 pp.

Gifford, R. M. (1979). Growth and yield of CO_2-enriched wheat under water-limited conditions. Aust. J. Plant Physiol. 6:367-378.

Gifford, R. M., P. M. Bremner, and D. B. Jones (1973). Assessing photosynthetic limitation to grain yield in a field crop. Aust. J. Agric. Res. 24:297-307.

Glantz, M. H., J. Robinson, and M. E. Krenz (1982). Climate-related impact studies: a review of past experiences. In Carbon Dioxide Review: 1982, W. C. Clark, ed. Oxford U. Press, New York, pp. 57-93.

Hameed, S., R. Cess, and J. Hogan (1980). Response of the global climate to changes in atmospheric composition due to fossil fuel burning. J. Geophys. Res. 85:7537-7545.

Hanel, R. A., B. J. Conrath, V. G. Kunde, C. Prabhakara, I. Revah, V. V. Salomonson, and G. Wolford (1972). The Nimbus 4 infrared spectroscopy experiment, 1. Calibrated thermal emission spectra. J. Geophys. Res. 11:2629-2641.

Hansen, J., D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind, and G. Russell (1981). Climate impact of increasing atmospheric carbon dioxide. Science 213:957.

Hardman, L. E., and W. A. Brun (1971). Effect of atmospheric CO_2 enrichment at different developmental stages on growth and yield components of soybeans. Crop. Sci. 11:886-888.

Hummel, J. R., and R. A. Reck (1981). The direct thermal effect of $CHClF_2$, CH_3CCl_3 and CH_2Cl_2 on atmospheric surface temperatures. Atmos. Environ. 15:379-382.

Interfutures Project (1979). Facing the Future. Organization for Economic Cooperation and Development (OECD), Paris.

International Institute for Applied Systems Analysis (1981). Energy in a Finite World: A Global Systems Analysis. Ballinger, Cambridge, Mass.

Jensen, M. E. (1982). Overview-irrigation in U.S. arid and semiarid lands. Prepared for the Office of Technology Assessment, Water-Related Technologies for Sustaining Agriculture in Arid and Semiarid Lands.

Jones, P. D. (1981). Summary of climatic events during 1981. Clim. Mon. 10:113-114.

Jones, P. D., and T. M. L. Wigley (1980). Northern hemisphere temperatures, 1881-1979. Climate Monitor 9:43-47.

Keeling, C. D., and R. B. Bacastow (1977). Impact of industrial gases on climate. In Energy and Climate. Geophysics Study Committee, National Research Council, National Academy Press, Washington, D.C.

Langbein, W. B., et al. (1949). Annual Runoff in the United States. U.S. Geological Survey Circular 5. U.S. Dept. of the Interior, Washington, D.C. (reprinted, 1959).

Lorenz, E. N. (1970). Climatic change as a mathematical problem. J. Appl. Meteorol. 9(3):325-329.

Luther, F. M., and M. C. MacCracken (1983). Empirical Development of a Climate Response Function: An Analysis of the Propositions of Sherwood B. Idso. Report UCID-19792 (draft). Lawrence Livermore Laboratory, Livermore, Calif., March 1983, 56 pp.

Mar, B. (1982). Commentary. In Carbon Dioxide Review: 1982, W. C. Clark, ed. Oxford U. Press, New York, pp. 96-98.

Marchetti, C. (1980). On energy systems in historical perspective. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Marchetti, C., and N. Nakicenovic (1979). The dynamics of energy systems and the logistic substitution model. RR-79-13. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Marland, G., and R. M. Rotty (1983). Carbon dioxide emissions from fossil fuels: a procedure for estimation and results for 1950-1981. DOE/NBB-0036. NTIS, Springfield, Va.

Matthews, S. W. (1976). What's happening to our climate? Nat. Geographic Mag. 150:576-615.

Mauney, J. R., K. E. Fry, and G. Guinn (1978). Relationship of photosynthetic rate to growth and fruiting of cotton, soybean, sorghum, and sunflower. Crop Sci. 18:259-263.

Mercer, J. H. (1978). West Antarctic Ice Sheet and CO_2 greenhouse effect: a threat of disaster. Nature 271:321-325 (January 1978).

Meyer-Abich (1980). Chalk on the white wall: on the transformation of climatological facts into political facts. In Climatic Constraints and Human Activities, J. Ausubel and A. K. Biswas, eds. Pergamon Press, Oxford.

Mitchell, J. M. (1979). Some considerations of climatic variability in the context of future CO_2 effects on global-scale climate. In Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels, W. P. Elliott and L. Machta, eds. CONF-770385. U.S. Dept. of Energy, Washington, D.C., pp. 91-99.

Nakicenovic, N. (1979). Software Package for the Logistic Substitution Model. Report RR-79-12. International Institute for Applied Systems Analysis, Laxenburg, Austria.

National Research Council (1975). Understanding Climatic Change: A Program for Action. Report of the U.S. Committee for the Global Atmospheric Research Program. National Academy of Sciences, Washington, D.C., 239 pp.

National Research Council (1982). Carbon Dioxide and Climate: A Second Assessment. Report of the CO_2/Climate Review Panel, J. Smagorinsky, chairman. National Academy Press, Washington, D.C.

Niehaus, F., and J. Williams (1979). Studies of different energy strategies in terms of their effects on the atmospheric CO_2 concentration. J. Geophys. Res. 84:3123-3129.

Nordhaus, W. D. (1977). Strategies for the control of carbon dioxide. Cowles Foundation Discussion Paper No. 443. Yale U., New Haven, Conn.

Nordhaus, W. D. (1980). Thinking about carbon dioxide: theoretical and empirical aspects of optimal control strategies. Cowles Foundation Discussion Paper No. 565. Yale U., New Haven, Conn.

Olson, J. S., and J. A. Watts (1982). Carbon in land vegetation. In Carbon Dioxide Review: 1982, W. C. Clark, ed. Oxford U. Press, New York, pp. 435-437.

Paltridge, G. W., and C. M. R. Platt (1976). Radiative Processes in Meteorology and Climatology. Elsevier, New York, 318 pp.

Perry, H., and H. H. Landsberg (1977). Projected world energy consumption. In Energy and Climate. Geophysics Study Committee, National Academy of Sciences, Washington, D.C.

Ramanathan, V. (1975). Greenhouse effect due to chlorofluorocarbons: climatic implications. Science 190:50-52.

Revelle, R. R. (1982). Carbon dioxide and world climate. Sci. Am. 247(2):36-43.

Revelle, R., and W. Munk (1977). The carbon dioxide cycle and the biosphere. In Energy and Climate. Geophysics Study Committee, National Research Council, National Academy of Sciences, Washington, D.C.

Rotty, R. (1977). Present and future production of CO_2 from fossil fuels. ORAU/IEA(O)-77-15. Institute for Energy Analysis, Oak Ridge, Tenn.

Rotty, R., and G. Marland (1980). Constraints on fossil fuel use. In Interactions of Energy and Climate, W. Bach, J. Pankrath, and J. Williams, eds. Reidel, Doredrecht, pp. 191-212.

Schilling, H. D., and R. Hildebrandt (1977). Primärenergie-Elektrische Energie. Clückauf, Essen, FRG.

Schneider, S. H., and R. E. Dickinson (1974). Climate modeling. Rev. Geophys. Space Phys. 12:447-493.

Sioli, H. (1973). Recent human activities in the Brazilian Amazon region. In Tropical Forest Ecosystems in Africa and South America, B. J. Meggers et al., eds. Smithsonian Institution, Washington, D.C.

Sionit, N., H. Helmers, and B. R. Strain (1980). Growth and yield of wheat under CO_2 enrichment and water stress. Crop Sci. 20:687-690.

Sionit, N., D. A. Mortensen, B. R. Strain, and H. Helmers (1981). Growth response of wheat to CO_2 enrichment and different levels of mineral nutrition. Agron. J. 74:1023-1027.

Stewart, H. (1981). Transitional Energy Policy 1980-2030. Pergamon, Oxford.

Stockton, C. W., and W. R. Boggess (1979). Geohydrological implications of climate change on water resource development. U.S. Army Coastal Engineering Research Center, Fort Belvoir, Va.

Takahashi, T., D. Chipman, and T. Volk (1983). Geographical, seasonal, and secular variations of the partial pressure of CO_2 in surface waters of the North Atlantic Ocean: the results of the North Atlantic TTO Program. In Proceedings: Carbon Dioxide Research Conference: Carbon Dioxide, Science and Consensus. U.S. Dept. of Energy Report CONF 820970, Part II, pp. 123-145.

U.S. Committee for the Global Atmospheric Research Program (1975). Understanding Climatic Change: A Program for Action. National Academy of Sciences, Washington, D.C., 239 pp.

U.S. Department of Energy (1982). Effects of CO_2 on mammalian organisms. Report of a workshop, June 5-6, 1980, Bethesda, Maryland. CONF-8006249. NTIS, Springfield, Va.

U.S. Water Resources Council (1978). The Nation's Water Resources, The Second National Water Assessment. U.S. Govt. Printing Office, Washington, D.C.

Vinnikov, K. Ya., G. V. Gruza, V. F. Zakharov, A. A. Kirillov, N. P. Kovyneva, and E. Ya. Ran'kova (1980). Current climatic changes in the northern hemispere. Sov. Meteorol. Hydrol. 6:1-10.

Wang, W. C., and P. H. Stone (1980). Effect of ice-albedo feedback on global sensitivity in a one-dimensional radiative-convective climate model. J. Atmos. Sci. 37:545.

Wang, W. C., Y. Yung, A. Lacis, T. Mo, and J. Hansen (1976). Greenhouse effects due to man-made perturbation of trace gases. Science 194:685-690.

Wang, W. C., J. P. Pinto, and Y. Yung (1980). Climatic effects due to halogenated compounds in the earth's atmosphere. J. Atmos. Sci. 37:333-338.

White, G. F. (1983). Water resource adequacy: illusion and reality. Natural Resources Forum 7(1):11-21.

Woodwell, G. M., R. A. Houghton, and N. R. Tempel (1973). Atmospheric CO_2 at Brookhaven, Long Island, New York: patterns of variation up to 125 meters. J. Geophy. Res. 78:932-940.

Wong, S. C. (1979). Elevated atmospheric partial pressure of CO_2 and plant growth. Oecologia 44:68-74.

World Climate Programme (1981). On the assessment of the role of CO_2 on climate variations and their impact. Report of a WMO/UNEP/ICSU meeting of experts in Villach, Austria, November 1980. World Meteorological Organization, Geneva, Switzerland.

World Energy Conference (1978). World Energy Resources 1985-2020, An Appraisal of World Coal Resources and Their Future Availability; World Energy Demand (Report to the Conservation Commission). IPC Science and Technology Press, Guildford, U.K.

World Meteorological Organization (1983). Report of the Meeting of Experts on Potential Climatic Effects of Ozone and Other Minor Trace Gases. Report No. 14. WMO Global Ozone Research and Monitoring Project, Geneva, Switzerland, 38 pp.