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Projecting Future Sea Level Rise

Methodology, Estimates to the Year 2100, & Research Needs

PROJECTING FUTURE SEA LEVEL RISE

Methodology, Estimates to the Year 2100, and Research Needs

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PREFACE

The primary objective of this report is to estimate the range of future sea level rise. This information should help coastal engineers, planners, coastal zone managers, water supply and quality planners, and site planners to make better decisions in coastal areas. Scientists and federal research policy makers can use this report in choosing research to improve sea level rise estimates.

This report has undergone an extensive peer review to ensure its accuracy and completeness. Nevertheless better estimates of sea level rise will be forthcoming as scientific knowledge improves.

No EPA policy is implied in this document. Comments are welcome and should be sent to John Hoffman, PM-221, Strategic Studies Staff, EPA, Washington, D.C. 20460.

ACKNOWLEDGMENTS

Several people made valuable contributions to this study. Dr. Alan Truelove of Pechan and Associates did much of the early computer programming. Dr. Sergej Lebedeff, Dr. Gary Russell, Dr. Andrew Lacis, and Dr. James Hansen of the Goddard Institute for Space Studies (GISS) provided computer programs and technical advice on the temperature-flux equations, thermal-expansion model, and ice-sheet melting. Dr. Robert Thomas and Dr. David Thompson of the Jet Propulsion Laboratory provided information on glacial processes. Dr. William Emanuel of Oak Ridge National Laboratories provided the computer program and technical advice on the carbon-cycle model. CO_2 projections were derived from runs of a modified version of the World Energy Model provided by the Institute of Energy Analysis, Oak Ridge Associated Universities. Loren Dunn of EPA made valuable contributions to earlier versions of this effort. Wynne Cougill and Steven Seidel made editorial suggestions. Tom Glover provided graphics and Carolyn Acklin typed numerous drafts.

We would like to thank more than one hundred peer reviewers, too numerous to name, who took time to comment on this report. All errors, omissions and inaccuracies, however, are the responsibilities of the authors.

REPORT SUMMARY AND FINDINGS

Concentrations of atmospheric CO_2 and other greenhouse gases will continue to increase in coming decades. Two National Academy of Sciences panels have concluded that higher levels of these gases will almost certainly produce a large global warming. That warming, by thermally expanding the oceans and by causing the transfer of ice and snow resting on land to the oceans, should raise sea level substantially faster than the rise that has taken place during the past century.

Although current knowledge is inadequate to make a precise prediction of future sea level rise, it is sufficient to predict the likely range. Many factors were considered in generating the estimates of sea level rise contained in this report: population and productivity growth, atmospheric and climatic change, and oceanic and glacial response. High and low assumptions for these principal determinants of sea level rise were derived from the literature. When linked together the various assumptions allowed the estimation of high and low paths of future sea level rise. Based on this work, the following findings can be stated:

(1) GLOBAL SEA LEVEL WILL ALMOST CERTAINLY RISE IN COMING DECADES.

- A global rise of between 144 cm (4.8 feet) and 217 cm (7 feet) by 2100 is most likely.
- A global rise as low as 56 cm (1.9 feet) or as high as 345 cm (11 feet) by 2100 cannot be ruled out.
- Along most of the Atlantic and Gulf Coasts of the United States, the rise will be 18 to 24 cm (0.6 to 0.8 feet) more than the global average.

(2) ESTIMATES OF FUTURE SEA LEVEL RISE CAN BE USED TO REDUCE ITS ADVERSE IMPACTS.

- Sea level rise will increase shoreline retreat, erosion, flooding, and saltwater intrusion in coastal areas. Important economic impacts could result.
- Many, if not most of the adverse economic impacts of sea level rise can be avoided if timely actions are taken in anticipation of these effects.
- Professionals and policymakers need to assess the vulnerability of forthcoming decisions and the existing infrastructure to sea level rise.

(3) THE RANGE OF FUTURE SEA LEVEL RISE ESTIMATES COULD BE NARROWED BY ACCELERATING RESEARCH.

- Differences in estimates of sea level rise are due to deficiencies in scientific knowledge and in the methods used for constructing estimates. These deficiencies can be corrected.

- The most important research opportunities for improving sea level rise estimates are in estimating the transfer of ice and snow from land to sea, understanding the growth of the minor trace gases, and narrowing estimates of the sensitivity of the climate system to increased greenhouse gases. Many opportunities exist for improving knowledge in these areas.

- Under current funding, estimates of sea level rise will improve very slowly.

- Greater and more secure funding of interdisciplinary teams could produce a more rapid improvement in estimates.

CHAPTER 1

INTRODUCTION

Sea level can be expected to rise substantially throughout the coming decades as a result of a global warming caused by rising concentrations of atmospheric carbon dioxide,[1/] methane, nitrous oxide, and chlorofluorocarbons. The anticipated sea level rise would increase coastal erosion and flooding; groundwater tables would rise; and saltwater would intrude into rivers, bays, and aquifers.[2/]

Most coastal planners and decision makers are not considering the effects of sea level rise. Consequently, facilities are being located without adequate consideration of the costs of protecting them from erosion, flooding, or storm waves; important environmental protection decisions are being based on inadequate assessments of their future effectiveness; and entire communities are being planned without adequate consideration of the coastal works that will be necessary to protect their physical infrastructures and capital investments.[3/] Decision makers and technical personnel need estimates of sea level rise to evaluate the vulnerability of their decisions to changing risks.

A tremendous reserve of knowledge has been accumulated by natural and social scientists about the factors that will determine sea level rise - population growth, climatic change, oceanic heat absorption, glacial discharge, and atmospheric composition. This study uses that knowledge to project low and high ranges for future sea level rise. Because the range of assumptions used to project sea level rise varied from the very conservative to the less restrictive, the estimates produced here are likely to encompass the true rate of future sea level rise.

This report is organized as follows:

- Chapter 2 reviews the scientific basis for the belief that global warming will occur and cause sea level to rise.
- Chapter 3 presents the approach, the assumptions, and the models used to estimate sea level rise.
- Chapter 4 presents the results of our analysis: the low, high, and mid-range sea level rise scenarios.
- Chapter 5 reviews the research conducted on the impacts of sea level rise and discusses the need for further research on this subject.
- Chapter 6 presents a review of the research under way to improve estimates of sea level rise, along with options for accelerating the efforts to improve these estimates.
- Appendix A provides a summary of a larger set of sea level rise scenarios, including "special case" scenarios.
- Appendix B provides technical details of the models and assumptions used to generate the scenarios on thermal expansion.
- Appendix C provides details on the methods used for estimating snow and ice contributions, including a detailed analysis of the melting estimated under doubled CO_2 in a three-dimensional global climate model.

Each chapter is followed by end notes that provide references and explanations of the text. It should be noted that the estimates of sea level rise presented in this report differ from those of the peer review and first edition (July, 1983) because of improvements made in the treatment of trace gases.

END NOTES TO CHAPTER 1

1. Charney, Jules, et al., 1979. Carbon Dioxide and Climate: A Scientific Assessment. Washington, D.C.: National Academy of Sciences Press. The warming predicted in this report is 1.5°C to 4.5°C for a doubling of CO_2.

2. For an overview of the impacts of sea level rise and decisions that may be influenced, see:
Titus, James G., et al., 1983. Sea Level Rise Conference Document (draft). Washington, D.C.: EPA., or
Barth, Michael C. and James G. Titus, (eds). Sea Level Rise to the Year 2100. Stroudsburg, PA: Hutchinson Ross (in press).

3. For example, the 100-year floodplain defined in Federal Emergency Management Agency (FEMA) maps is being used at EPA in making many decisions for coastal areas. The maps have not, however, included any sea level rise in setting the flood boundaries. Consequently, facilities may face greater hazards or have shorter useful lives than planned for.

CHAPTER 2

THE SCIENTIFIC BASIS FOR PROJECTING SEA LEVEL RISE

Global sea level depends primarily on three factors: (1) the total amount of water that rests in ocean basins rather than on land; (2) ocean temperatures at various depths, which determine ocean density and volume; and (3) the shape (bathymetry) of the ocean floors.[1/] Global warming could increase the water resting in the oceans and the volume of that water, and thereby raise sea level. Because changes in bathymetry are slow and unlikely to accelerate, this report considers only the first two factors.

This chapter discusses the scientific basis for expecting a global warming to occur, and the linkages between that warming and sea level.

GREENHOUSE GASES HELP DETERMINE THE PLANET'S TEMPERATURE

The earth's temperature is determined by three factors: the sunlight it receives, the sunlight it reflects, and the infrared radiation absorbed by the atmosphere.[2/] Without the influence of the atmosphere, incoming visible radiation (in the form of sunlight) and outgoing radiation (in the form of invisible infrared radiation) would balance to yield a certain surface temperature. However, the atmosphere contains gases such as CO_2 and water vapor that absorb some of the infrared radiation. These gases are warmed by the radiation and radiate energy back to the earth's surface, raising its temperature.

The larger the percentage of infrared radiation blocked by the atmosphere, the warmer the earth's surface temperature. This feature of CO_2 and certain other gases is known as the "greenhouse effect."

The greenhouse effect is an important factor determining a planet's temperature, as observations of the temperatures of other planets confirm (see Table 2-1).[3]

TABLE 2 – 1

THE GREENHOUSE EFFECT ON THE INNER PLANETS: PREDICTION AND OBSERVATIONS

	Sunlight Received (watts per square meter)	Sunlight Reflected (percentage)	Temperature Without An Atmosphere	"Opacity" Of Atmosphere To Infrared*	Predicted Temperature With Simple Models**	Actual Temperature
VENUS	2613	75	– 40°C	~ 100	429°C	427°C
EARTH	1367	30	– 18°C	~ 1	17°C	15°C
MARS	589	15	– 56°C	~ .1	-52°C	-53°C

* Higher number indicates greater ability to trap infrared radiation.
***Average of two simple models: radiative equilibrium and convective* equilibruim.

Source: Modified from Hansen, J. Lacis, A. and Rind, D., "Climate Trends Due to Increasing Greenhouse Gases", Coastal Zone 83. New York: ASCE, 1983.

Contrary to popular belief, Venus is not hotter than Earth because it is nearer to the sun, but because its atmosphere is 97 percent CO_2. Although Venus receives more sunlight (2613 watts per square meter) than Earth (1367 watts per square meter), it reflects 75 percent of this radiation (which explains its brightness), compared with 30 percent for Earth. If the atmospheres of the planets did not differ in their ability to absorb infrared, Earth, with its lower reflectivity, would be 23°C degrees warmer than Venus. Similarly, with its very low reflectivity, Mars would be only 15°C cooler than Earth.

However, these planets have atmospheres with very different capabilites of absorbing infrared. The atmosphere of Mars has almost no water vapor and a low level of CO_2. According to simple models of the greenhouse effect, its temperature should rise only slightly. In contrast, according to the same models, Venus's atmosphere of 97 percent CO_2 should raise its temperature to a scorching 432°C (775°F), and Earth's atmosphere of 0.03 percent CO_2 and considerable water vapor should warm it by 30°C to an average of 17°C (63°F). Space probes to Mars and Venus and measurements on Earth confirm that their actual temperatures rise as predicted.

This and other evidence has led scientists to believe that as atmospheric levels of CO_2 and other greenhouse gases increase, Earth's temperature will rise. Using more comprehensive models of the greenhouse effect, it has been relatively simple to estimate that if no other changes take place in atmospheric composition (i.e., concentration of other greenhouse gases) or the albedo (reflectivity) of the planet, a doubling of atmospheric CO_2 concentrations will warm the earth's surface temperature 1.2°C.[4/]

Projecting the extent of the future warming is complicated by the fact that the initial warming will change reflectivity and atmospheric composition in a way that will almost certainly amplify the direct warming. For example, the 1.2°C temperature rise will increase water vapor levels in the atmosphere, trapping more infrared radiation, and will also melt snow and ice, decreasing the reflectivity of the earth. Other climatic effects, such as changes in cloud cover and cloud heights, could increase or diminish these amplifications by amounts that cannot be predicted accurately.

The 1979 report of the National Academy of Sciences (NAS), prepared by a review panel of leading climatologists, reflected the agreement of the scientific community on the effects of these feedbacks. The panel members summarized their view by stating: "We have tried but have been unable to find any overlooked physical effect that could reduce the currently estimated global warming due to a doubling of CO_2 to negligible proportions. . . ."5/ Unfortunately, the panel's agreement that a large warming will occur did not permit it to develop a narrow range for the estimated global temperature increase. However, it was able to conclude that the earth's equilibrium temperature increase for doubled CO_2 would be at least 1.5°C (2.7°F) and not more than of 4.5° (8.1°F).

Since 1979, scientific consensus has continued to grow that the warming will be significant. In 1982, a second NAS panel reviewed new evidence and confirmed the conclusions of the first panel.6/ More recently, the World Meteorological Organization and other researchers have concluded that other gases whose atmospheric concentrations are increasing could double the warming from CO_2 alone.7/ Thus, by the time CO_2

doubles, the earth's total equilibrium temperature increase is likely to be between 3°C to 9°C (5.4°F to 16.2°F).

CONCENTRATIONS OF GREENHOUSE GASES WILL ALMOST CERTAINLY DOUBLE IN THE NEXT CENTURY

In the past 180 years, atmospheric CO_2 appears to have risen approximately 20 percent, from between 260 and 290 ppm to 340 ppm. Very accurate monitoring began in 1958; since then, atmospheric CO_2 has increased 8 percent, from 315 ppm to 340 ppm.8/

Atmospheric levels of other gases have also risen. Methane increased annually by about 1 to 2 percent from 1970 to 1980, chlorofluorocarbons by about 6 percent over the same period. and nitrous oxide by about 0.2 percent per year from 1975 to 1980.9/

Economic activities have caused most of these increases. For CO_2, the most important cause of emissions has been the combustion of oil, gas, and coal, with deforestation probably contributing a small percentage. Burning fossil fuels (hydrocarbons) oxidizes carbon ($C^{+4} + 2O^{-2} \rightarrow CO_2$), inevitably releasing CO_2.

Future energy use and fuel selection will thus be the primary determinants of the rate of CO_2 emissions. Because fossil fuels have important competitive advantages and play a critical role in existing energy systems, their use is expected to grow even if radical policies are undertaken to curtail their use. For example, Seidel and Keyes found that even a 300 percent worldwide tax on fossil fuel use would delay a 2°C temperature rise only five years.[10/]

Because only a fraction of the emissions will remain in the atmosphere, concentrations of atmospheric CO_2 cannot be predicted by emissions alone. Nevertheless, although disagreement exists about the exact fraction, an almost universal consensus exists that it will be great enough to ensure that atmospheric CO_2 levels will at least double in the next century.[11/]

The future rates of increase for the other greenhouse gases are less certain. Much less is known about the sources of methane, nitrous oxide, and chlorofluorocarbons[12/] than the sources of CO_2. Furthermore, scientific understanding about the fate of these gases once they enter the atmosphere is also insufficient. Nevertheless, atmospheric concentrations of these gases are likely to increase substantially, and in the case of chlorofluorocarbons, probably at a rate faster than CO_2.

THE OCEANS WILL ALSO INFLUENCE THE RATE OF FUTURE WARMING

The rate of future warming will depend on more than the earth's equilibrium temperature sensitivity and the rate of increase in atmospheric CO_2 and other greenhouse gases. It will also depend on the time it takes for the climatic system to reach the equilibrium temperature.

The most important factor delaying the warming will be the oceans' capacity to absorb heat that would otherwise warm the atmosphere.[13/] As surface air temperatures increase, a temperature difference will develop between the surfaces of the atmosphere and the oceans, causing heat to be moved to the oceans. This heat will slowly pass downward to the lower and cooler layers. In this way, the oceans will act as heat "sinks", somewhat delaying the full atmospheric warming.

EXPECTED TEMPERATURE INCREASES WILL BE SIGNIFICANT

The expected global warming will be large compared to historical temperature changes, and even more significant compared to historical rates of temperature change. In the last two million years, the earth has never been more than 2 to 3°C warmer than it is today.[14/] In the last hundred thousand years, it has been at most 1°C warmer, and in the last thousand years, at most 0.5°C warmer. Since the Wisconsin Ice Age (18,000 years ago), the earth has warmed about 4°C,[15/] and in the last century, about 0.4°C.[16/] The projected warming for the next century would be ten times as rapid as the historical warming trend.

The expected warming will also be large compared to geographical temperature differences. A 3°C warming would leave San Francisco as warm as San Diego is today. A 9°C warming would raise New York City's average temperature to the current temperature of Daytona Beach, Florida.

THERMAL EXPANSION AND GLACIAL DISCHARGES COULD RAISE SEA LEVEL

As global temperature rises, the sea level can be raised in two ways:

- <u>Thermal expansion</u>

  Warming will decrease the density of ocean water, and thus increase its volume. Because the same water will take up more space, the levels of the oceans will rise. The rate of this rise directly depends on the amount of heat the oceans absorb.

- Transfer of snow and ice from land to sea

  Warming can transfer snow and ice from land to sea by melting (if the meltwater runs off into the ocean) or deglaciation (glaciers breaking up or moving more rapidly into the ocean). Sea level will rise as a result if these effects are not offset by the additional accumulation of snowfall on land. Both of these effects are likely to occur with the warming predicted for the next century. The rate at which they would occur, however, is less certain than that of thermal expansion and may not be proportional to the rate of warming. Deglaciation, in particular, may be a phenomenon in which a threshold exists. Once this threshold is passed, the deglaciation may become a self-reinforcing process, whose timing depends on many things other than the magnitude of the warming.

Geologic history indicates that these physical mechanisms describe the behavior of the earth. During warmer periods in earth's history, sea level has been higher than in colder periods, varying by over one hundred meters.

END NOTES TO CHAPTER 2

1/ Winds, currents, and land subsidence and emergence may cause local sea level to change at rates different from global sea level. For specific applications, the global estimates in this document should be adjusted by comparing historical local and global sea level trends.

2/ Hansen, James E., A. Lacis, and D. Rind, 1983. "Climatic trends due to increasing greenhouse gases," in Coastal Zone '83, Orville T. Magoon, ed. New York: American Society of Civil Engineers. 3:2796-810.

3/ Ibid.

4/ Ibid.

5/ Charney, Jules, et al., 1979. Carbon Dioxide and Climate: A Scientific Assessment. Washington, D.C.: National Academy of Sciences Press.

6/ Smagorinsky, J., 1982. Carbon Dioxide and Climate: A Second Assessment. Washington, D.C.: National Academy of Sciences Press.

7/ World Meteorological Organization, Sept. 1982. WHO Global Ozone Research and Monitoring Project, Report No. 14 and Lacis, A., et al., 1982. "Greenhouse effect of trace gases, 1970-1980." Geophysical Research Letters. 81:10:1035-8.

8/ Keeling, C.D., et al., 1976. "Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii." Tellus, 28, and Rotty, Ralph, 1979. "Energy demand and global climate," in Man's Impact on Climate, Wilfred Bach, et al., eds. New York: Elsevier Scientific Publishing.

9/ World Meteorological Organization, op. cit.

10/ Seidel, Stephen and Dale Keyes, 1983. Can We Delay A Greenhouse Warming? Washington, D.C: U.S. Environmental Protection Agency. These authors demonstrate that strong efforts to curtail fossil fuel growth, such as a tax that quadruples the costs of these fuels, will delay the increase in emission levels and temperature rise by only a few years. An unconventional counterview that argues that it is theoretically possible to reverse the growth is provided in Lovins, A., et al., 1981. Least Cost Energy. Andover, Mass: Brick House Publishing Company.

11/ Keeling, C.D., op. cit., and Rotty, R., op. cit.

12/ Chlorofluorocarbons will have two effects on climate. Their radiative effect will be warming. Although ozone absorbs infrared radiation, the depletion of ozone in the upper stratosphere by CFCs will have a slight warming effect; the increased incoming ultraviolet radiation will be greater than the increased outgoing infrared radiation. Other perturbants, such as nitrogen oxides from airplanes, may increase ozone in the lower stratosphere, which because of pressure broadening, would make ozone a better infrared obsorber, thus making increases at this lower altitude produce a net warming. Although the total temperature effect of the changes in stratospheric ozone are still uncertain, the warming contributed by this factor may be significant. See Wuebbles, D., 1983. "Effect of coupled anthropogenic perturbations on stratospheric ozone," Journal of Geophysical Research. 88:C2:1444-1456.

13/ Charney, J., op. cit., and Smagornisky, J., op. cit. It is estimated that the oceans take several decades to feel the full effect of atmospheric warming. Thus, much of the equilbirium warming from greenhouse gases added to the atmosphere in the 1970s has not yet occurred.

14/ Flohn, H., 1981. Life on a Warmer Earth. Laxenburg, Austria: International Institute for Applied Systems Analysis.

15/ Hansen, James E., A. Lacis, and D. Rind, 1983. op. cit.

16/ Hansen, James E., A. Lacis, and D. Rind, 1981. "Climate impact of increasing atmospheric carbon dioxide," Science. 213:4511:957-66.

CHAPTER 3

THE APPROACH, ASSUMPTIONS, AND MODELS USED TO ESTIMATE SEA LEVEL RISE

Estimating global sea level rise requires considering all of the possible changes in the social and natural systems that could influence future climate and sea level.[1/] Existing scientific knowledge is inadequate to make a precise prediction of the extent of these changes. Consequently, we generated a range of estimates, called scenarios.

Each scenario used a different set of assumptions (see Figure 3-1). For each factor that could affect sea level, a range of assumptions was developed by consulting the literature and the appropriate scientists. Thus, the full set of assumptions covered the likely ranges for each factor, although not necessarily the most extreme possibilities.

Models were selected that allowed various assumptions to be combined to generate yearly estimates of sea level rise. The models were chosen for their ability to accomplish this task in a reliable, flexible, and cost-effective manner.

Many scenarios were generated, but four critical ones were named. The "low scenario" consists of the most conservative assumptions for each factor, while the "high scenario" consists of the least conservative. Although the determinants of sea level rise are not likely to be all at the high ends or low ends of their ranges, these possibilities cannot be ruled out.

FIGURE 3-1

SUMMARY OF HIGH AND LOW ASSUMPTIONS USED TO ESTIMATE SEA LEVEL RISE

	Assumption	
	Low	High
Population Growth --------	All scenarios assumed the world will reach zero population growth by 2075	
Productivity Growth-------	2.2% per year; decreases to 1.7% by 2100	3.5% per year; decreases to 2.2 % by 2100
Energy Technologies-------	Best estimate, Nuclear costs halved arbitrarily.	Best estimates
Unexpected Additions------ To Fossil Fuel Base	None	None
Energy Conservation-------	All Countries Move Toward High Efficiency (60% improvement in energy efficiency).	
Fraction Airborne (CO_2) --	53%	ORNL Model; 60% increases to 80 %
Nitrous Oxide-------------	0.2% per year growth	0.7% per year growth
Chlorfluorocarbons--------	Emissions increase 0.7% of 1980 level per year	Emissions increase 3.8% of 1980 level per year
	60-year half-life for $CFCl_3$ and 120-year half-life for CF_2Cl_2	
Methane-------------------	1% per year growth	2% per year growth
Temperature Sensitivity---	1.5°C for CO_2 doubling	4.5°C for CO_2 doubling
Heat Diffusion of Ocean---	1.18 cm^2/sec	1.9cm^2/sec
Glacial Discharge---------	Equal to Thermal Expansion	Twice Thermal Expansion

Two mid-range scenarios were developed. They differ only in their estimates of snow and ice contributions to sea level rise; the estimates of the mass transfer of ice and snow from land to sea are much less reliable than estimates of thermal expansion. The mid-range scenarios used assumptions that fell between those used in the low and high scenarios (except in the case of fraction airborne, where we used the ORNL model). Although it is currently impossible to estimate probabilities, we believe that the actual sea level rise will probably fall between the two mid-range scenarios.

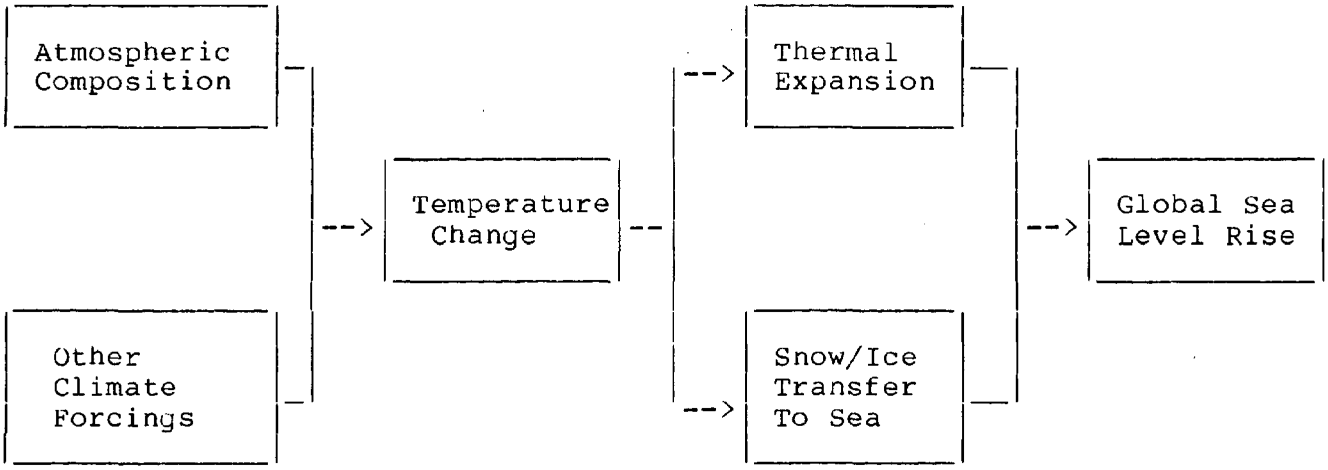
The remainder of this chapter presents the assumptions and models used to develop the scenarios. Technical details about the assumptions and models are provided in Appendix B.

YEARLY RISES IN SEA LEVEL WERE SIMULATED

The yearly rise in sea level can be estimated by projecting yearly changes in the natural systems that determine it. Four systems must be considered: atmospheric composition, the climate, the oceans, and the cryosphere (the part of the world that is ice or snow). Changes in the atmosphere will produce changes in temperature, which in turn produce thermal expansion and the transfer of snow and ice from land to sea (Figure 3-2). Below, we also discuss possible changes in other factors that determine global temperature, such as changes in solar irradiation or volcanic aerosols. (A permament increase in the average level of aerosols would block sunlight and cool the earth.)

Figure 3-2

Yearly Modeling Sequence



Atmospheric Composition

Projecting changes in the atmospheric concentrations of CO_2 and other greenhouse gases required projecting emissions of these gases and their fate as a result of atmospheric chemistry and other biogeochemical cycles that can create and destroy them or remove them from the air. In general, only a percentage of the emissions of each gas is retained in the atmosphere in a chemical form that absorbs infrared radiation.

Estimating future CO_2 emissions required estimating future economic growth and fuel use. Because economic growth is determined by the rate of population increase, productivity growth, and technological change, it was necessary to make assumptions about each of these factors and to integrate them in a consistent manner.

The following assumptions were used:

- Worldwide Population Growth was assumed to level off by 2075 for all scenarios, based on the work of Keyfitz et al.[2/]

- Productivity Growth for labor was assumed to decline for both the high and low scenarios.

    - In the high scenario, the growth rate began at 3.5 percent (per year) in 1980 and linearly decreased to 2.2 percent by 2100.

    - In the low scenario it linearly declined from 2.2 percent in 1980 to 1.7 percent by 2100.

  The past 30 years have experienced a higher rate of productivity growth than either of these assumptions.

- Energy Production Technologies for various fuels were assumed to improve:

    - for the low scenario, a best guess of future technologies and costs was used.

    - for the high scenario the same estimates were used except the cost of nuclear energy was assumed to be cut in half in 1983.

- Fossil Energy Resources were assumed to stay at current levels with no new major discoveries.

- Energy Use per unit of output (measured in GNP) was assumed to decline by over 60 percent between 1975 and 2100, reflecting two assumptions: (1) as economies develop, they will become more service oriented, and (2) energy technologies will become more efficient, partly in response to higher prices.

A world energy model developed by the Institute for Energy Analysis at Oak Ridge Associated Universities was used to integrate the assumptions.[3/] The model divides the world into nine regional sectors. Market mechanisms are used to select energy sources and trade supplies in and between each region. CO_2 emissions are generated by using well-established coefficients for each fuel.

As mentioned, not all the CO_2 emissions remain in the atmosphere. Some are removed by green plants, and some are absorbed by the oceans. Unfortunately, knowledge of these percentages is uncertain because the movement of carbon between various "storage compartments" in the earth (the oceans, biosphere, and the atmosphere) is only partially understood. Two assumptions were made for predicting the fraction airborne:

- For the high scenario, a model of the carbon cycle developed at Oak Ridge National Laboratories (ORNL) was used.4/ The model represents, at a very high level of aggregation, many of the physical and chemical mechanisms that regulate the exchanges of carbon between the various natural compartments that absorb and release it. The fraction airborne increased over time from 60 to 80 percent.
- For the low scenario, the percentage of carbon dioxide remaining in the atmosphere was assumed to be equal to its historical average of 53 percent.5/ This assumption is conservative for several reasons. Like a sponge, the upper layers of the oceans have a limited absorption capacity.6/ Thus, as the emissions of CO_2 increase, the percentage taken up by the oceans should decrease. Also, warming of the oceans and the resulting changes in circulation could lower the capacity of the oceans to absorb CO_2.7/
- For the mid-range scenario, the ORNL model was used.

High and low assumptions about CO_2 emissions and the fraction airborne were used to generate high and low estimates of the yearly increase in atmospheric CO_2. Under the low scenario, atmospheric concentrations of CO_2 will double by 2085, for the high scenario, by 2055.

Projections of the concentrations of chlorofluorocarbons and other trace gases involved much less sophistication than our projections of CO_2 concentrations.[8/]

- The low scenario assumed that emissions of chlorofluorocarbons grew at 0.7 percent of the 1980 level (1.8 million kg) annually until being capped in 2020 and that $CFCl_3$ (CFC-11) and CF_2Cl_2 (CFC-12) have half-lives of 60 and 120 years, respectively.
- The mid-range scenario assumed that emmissions of $CFCl_3$ and CF_2Cl_2 grew at 2.5 percent of the 1980 level (6.4 million kg) per year until 2020 and then are capped.
- The high scenario assumed that emissions of $CFCl_3$ and CF_2Cl_2 grew at 3.8 percent of the 1980 level (9.8 million kg) per year until being capped in 2020.

The low assumption implies that atmospheric concentrations will gradually approach an equilibrium concentration by 2100. Although the high assumption implies that concentrations will grow faster, it is not really an upper bound for likely future concentrations. It is possible that chlorofluorocarbon emissions will never be capped, or that their use in developing countries will parallel that of the developed countries (a growth not anticipated in the high scenario).

Nitrous oxide concentrations are also assumed to increase:[9/]

- The low scenario assumed 0.2 percent per year growth.
- The mid-range scenario assumed 0.45 percent per year growth.
- The high scenario assumed 0.7 percent per year growth.

Finally, methane is also assumed to grow:[10]

- o The low scenario assumed 1.0 percent growth per year.
- o The mid-range scenario assumed 1.5 percent growth per year.
- o The high scenario assumed 2.0 percent growth per year.

Our analysis did not consider changes in ozone concentrations at different altitudes, which may prove to be important. Ozone depletion in the upper stratosphere caused by chlorofluro-carbon emissions will tend to have a warming effect because the loss of ozones' infrared absorbing capibility at this altitude will be more than offset by the additional U-V energy allowed to penetrate to the earth's surface. Higher ozone levels in the lower stratosphere and upper troposphere, caused by NO_x emissions from airplanes, will cause additional warming because at those altitudes the additional infrared that is absorbed outweighs the reduction in ultraviolet that penetrates to the surface.[11] Other minor greenhouse gases, such as CCl_4, CF_4, NH_3, and $C_2Cl_3F_3$ (CFC-113) could also contribute to the warming, but were not considered in this analysis.

Climatic Responses

As the atmospheric abundance of gases that absorb infrared radiation increases, the earth's temperature will rise. The extent of the ultimate warming will depend on how much the initial warming alters the levels of other infrared-absorbing gases such as water vapor, or its reflectivity, by changing ice and cloud cover.[12] These "feedbacks" may amplify the initial warming considerably. Because the magnitudes of these factors are not precisely known, a large range of temperature changes was used to represent all of these uncertainties:

- <u>The high scenario</u> used the National Academy of Sciences' (NAS) estimate of a 4.5°C rise for a CO_2 doubling.
- <u>The mid-range scenario</u> used the NAS middle estimate of 3.0°C.
- <u>The low scenario</u> used the NAS low estimate of 1.5°C.

To integrate these assumptions about thermal sensitivity and the changes in atmospheric concentrations, we used an equation obtained from the Goddard Institute for Space Studies based on a one-dimensional radiative convective model. (See Appendix B). Coupled with a box-diffusion model that calculates the heat absorbed by oceans, the equation allowed a consistent integration of changes in greenhouse gases, thermal sensitivity, and the oceans' absorption of heat.[13/]

Thermal Expansion of Ocean Waters

Because ocean waters circulate slowly, the deeper layers of the ocean will warm very slowly, and for our purposes, can be ignored. As the top layers warm, however, the ocean's volume will expand. Although the percentage expansion is small, the resulting sea level rise could be significant from the human perspective.

As discussed, the downward movement of heat was projected with a simple box diffusion model. While this model does not represent the ocean circulation processes that actually transport heat, it is probably a good surrogate for the likely effects of such processes for the time span of 100 years. Nevertheless, to ensure the validity of the sea level rise estimates, we used different assumptions:

- For the high assumption, a rate of heat diffusion compatible with higher estimates of observed movement of chemical and radioactive tracers was used (1.9 cm^2/sec).
- For the low assumption, a rate of 1.18 cm^2/sec was used, which is compatible with a more conservative interpretation of tracer studies.[14/]
- For the mid-range assumption, the average of the high and low assumptions (1.54 cm^2/sec) was used.

The expansion of the seas was then computed using known coefficients of expansion for the temperature, salinity, and pressure of each ocean layer. We did not disaggregate thermal expansion to reflect the geographical variation of ocean temperatures. Because water expands by different amounts at different temperatures, disaggregation would improve sea level rise estimates. However, the one-dimensional description of temperature and salinity provides a good first approximation.

The Cryosphere

Most discussions concerning sea level rise have focused solely on the possible contributions of ice and snow resting below sea level in West Antarctica moving into the sea,[15/]

while only a few articles have discussed thermal expansion. Yet no glaciologist has estimated the potential contributions of ice and snow to sea level in the next century. In this section, we discuss the several methods developed to perform this task. Because the contributions of ice and snow to sea level rise could be more important than thermal expansion, these methods should be improved as soon as possible.

Size and Potential Source of the Land-Based Contributions

The amount of water contained in the ice and snow of Antarctica, Greenland, Northern Europe, Asia, and North America or in alpine glaciers is equivalent to about 70 meters of sea level rise (see Table 3-1). The Arctic Ocean consists of sea ice; therefore, its melting or breakup would not directly raise sea level.

Global warming can influence the percentage of the earth's water resting on land by several means:

- It can melt ice and snow. Melt water that runs off into the sea will raise sea level.
- It can increase the rate of flow of land-based ice sheets toward the sea. This deglaciation would add ice to the oceans, thereby raising sea level.
- It can cause the atmosphere to carry more moisture to cold areas in the form of snow, thereby increasing snowfall accumulation and decreasing sea level.

Estimates of ice and snow contributions to sea level rise can be made for each of these sources separately, or through an aggregate estimating method. Both approaches are used here.

TABLE 3-1

DISTRIBUTION OF ICE AND SNOW

		Area	Volume	Sea-Level Equivalent
		$10^6 km^2$	$10^6 km^3$ water	m
Snow and Ice on Land				
Antarctica 1,2		13.9	28.0	70
Greenland		1.8	2.7	7
Small Ice Caps and Mountain Glaciers		0.5	0.24	0.3
Ground Ice (Excluding Antarctica)				
Continuous		7.6		
Discontinuous		17.3		1.0
Sea Ice				
Arctic:	Max.	15.5	$5.0x10^4$	
	Min.	8.4	$2.0x10^4$	
Antarctic:	Max.	20.0	$3.0x10^4$	
	Min.	2.5	$5.0x10^3$	
Total Land Ice, Sea Ice and Snow				
Jan.	N. Hemisphere	58		
	S. Hemisphere	18		
July:	N. Hemisphere	14		
	S. Hemisphere	25		
Global Mean Annual		59		

---

1 Excludes peripheral, floating ice shelves (which do not affect sea level).

2 Roughly 10 percent of the Antarctic ice is in West Antarctica, and 90 percent is in East Antarctica.

Source: N. Untersteiner, "Sea ice and ice sheets role in climatic variations, Appendix 7," of GARP Pub. series 16: <u>Physical Basis of Climate and Climate Modeling</u>. World Meteorological Council of Scientific Unions, 206-24. April 1975.

Predicting Snow and Ice Contribution Using Climate Models

The most comprehensive tool for understanding climatic change is the three-dimensional general circulation model (GCM). By solving a series of equations that represent the fundamental laws of atmospheric structure and motion, such models simulate the earth's weather on an hour-by-hour basis, moving moisture and heat upwards and downwards, north and south, east and west. Although the models represent the actual atmosphere, solar irradiation, and the reflectivity of the earth with a fair degree of accuracy, the topography used is coarse; variations in large geographic regions are averaged together, and each grid is treated as a plateau.

By accumulating hourly and then daily weather statistics, these models can generate years of data that represent the climate of different regions. Since the models do not yet represent all of the processes that determine climate, one finds some discrepencies. Nevertheless, in most aspects, a GCM simulates weather fronts realistically: rain, snow, heat and cold are generated by the same mechanisms active in the actual climate system. By comparing projections of these models (assuming today's CO_2 levels) against observed weather and climate, GCMs ahve been shown to accurately reproduce the world's weather patterns.

Several research groups have developed GCMs to explore the effects of changes in the atmosphere's composition: NOAA Geophysical Fluid Dynamics Laboratory (GFDL), the National Center for Atmospheric Research (NCAR), and the Goddard Institute for Space Studies (GISS) have undertaken three well-known efforts in the United States.16/ Each group has run its GCM assuming the current atmosphere and doubled CO_2 concentrations. While some of the model predictions differ about climatic change, they are qualitatively similar.

The GISS group has used its model to estimate the size and geographical distribution of snow and ice in a warmer world. In fact, the group has done two doubled CO_2 experiments, which differed only in their techniques for computing sea ice, a key factor in determining the effects of atmospheric change on Antarctica. One model run started with somewhat more sea ice, and one with somewhat less sea ice than currently exists in Antarctica. This provided a method to check the sensitivity of the models to this initial condition.

Both doubled CO_2 runs showed a substantial net melting of land-based snow and ice. Both "control" runs (i.e., using current atmosphere and climate) showed nearly stable amounts of snow and ice. Thus, the results of the four runs increase our confidence that global warming will significantly decrease snow and ice resting on land. The run deemed most accurate showed a melting equivalent to a sea level rise of about one centimeter per year.[17/] (See Appendix C for details and possible sources of error.) Snowfall accumulation increased in the run, but was overwhelmed by additional melting. This contrasted sharply with the results of the model runs using today's temperature and CO_2, which showed almost stable levels of ice and snow on land.

These results need to be analyzed in greater depth than was possible for this study, and model experiments should be made with a more realistic treatment of ice sheet decay. Studies should also be made using other GCMs, and collateral evidence should be reviewed and integrated into the analysis. Nevertheless, these two GCM experiments provide evidence that a global warming would decrease the mass of the ice sheets by the melting and ensuing runoff.

One aspect of the GISS results that particularly needs more analysis is the runoff of meltwater, not all of which will escape to the sea. In many fringe areas of the ice sheets, where much of the melting will take place, most of the water probably will run off into the ocean; however, the percentage of runoff will be low in the antarctic interior. Water that does not run off will percolate into the ice and refreeze, which may cause ice softening and crevasing.

Glaciologists should use GCM outputs and information about glaciers and the topography of the land underlying ice to estimate the percentage of meltwater that will run off. They should also consider the degree to which changes in the physical characteristics of the ice sheet induced by refreezing will lead to faster deglaciation. (A brief discussion appears in the next section and in Appendix C.)

Another important feature of the GISS modeling is that the estimated melting of one centimeter per year was computed on the basis of a world whose atmospheric levels of CO_2 have already doubled. Thus, the GCM results do not directly provide a realistic time trend of sea level rise as CO_2 and other greenhouse gases approach and then exceed this level of warming. Computation of a time trend would have required estimating (1) the percentage of the meltwater that runs off into the oceans; (2) the degree to which the meltwater that does not run off accelerates glacial movement; and (3) the scale of melting that occurs as the earth warms. These steps could not be undertaken in this study. Thus, instead of directly using the one centimeter per year of melting as a scenario, the GISS output was taken as a qualitative confirmation that ice and snow can be expected to contribute significantly to sea level rise.

Deglaciation as a Source of Land-to-Sea Transfer of Snow and Ice

The possibility of a major deglaciation (the removal of ice by a process other than melting in place) cannot be ignored. Geological evidence suggests that changes in global temperatures can cause the large ice sheets that rest on Antarctica to break up and "fall" into the oceans. For example, during the last interglacial (120,000 years ago), which was about 1°C warmer than today, the West Antarctic ice sheet may have completely disappeared.[18/]

Several ice sheets that contain significant quantities of water are thought to be vulnerable to warming. Thousands of feet thick and resting mainly on land, these sheets are held in place and prevented from entering the ocean by floating "ice shelves" and pinnings below sea level. As global warming occurs, the waters around these shelves and pinnings may become warmer and melt them, allowing the ice sheets to begin to slide into the oceans. Furthermore, meltwater that does not run off, but percolates into the sheets and then refreezes, will tend to soften the ice, making rapid movement of ice more likely. Polar warming, which may be several times the magnitude of the average global increase, thus makes it possible for "the bottle to be uncorked."

Because it is marine-based (resting on the ocean floor), the ice sheet most vulnerable to such a deglaciation is the West Antarctic ice sheet. If all of that ice enters the ocean, sea level will rise five to six meters. Bentley has estimated 500 years, and Hughes 200 years, as the earliest time this could possibly happen.[19/] Although both estimates were made in the absence of detailed information about melting rates, sea ice retreat, and ocean and air temperatures, the possibility of a complete disintegration in 200 to 500 years cannot be ruled out.

Accurate estimation of the partial deglaciation of the West Antarctic, East Antarctic, and Greenland ice sheets for the next 120 years will require detailed studies of the specific ice sheets. Such studies should consider such factors as the predicted temperature of the upper surface of the ice, surface precipitation rates, ocean water temperatures, melting of ice shelves from the bottom, speeds of ocean currents and their ability to remove ice, the specific topography of the "gates" (narrow areas that constrict the flow of ice), and the specific location of grounding lines (land on which marine ice sheets rest).20/ These factors will determine the speed of discharges. Unfortunately, such studies have not yet been made for deglaciation in the next century.

Method Used to Estimate Snow and Ice Transfers from Land to Sea

In the absence of appropriate studies of the various ice fields, another approach had to be used that was much less direct:

- A range of historic sea level rise estimates was gathered from the literature.
- An estimate of the historical sea level rise attributable to thermal expansion of the oceans was obtained from the literature.
- High and low ratios of ice and snow contributions to thermal expansion were computed using different estimates of the historical sea level rise with the single estimate of past thermal expansion.
- These ratios were assumed to remain constant in the future (implying that snow and ice contributions will proceed in marginal steps and that deglaciation, when averaged across all ice sheets, will also be a proportional phenomenon).

Estimates of the Last Century's Sea Level Rise

In the last century, measurements of tidal heights have been collected in harbors around the world. On the basis of these measurements, several researchers have concluded that worldwide sea level has been rising. (See Table 3-2 on the next page.)

Differences between sea level rise estimates can be attributed to several factors that make precise interpretation of the data difficult. Tidal gauges are influenced by local conditions that do not influence worldwide sea level, such as river flow, weather, and emergence or submergence of land. Furthermore, they are not distributed uniformly, and large parts of the oceans are unmeasured.

To overcome these problems, the various researchers employed different approaches. Some researchers averaged all available stations. Others chose a few stations in each typical geographic zone and assumed them to be "representative." At least one group of researchers also attempted to factor out local tectonic influences.[21/] Despite the differences, however, the estimates of sea level rise have been remarkably similar. Most of the researchers have concluded that worldwide sea level has risen between 10 and 15 centimeters in the last century.[22/]

TABLE 3-2

ESTIMATES OF GLOBAL SEA LEVEL RISE

(cm per century)

Author	Estimate
Thorarinsson (1940)	> 5 cm
Gutenberg (1941)	11 ± 8 cm
Kuenen (1950)	12 to 14 cm
Lisitzin (1958)	11.2 ± 3.6 cm
Wexler (1961)	11.8 cm
Fairbridge and Krebs (1962)	12 cm
Hicks (1978)	15 cm (U.S. only)
Emery (1980)	30 cm
Gornitz et al (1982)	12 cm (10 cm excluding long-term trend)
Barnett (1983)	15 cm

Sources: Adopted from Barnett (1983) and Hicks (1978)

Determining the Ratios

Using available estimates on past temperatures and the rates of heat absorption in the oceans, Gornitz et al. estimated past sea level rise due to thermal expansion to be 4 to 5 cm the last century.23/

- For the low scenario, a 10-centimeter estimate of historical sea level rise was used, thus implying a one-to-one ratio of the contribution of snow and ice to thermal expansion.
- For the high scenario, the higher sea level rise estimate of 15 cm was used, thus implying a ratio of two-to-one.

Deficiencies in Our Estimates of Snow and Ice Contribution

Although the GISS 3-D experiments yield a similar magnitude for the rate of sea level rise as the ratio method, we have no illusions about the adequacy of these projections. If estimates based on process models of deglaciation had been available, we would have used them. The ratios depend on estimates of change which are themselves subject to mis-estimation. Futhermore, the physical basis for extrapolating the historical ratio into the future is weak at best. Past "associations" may not continue in the face of much larger temperature increases.

To remedy this situation, EPA and NASA have assembled a team of glaciologists, oceanographers, and climatologists, who, with limited funding, will use "process models" and judgment to estimate a range for possible meltwater runoff and deglaciation. A comprehensive well-funded effort, however, is still not on the research agenda of any federal agency.

CHANGES IN VOLCANIC AEROSOLS AND SOLAR IRRADIATION COULD INFLUENCE CLIMATE

From decade to decade solar irradiation and volcanic aerosols in the atmosphere may vary. An increase in aerosols can have a cooling effect, while an increase in solar irradiation will have a warming effect. In coming decades it is likely that there will be fluctuations for both factors, but there is no reason to expect a consistent long-range trend. Nevertheless, to test the possible influence of a strong shift in these factors, these changes were examined:

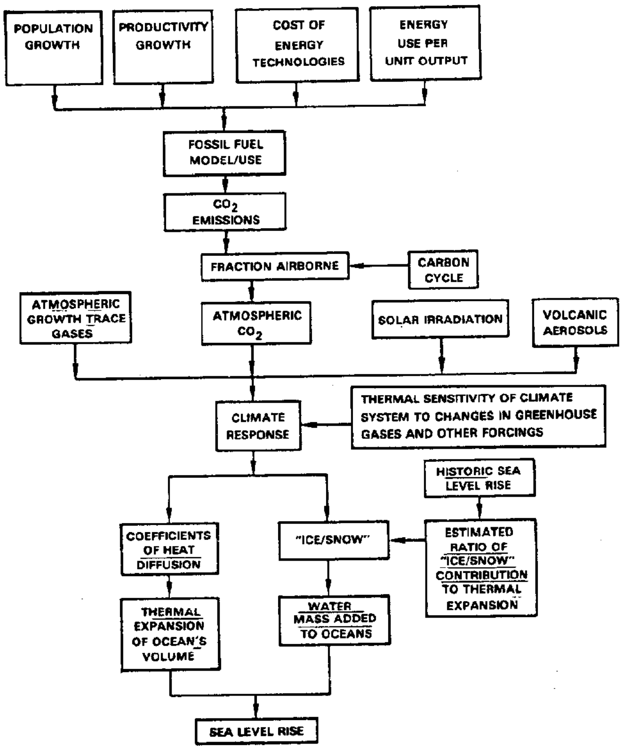
- For the minimum case, we assumed high volcanic activity and a reduction in solar radiation. A level of optical thickness was chosen that was five times the historical average over the last 80 years.[24/] A linear trend equal to a 0.5 percent reduction in solar radiation by 2100 was assumed.[25/]
- For the maximum case, we assumed solar irradiation increased by a linear trend to a 0.5 percent increase by 2100, with no change in volcanic activity.
- For the high volcanic case, we assumed high volcanic activity, but no change in the solar constant.

These and other special-case scenarios are reported in Appendix A. They suggest that the greenhouse effect is not likely to be overwhelmed by volcanoes or changes in solar irradiation.

END NOTES CHAPTER 3

1. The figure below shows a schematic relationship of the factors considered in estimating the sea level rise:

BASIS FOR SCENARIOS



For each factor or relationship high and low assumptions were developed using the published literature.

2. Keyfitz, Nathan, et al., 1983. Global Population (1975-2075) and Labor Force (1975-2050). Oak Ridge, TN: Oak Ridge Associated Universities, Institute for Energy Analysis.

3. Edmonds, Jae, and John Reilly, 1982b. "Global energy and CO_2 to the year 2050." Washington, D.C.: Oak Ridge Associated Universities.

4. Emanuel, W. R., and Killough, G. G., computer tape provided with 17-layer ocean model. Oak Ridge, TN: Oak Ridge National Laboratories.

5. Siegenthaler, Ulrich, 1983. "Uptake of excess CO_2 by an outcrop diffusion model of the ocean." Journal of Geophysical Research. 88:C6:3599-608.

6. Broecker, Wallace Smith, and Tsung-Hung Peng, 1982. Tracers in the Sea. Palisades, N.Y.: Lamont - Doherty Geological Observatory, Columbia University.

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9. Weiss, R.F., Keeling, C.D., and Craig, H., "The Determination of Tropospheric Nitrous Oxide," Journal of Geophysical Research, Vol. 86, No. 68, August 20, 1981, pp. 7197-7202.

10. Rasmussen, R.A., Khalil, M.A.K., "Increase in the Concentration of Atmospheric Methane" Atmospheric Environment, Vol. 15, No. 5, 1981, pp. 883-886.

11. Lacis, A., personal communication, October, 1983.

12. Cloud responses would affect the total amplification because cloud cover, heights, and their optical properties (the amount of sunlight they reflect) could influence and change the radiation balance and the earth's temperature positively or negatively.

13. Hansen, James E., et al. 1981., "Climate impact of increasing atmospheric carbon dioxide." Science. 213:4511:957-66. The equation was modified by A. Lacis to allow the trace gases to be considered. A box diffusion model portrays the ocean as a column of water and treats the movement of heat as a passive tracer. The GISS group adpoted the model from Oeschger, H., et al., 1975. Tellus. 27:168.

14. Broecker, Wallace Smith, Tsung-Hung Peng, and R. Engh, 1980. "Modeling the carbon system," Radiocarbon. 22:3:565:-98.

15. For example, an article in Newsweek, ("Is Antarctica Shrinking", October 5, 1981) focused solely on the rise in sea level that might be caused by ice transfers, completely ignoring thermal expansion.

16. Manabe, Sykuro, and Richard T. Wetherald, 1975. "The effects of doubling the CO_2 concentration on the climate of a general circulation model." Journal of the Atmospheric Sciences. 32:1:3.

    Hansen, James, E., et. al., 1983. "Efficient three-dimensional global models for climate studies: models I and II." Monthly Weather Review. 111:4:609:62.

Washington, W.M. and D.L. Williamson, 1977. "A description of the NCAR global circulation models in methods of computational physics," in General Circulation Models of the Atmosphere, J. Chang, ed. New York: Academic Press, 17:111-172

17. Russell, G.; see Appendix C of this report.

18. Mercer, J.H., 1978. "West Antarctica ice sheet and CO_2 greenhouse effect: a threat of disaster." Nature. 271:5643:321.

19. Bentley, Charles R., 1983. "West Antarctic ice sheet: diagnosis and prognosis," in Proceedings: Carbon Dioxide Research Conference: Carbon Dioxide, Science and Consensus 1983, Washington, DC: Department of Energy. U.S. CONF-820970.

    Hughes, T., 1983. "The stability of the west Antarctic ice sheet: what will happen," in Proceedings: Carbon Dioxide Research Conference: Carbon Dioxide, Science and Consensus 1983. Washington, DC: U.S. Department of Energy. CONF-820970.

20. Ibid.

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CHAPTER 4

SEA LEVEL SCENARIOS TO THE YEAR 2100

This chapter presents our estimates of sea level rise, using the methods described in the previous chapter. It also discusses alternative approaches for projecting sea level rise that yield similar estimates, increasing our confidence in these results.

Table 4-1 presents the four major scenarios. The low and high scenarios use low and high assumptions, respectively, for each of the factors influencing sea level rise. The two mid-range scenarios use the medium estimate of sea level rise attributable to thermal expansion. However, given the greater uncertainty about snow and ice contributions to sea level rise, the mid-range high and mid-range low use the two-to-one and one-to-one assumptions for glacial contributions to sea level rise, respectively.

TABLE 4.1

SCENARIOS OF FUTURE SEA LEVEL RISE
(centimeters)

	Year				
Scenario	2000	2025	2050	2075	2100
High	17.1	54.9	116.7	211.5	345.0
Mid-range high	13.2	39.3	78.9	136.8	216.6
Mid-range low	8.8	26.2	52.6	91.2	144.4
Low	4.8	13.0	23.8	38.0	56.2
Current Trends	2.0-3.0	4.5-6.8	7.0-10.5	9.5-14.3	12.0-18.0

We believe that the actual rate of sea level rise is more likely to fall between the two mid-range estimates than outside of them. Because the high and low scenarios employ more extreme assumptions, neither is likely to occur. However, the possibility can not be ruled out.

SEA LEVEL RISE WILL ACCELERATE UNDER ALL ASSUMPTIONS

Even in the low scenario, sea level will rise twice as fast as its historical rate in the next 20 years, and from 2000 to 2025, at three times the historical rate. In the high scenario, the sea will rise about ten times its historical rate from 1980 to 2025. Over the last quarter of the 21st century, the high scenario predicts the sea to rise at over 40 times the historical rate.

The mid-range scenarios predict that from 1980 to 2000, sea level will rise almost as much as it has in the last century. Given local trends on much of the East and Gulf Coasts of the United States, shoreline retreat in the next 20 years could be one-half that of the past century. In the following 25 years, worldwide sea level would rise at about eight times the historical rate, creating much greater erosion and flooding problems. Thus, in the next four decades (within the lifetimes of many projects now under design) the sea is likely to rise twice as much as it has in the last century.

AN ALTERNATIVE METHOD PRODUCES SIMILAR ESTIMATES OF SEA LEVEL RISE

To cross check our projections, we estimated sea level changes by another method: extrapolating past associations between temperature and sea level. Sea level rise in the last century has been estimated at 10 to 15 cm (4 to 6 inches). The surface temperature rise for the same period has been estimated at 0.4°C. Thus, the ratio of sea level rise to temperature is somewhere between 25 and 37 cm for each degree. Including the effects of trace gases, global warming should be equivalent to at least a quadrupling of CO_2 by 2100, which would raise surface air temperatures by 3.0°C to 9.0° (based on the National Academy of Sciences' range for climate sensitivity, ignoring delays caused by the heat absorbing-capacities of the oceans). Using the 25 cm to 37 cm ratio for the 3°C to 9°C range yields sea level rises of 75 cm to 333 cm. These estimates are in line with those produced by our more elaborate approach.

One other result is worth noting. Using a time series regression, Chylek and Kellogg estimated a 10 cm to 25 cm sea level rise per 1°C temperature rise. For a temperature rise of the magnitude projected, here, their result is consistent with a sea level rise of 30 cm to 225 cm.[1]

END NOTES TO CHAPTER 4

1. Chylek, Peter, and William Kellogg, 1982. "The Sea Level Climate Connection," unpublished paper, National Center for Atmospheric Research, Boulder, Colorado.

CHAPTER 5

IMPACTS OF SEA LEVEL RISE

The objective of this report is to project sea level rise, not to evaluate its impacts. Nevertheless, because our reason for estimating sea level rise is to help decision makers and professionals anticipate its effects and evaluate its importance, we provide a brief discussion of the impacts in this section.

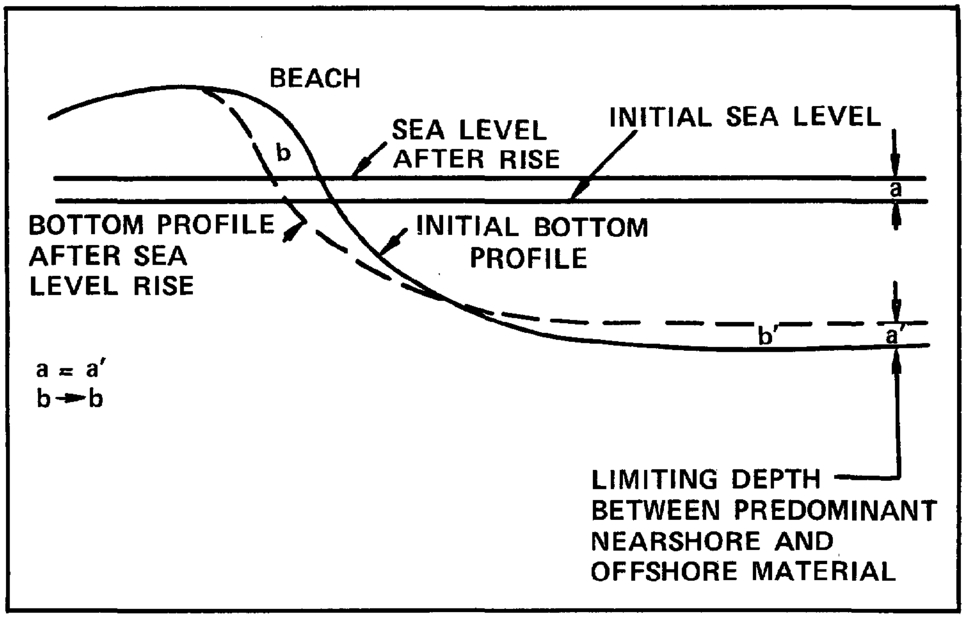
THE MOST SIGNIFICANT DIRECT IMPACTS WILL BE SHORELINE RETREAT, INCREASED FLOODING, AND SALT INTRUSION

Sea level rise will have three major types of physical effects: shoreline retreat, increased flooding, and landward movement of saltwater. Shorelines will retreat because very low land will be innundated and other land along the shore will erode. For example, a thirty centimeter (one foot) rise in sea level would erode most sandy beaches along the U.S. Atlantic and Gulf Coasts at least thirty meters (one hundred feet).

Even the historical sea level rise trend may be causing significant erosion.[1/] Most shorelines are maintained by the balance between sediment eroded by storms and sediment deposited back on the beach by waves during calm periods. However, a rise in sea level allows storm waves to strike and erode the beach farther inland, and makes calm waves less effective at "dredging" sand from the ocean floor and redepositing it onto the beach.

The Bruun Rule (illustrated by Figure 5-1)[2/], a method for quantifying the erosion impact, has been validated by field tests on the Great Lakes.[3] The shore maintains the equilibrium profile shown by the solid line. When sea level rises, this profile must also rise, which requires additional sediment equal to *b'*. Unless sediment is transported into the area by currents or by mechanical dredges, ocean waves will provide the sediment by eroding enough sand from the upper portion of the beach to equal *b*, producing the new profile shown by the dotted line. Applications of this theory have concluded that a rise in sea level of one centimeter can cause the shore to erode between one hundred and one thousand centimeters on the Atlantic and Gulf coasts of the United States.

FIGURE 5-1
BRUUN RULE



SHORE EROSION FOLLOWING A RISE IN SEA LEVEL ACCORDING TO THE BRUNN RULE (AFTER SCHWARTZ 1967) "THE BRUNN THEORY OF SEA LEVEL RISE AS A CAUSE OF SHORE EROSION," ADOPTED FROM THE JOURNAL OF GEOLOGY, 75, 76-92.

Low-lying areas not lost to a rising sea will experience increased flooding, for a number of reasons. The higher sea level will provide a higher base on which storm surges can build. Beach erosion and deeper water may allow large waves to strike further inland. Finally, higher water tables will decrease the land's drainage capacity, increasing runoff during storms.

Sea level rise will also cause salt water to move landward, intruding into groundwaters, rivers, and estuaries. In some rivers, salt may move upstream tens of kilometers. This effect may alter local availability of fresh water and alter ecosystems in some areas.4/

IMPACTS WILL DEPEND ON HOW PEOPLE ANTICIPATE SEA LEVEL RISE

Economic and environmental impacts will depend on how well people anticipate and plan for the physical changes associated with sea level rise. As busineses, governments, and individuals make decisions in coastal and low-lying areas, they have the opportunity to adjust to sea level rise before it occurs, which will decrease the eventual impacts of erosion, flooding, and saltwater intrusion.

Many decisions have outcomes that last long enough to be affected by sea level rise, e.g., where to locate roads, wastewater treatment plants, and chemical and nuclear waste storage facilities. (See Table 5-1.) A coastal highway may determine development patterns long after the pavement and the structures along the road have been replaced. Similarly, although a nuclear power plant built today may only be designed to operate

TABLE 5-1
CATEGORIES OF DECISIONS SEA LEVEL RISE WILL INFLUENCE

LOCATIONAL DECISIONS

- WHERE TO PUT PRIVATE DEVELOPMENT AND REDEVELOPMENT
  - HOUSING
  - FACTORIES
  - RESORTS
  - ENERGY FACILITIES
  - HAZARDOUS WASTE SITES
- PUBLIC DEVELOPMENT DECISIONS—ROADS
  - UTILITIES
  - PORT INFRASTRUCTURES
  - PARKS
  - BRIDGES
- PURCHASE OF LANDS FOR CONSERVATION

STRUCTURAL AND SITE DESIGN DECISIONS

- HOW TO BUILD FACILITIES
  - THEIR MOVABLILITY
  - SITE CONTOURING
  - CONSTRUCTION TYPE AND QUALITY
  - PLANNED LIFETIME OF STRUCTURE
- R&D ON HOW TO IMPROVE OPTIONS
  - SUCH AS MAKING STRUCTURES MORE "SEA LEVEL RESISTANT"
  - MAKING STRUCTURES MOVE MOVABLE
- HOW TO MAKE LOW-COST DESIGN CHANGES TO REDUCE ADVERSE EFFECTS

PROTECTIVE MEASURES AGAINST FLOODS AND EROSION

- PROTECTIVE FACILITIES SUCH AS SEAWALLS
  - HEIGHT
  - TYPE
  - FOUNDATION SIZE (SO THEY CAN BE EXPANDED LATER)
- BEACH NOURISHMENT DECISIONS
- VEGETATION PLANTING AND MAINTENANCE DECISIONS
- RIVER CHANNELING AND RECHANNELING DECISIONS
- LAND ACQUISITION AND SET ASIDE FOR PUBLIC AND PRIVATE WORKS FOR FUTURE PROTECTION
- LOCAL ZONING AND OTHER LAND-USE CONTROLS TO REDUCE DEVELOPMENT IN WRONG AREAS
- FLOOD PROTECTION REQUIREMENTS FOR HAZARDOUS FACILITIES

DECISIONS ABOUT FLOOD MITIGATION PLANNING

- EVACUATION PLANS
- POST-DISASTER PLANS
- INSURANCE POLICIES, SUBSIDIES AND COSTS

for 30 years, its location may become the only available site for power generation in a given region for hundreds of years.

The wide range of sea level rise scenarios makes planning more difficult than it would be if we were certain about a particular forecast. Nevertheless, prudence demands that decision makers plan for at least the low sea level rise scenario, which would change many decisions. For other decisions, the low scenario presents few risks, but the high scenario would pose major problems. In such cases risk analysis can be used to balance the benefits and costs of various planning options for for each sea level rise scenario.

QUANTITATIVE ESTIMATES SHOW LARGE PHYSICAL EFFECTS AND ECONOMIC IMPACTS FROM ANTICIPATED SEA LEVEL RISE

Few studies of the physical consequences of sea level rise have been undertaken. Schneider and Chen concluded that a 4.7-meter (15-foot) rise in sea level would innundate over one-fourth of Louisiana and Florida, as well as one-eighth of Delaware, Maryland, and the District of Columbia.5/

EPA has funded case studies on the impacts of sea level rise for the areas around Charleston, South Carolina and Galveston, Texas. Detailed results of these studies are available in Sea Level Rise Conference Document.6/ A forthcoming book entitled Sea Level Rise to the Year 2100, will contain papers by the same researchers, as well as the reactions of coastal decision makers who attended that conference.7/

Both case studies found that sea level rise will have significant impacts. Research Planning Institute concluded that a 1.5 meter (five foot) rise in sea level would innundate one-quarter of Charleston if no additional bulkheads or seawalls were constructed.8/ They also calculated that areas in Charleston that are now flooded once every 100 years would be flooded once every 10 years. Leatherman concluded that a 1.5 meter rise would claim much less land around Galveston, provided that the existing network of levees and seawalls were maintained.9/ However, he estimated that such a rise would double the area flooded every 15 years. Because Galveston is already vulnerable to storms, Gibbs concluded that the resulting annual storm damage in this area would increase to $105 million from $23 million.10/

Quantitative projections of the effects of sea level rise on salinity in surfacewater and groundwater have only been made in limited cases. The Delaware River Basin Commission has estimated the effects of historical sea level trends on salt concentrations in the Delaware River.11/ It plans to examine the effects of the scenarios reported here, which may threaten aquifers recharged by the river and possibly Philadelphia's current water intakes during droughts However, no comprehensive analyses have been undertaken of salinity intrusions from sea level rise.

CURRENT AND FUTURE EFFORTS TO STUDY SEA LEVEL RISE IMPACTS

The National Academy of Engineering's Marine Board plans to assess the engineering implications of sea level rise.[12/] Port and coastal structures are designed for lifetimes of 100 years and possibly longer. The Marine Board is interested in determining whether the evidence of possible sea level rise justifies designing structures to withstand such a rise. It also intends to determine whether the existing network of tidal gauge stations is sufficient to detect a CO_2-induced rise in global sea level. EPA is working with the Delaware River Basin Commission to determine the impact of sea level rise on drinking water. Projects in Maryland, New Jersey, and New York are being considered, and others are being sought. [13/]

The prospect of sea level rise of the magnitude estimated in this study is so new, however, that much more basic research and study needs to be done on its effects, the methods for estimating them, and on the economic importance of anticipating the rise.

A variety of academic and professional disciplines need to define research and action agendas for understanding and preparing for sea level rise. For example, planners should review zoning standards and architects should review building codes. Coastal geologists should develop better means of projecting erosion. Paleo-sea-level researchers should consider how their substantial body of knowledge can be used for understanding the response of the land to sea level change, for validating climatic models, and for adjusting global sea level estimates by regional influences.[14/]

The need for additional research is further underscored by EPA's pilot studies, which demonstrate that half the damages can be prevented with adequate planning. Ignoring this opportunity could be very costly to society. In the next chapter, we discuss the research necessary to improve sea level rise projections. However, preparing for sea level rise will also require a much better understanding of its effects.

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CHAPTER 6

RESEARCH NEEDED TO IMPROVE ESTIMATES OF SEA LEVEL RISE

Little research has been conducted to estimate future sea level rise. Improving the scenarios developed in this report will require appropriate research and accurate monitoring of the underlying physical systems. Although some of the scientific problems may resist solution, a larger and better-focused research effort could solve most of them in time for the resulting information to be useful to coastal decision makers. A key determinant of progress will be the priority society attaches to this research.

This chapter examines the sources of variation in the estimates of sea level rise, to help identify the most promising opportunities for additional research. It also discusses principles for managing this research.

MONITORING SEA LEVEL WILL NOT BE SUFFICIENT

The low and high scenarios differ by a factor of six. This range makes it difficult for managers to decide how to reduce the adverse impacts of sea level rise. A "wait and see" approach would eventually reveal which scenario is most accurate. But because most forthcoming decisions cannot be postponed the several decades that this might require, these managers need a smaller uncertainty range. This can be achieved by reducing the uncertainties surrounding the individual assumptions that must be made to project sea level rise.

Interpreting the observed sea level rise will be difficult. Many factors that cause short-term variations in global temperature and sea level have not been modeled, including the internal dynamics of the climate system, changes in ocean circulation, and year-to-year fluctuations in volcanic activity. Thus, if the sea rises 9 to 13 centimeters by 2000 (the most probable range), then it will be difficult to determine the amount of this rise caused by the greenhouse warming, as opposed to temporary fluctuations caused by other factors, unless better monitoring and research is undertaken. It will be even more difficult to determine the percentage of the rise that should be attributed to thermal expansion versus glacial contribution. Better research and monitioring could help ensure that our ability to forecast sea level rise improves as additional data becomes available.

UNDERSTANDING THE SOURCES OF DIFFERENCES BETWEEN SCENARIOS CAN HELP FOCUS RESEARCH PRIORITIES

The estimates of thermal expansion vary by a factor of four. However, the greatest source of uncertainty is the rate of transfer of snow and ice from land to sea, which varies by a factor of eight between the low and high scenarios. Unfortunately, there has been insufficient funding of coordinated work between glaciologists, climate modelers, and Southern Hemisphere oceanographers to estimate this important source of sea level rise.

Examining the sources of uncertainty is a first step toward developing research priorities. Figure 6-1 shows the contribution of each major factor to the current uncertainty of sea level rise from thermal expansion, using the low scenario as a baseline. Assumptions were changed one-at-a-time from low to high for each factor. The first four factors (CO_2 emissions, chlorofluorocarbons, nitrous oxide, and methane) were approximately additive in their effects. Because the other factors were not, changing them in a different order would change these estimates somewhat. Nevertheless, this figure conveys the relative importance of the uncertainties for each of the various factors in 25-year time spans.

This figure reveals some important insights for setting research priorities. The best way to improve estimates of sea level rise to the year 2025 would be to improve estimates of temperature (climate) sensitivity, and next, the concentrations of the trace gases. In the longer term, the level of CO_2 becomes quite important.

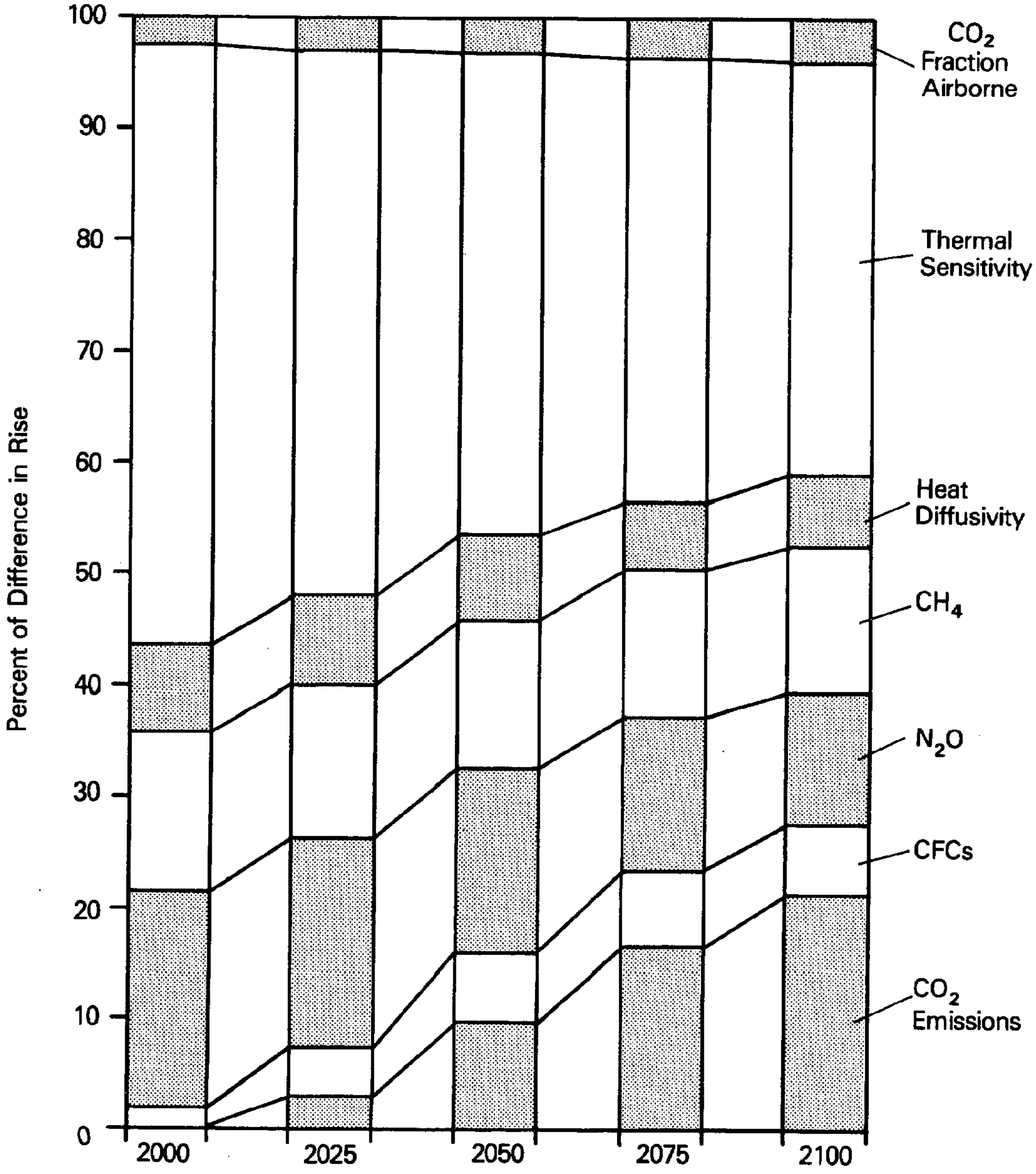
The atmospheric fraction airborne for CO_2 and diffusivity do not appear to be the major sources of uncertainty. It is possible that increasing temperatures may stratify the ocean, and increase fraction airborne and decrease diffusivity beyond the ranges of our assumptions. However, although these effects would both raise atmospheric temperatures, their effects on sea level rise would tend to offset one another.

Appendix A shows that in the long run, the impact of extreme and unexpected forms of natural variation (volcanoes and solar radiation) are unlikely to be important, except in the early stages when they could mask the overall trend.

Unless these factors are carefully monitored, their variability could reduce the ability of scientists to understand the other factors.

Figure 6-1

RELATIVE CONTRIBUTION OF FACTORS TO THE DIFFERENCE IN SEA LEVEL RISE BETWEEN THE HIGH AND LOW SCENARIOS



NOTE: Factors were evaluated in the order that they appear starting at the top.

OPPORTUNITIES EXIST FOR MORE RESEARCH

The greatest needs are:

- projecting the transfer of ice and snow from land to sea;
- estimating the atmospheric changes in the trace gases methane, nitrous oxide, and the chlorofluorocarbons; and
- estimating the sensitivity of the climatic system to atmospheric and other changes.

As discussed earlier, in response to these findings, EPA, in cooperation with NASA, has already initiated work to improve our understanding of snow and ice melting, oceanic warming around Antarctica, and glacial ice discharge. An interdisciplinary team of scientists from the Goddard Institute for Space Studies (GISS), NASA, and Lamont Doherty Geological Observatory has formed to improve the scenarios. They will use output from the GISS general circulation models; ice sheet/ice shelf process models; estimates of oceanic changes provided by a southern hemisphere oceanographer; and a thorough literature review of ice fields.

In early 1984, another scenario report will be issued that incorporates the results of this project and refines the thermal expansion model so that it reflects a geographically disaggregated absorbtion of heat by the world's oceans. That effort should increase the reliability of the scenarios somewhat. In the longer term, however, more precise and reliable estimates of sea level rise will become available only if efforts are made to improve our underlying knowledge of the relevant natural systems.

Several projects need to be undertaken to improve the basic scientific understanding of glacial processes:

- <u>Better Monitoring of the Ice Packs</u>

  The amount of ice and snow in all ice fields must be carefully tracked, probably with a combination of observations from space and land.

- <u>Experiments with Ice Sheets</u>

  Basic aspects of ice processes must be studied, especially those that relate friction and ice movement and the influence of warming and refreezing on the forces that determine ice movement.

- <u>Better Topographical Surveys</u>

  Land under ice sheets that could affect the rate of discharge must be mapped better.

- <u>Parametric Studies with Ice Models</u>

  Studies that consider different interpretations of ice processes and environmental conditions need to be conducted with ice sheet and ice shelf models.

- <u>Improvements in Polar Climatology, Sea Ice, and Oceanography in Climatic Models</u>

  Representations of the climatic processes, melting of sea ice, and the oceanographic processes need to be improved, with interdisciplinary teams contributing to ensure that general circulation models treat these areas realistically.

A major effort should be undertaken to narrow the uncertainties regarding trace gases.

- <u>Develop Better Estimates of Sources and Sinks</u>

  Research has been insufficient to even determine the origins and fates of these gases

- <u>Develop a Better Understanding of Atmospheric Chemistry</u>

  The interactions of these gases in the atmosphere greatly influence their abundance, and should be better assessed.

- Integrate Atmospheric Chemistry and Climatic Modeling

  Because atmospheric chemistry depends on temperatures and atmospheric mixing, atmospheric chemists and climate modelers must work in closer contact with each other.

Knowledge of the speed of climatic change and the sensitivity of the climatic system to changes in atmospheric composition can be greatly enhanced in several ways.

- Develop a Better Representation of the Oceans

  Dynamic ocean models can be integrated into general circulation models in realistic ways in the next 10 years only if a major, well-funded effort is undertaken. This is critical to producing a more valid geographical distribution of precipitation and temperature changes needed to estimate ice and snow changes.

- Improve Data on Clouds

  Better observational data, a better theoretical understanding, and a better computational representation of cloud processes can reduce the uncertainty of the effect that clouds have on thermal sensitivity.

- Expand Computing Capability

  The acquisition and use of appropriately sized computers would allow more experiments, with different representations of various processes, to be run in general circulation models and also provide greater geographical resolution. These efforts would allow quantification of the uncertainties in regional precipitation, which would considerably improve estimates of ice melting and snowfall.

Sufficient personnel and resources are available to sustain present efforts. Over the longer term, however, progress will require training new people. While not particularly costly, this process takes time. Delaying its start would diminish society's ability to accelerate research later.

RESEARCH CAN BE MANAGED MORE EFFECTIVELY

Research to improve estimates of sea level rise should have three primary objectives:

- Establish Interdisciplinary Teams of Sufficient Size

  Progress will be impeded if interdisciplinary teams are not developed and brought to work together on a long-term basis. They must be large enough to address difficult long-term problems.

- Provide Long-Term and Secure Financial Support

  Interdisciplinary scientific teams will not evolve unless financial support is secure. The development and maturation of research efforts depends on a steady source of funding. These teams should be directed by eminent scientists.

- Develop Long-Term and Geographically Extensive Data Sets

  Efforts to collect data must ensure that geographically extensive data sets are collected over long periods of time without interruptions. The greater the extent and detail of the data, the more scientists can test their models for realism.

Although success in scientific research cannot be guaranteed, it can easily be thwarted by failing to develop the conditions that make it possible. The interdisciplinary nature of projecting sea level rise makes management of research a particularly important part of ensuring progress. The opportunity exists; the decision facing society is whether or not to employ the resources needed to meet this challenge.

APPENDIX A

SUMMARY OF SEA LEVEL RISE SCENARIOS INCLUDING SPECIAL CASES OF INCREASED VOLCANIC ACTIVITY AND CHANGES IN SOLAR RADIATION

The abbreviations used in the following tables are explained below:

CO_2 Scenario

no growth -- constant (1975) emissions
low growth -- low (1.674 %) annual growth in emissions
medium growth -- medium (2.074 %) annual growth in emissions
high growth -- high (2.345 %) annual growth in emissions

Thermal Sensitivity (T_e)

low -- 1.5°C per doubling of CO_2
medium -- 3.0°C per doubling of CO_2
high -- 4.5°C per doubling of CO_2

CH_4 Scenarios

no growth -- constant 1980 concentrations
vl (very low growth) -- 0.5 % annual compound growth
lg (low growth) -- 1.0 % annual compound growth
med (medium growth) -- 1.5 % annual compound growth
hg (high growth) -- 2.0 % annual compound growth
vh (very high growth) -- 2.5 % annual compound growth

N_2O Scenarios

no growth -- constant 1980 atmospheric concentrations
vl (very low growth) -- 0.1 % annual compound growth
lg (low growth) -- 0.2 % annual compound growth
med (medium growth) -- 0.45 % annaul compound growth
hg (high growth) -- 0.70 % annual compound growth
vh (very high growth) -- 0.90 % annual compound growth

CFC Scenarios

no growth -- constant 1980 emissions
lg (low growth) -- 1.8 million kg annual growth to 2020
med (medium growth) -- 6.4 million kg annual growth to 2020
hg (high growth) -- 9.8 million kg annual growth to 2020
vg (very high growth) -- 11.6 million kg annual growth to 2100

All Scenarios assume that emissions are constant after 2020 and that the half-lives of CF_2Cl_2 (CFC-12) and $CFCl_3$ (CFC-11) are 120 and 60 years (i.e., "lifetimes" are 150 and 75 years) respectively.

Volcanic Activity

average -- Historical average optical depth value of .007
high -- optical depth of .037 (average of highest two decades in last century. Both values are dimensionless; see Appendix B)

Solar Luminosity

average -- no net change in historical luminosity
low -- Linear decrease from historical average to 0.5 % less in 2100
high -- Linear increase from historical average to 0.5% more in 2100

Diffusivity Coefficient (k)

very low -- 0.20 cm^2/sec
low -- 1.18 cm^2/sec
medium -- 1.54 cm^2/sec
high -- 1.9 cm^2/sec
very high -- 4.0 cm^2/sec

CO_2 Retention (Fraction Airborne)

ORNL -- estimates from the ORNL carbon cycle model (.6 to .8)
low -- a constant fraction of 0.53

Case#	CO_2 Scenario	Thermal Sensi- tivity	Trace Gases			Vol- cano	Solar	Diffusivity Coefficient	CO_2 Reten- tion	Ocean Scenario	SEA LEVEL RISE ESTIMATE (cm)				
			CH_4	N_2O	CFC						2000	2025	2050	2075	2100
CO_2 GROWTH SCENARIOS															
MID-RANGE															
1	medium	medium	med	med	med	aver	aver.	medium	ORNL	Thermal Expansion Only	4.4	13.1	26.3	45.6	72.2
										with 1:1 Ice Discharge	8.8	26.2	52.6	91.2	144.4
										with 2:1 Ice Discharge	13.2	39.3	78.9	136.8	216.6
HIGH															
2	high	high	hig	hig	hig	aver	aver.	high	ORNL	Thermal Expansion Only	5.7	18.3	38.9	70.5	115.0
										with 2:1 Ice Discharge	17.1	54.9	116.7	211.5	345.0
LOW															
3	low	low	low	low	low	aver	aver	low	low	Thermal Expansion Only	2.4	6.5	11.9	19.0	28.1
										with 1:1 Ice Discharge	4.8	13.0	23.8	38.0	56.2
MAXIMUM (Major solar increase acompanies greenhouse warming)															
4	high	high	vh	vh	vh	aver	vh	high	ORNL	Thermal Expansion Only	6.5	21.6	46.9	86.4	143.0
MINIMUM (Major decreases in solar irradiation and increases in volcanic activity simultaneously)															
5	low	low	vl	vl	vl	high	low	very low	low	Thermal Expansion Only	1.1	3.3	6.5	10.9	17.0
NO GROWTH CO_2, OR TRACE GAS GROWTH															
6	no growth	medium	ng	ng	ng	aver	aver	medium	ORNL	Thermal Expansion Only	2.3	5.9	10.1	14.6	19.3
INFLUENCE OF DIFFUSIVITY															
7	medium	medium	med	med	med	aver	aver	very low	ORNL	Thermal Expansion Only	3.2	8.9	17.2	29.3	46.1
8	medium	medium	med	med	med	aver	aver	low	ORNL	Thermal Expansion Only	4.2	12.5	25.0	43.2	68.4
9	medium	medium	med	med	med	aver	aver	high	ORNL	Thermal Expansion Only	4.5	13.6	27.4	47.5	75.2
10	medium	medium	med	med	med	aver	aver	very high	ORNL	Thermal Expansion Only	4.9	15.5	30.8	53.3	84.2
INFLUENCE OF THERMAL SENSITIVITY															
11	medium	high	med	med	med	aver	aver	high	ORNL	Thermal Expansion Only	5.0	15.7	32.0	56.1	90.0
12	medium	low	med	med	med	aver	aver	low	ORNL	Thermal Expansion Only	3.1	8.8	17.2	29.3	45.5

INFLUENCE OF OTHER GREENHOUSE GASES

13	medium	medium	vl	med	med	aver	aver	medium	ORNL	Thermal Expansion Only	3.9	11.6	23.3	40.4	64.0
14	medium	medium	vh	med	med	aver	aver	medium	ORNL	Thermal Expansion Only	4.7	14.5	29.4	51.5	82.5
15	medium	medium	med	vl	med	aver	aver	medium	ORNL	Thermal Expansion Only	3.9	11.6	23.4	40.9	65.4
16	medium	medium	med	vh	med	aver	aver	medium	ORNL	Thermal Expansion Only	4.8	14.6	29.3	50.7	79.9
17	medium	medium	med	med	low	aver	aver	medium	ORNL	Thermal Expansion Only	4.3	12.8	25.2	43.5	68.8
18	medium	medium	med	med	vh	aver	aver	medium	ORNL	Thermal Expansion Only	4.4	13.4	27.2	47.3	75.0
19	medium	medium	vl	vl	low	aver	aver	medium	ORNL	Thermal Expansion Only	3.4	9.7	19.3	33.6	53.8
20	medium	medium	vh	vh	vh	aver	aver	medium	ORNL	Thermal Expansion Only	5.2	16.2	33.4	59.2	95.3

INFLUENCE OF VOLCANIC ACTIVITY

21	medium	medium	med	med	med	aver	aver	medium	ORNL	Thermal Expansion Only	4.4	13.1	26.3	45.6	72.2
22	medium	medium	med	med	med	high	aver	medium	ORNL	Thermal Expansion Only	3.1	10.8	23.0	41.2	66.7

INFLUENCE OF SOLAR LUMINOSITY

23	medium	medium	med	med	med	aver	low	medium	ORNL	Thermal Expansion Only	4.0	11.8	23.3	40.2	63.7
24	medium	medium	med	med	med	aver	high	medium	ORNL	Thermal Expansion Only	4.7	14.5	29.4	51.2	81.1

APPENDIX B

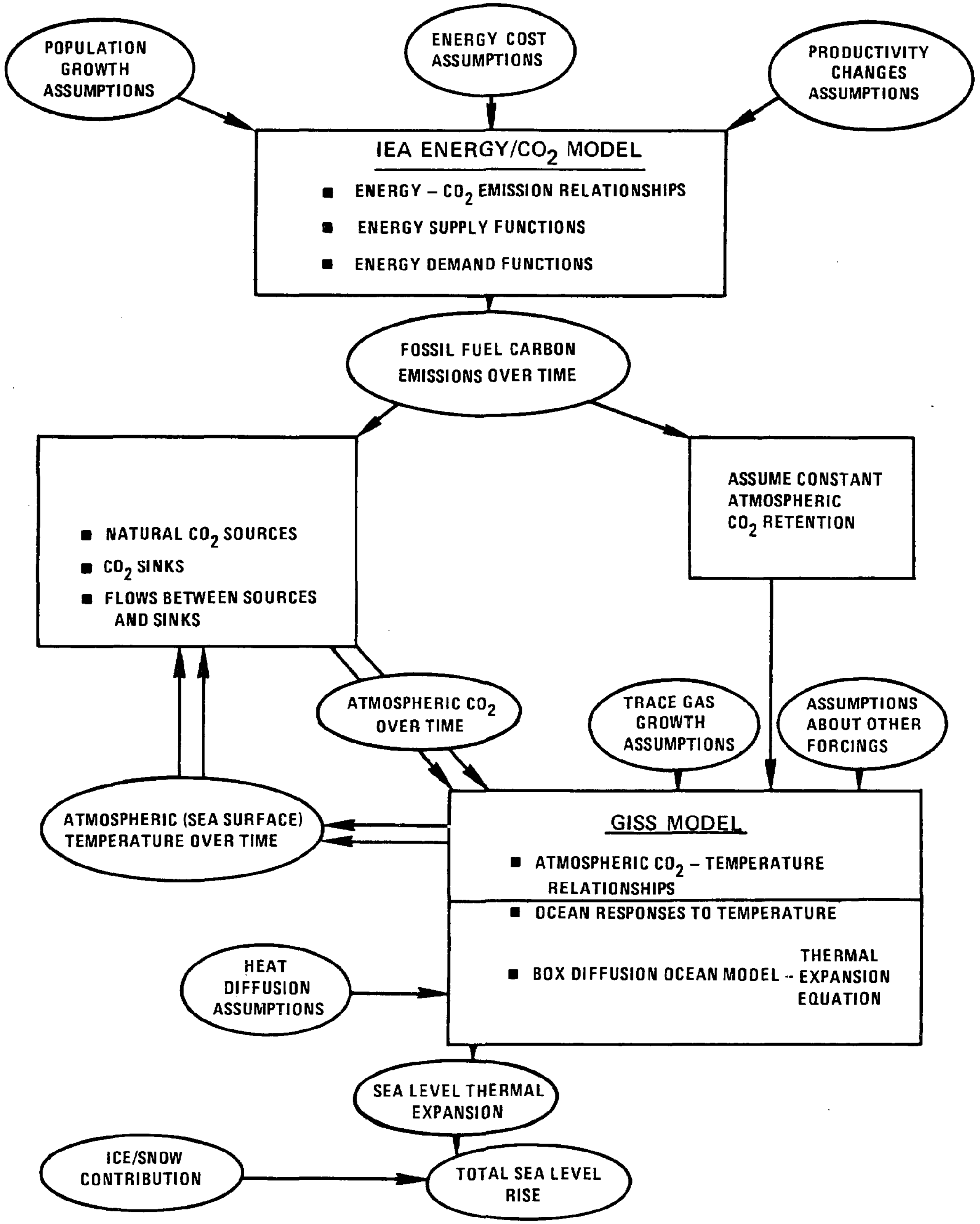
MODELS, ANALYTICAL METHODS, AND ASSUMPTIONS USED FOR ESTIMATING THE SCENARIOS OF SEA LEVEL RISE

Estimating the sea level rise produced by the temperature increases that will be associated with rises in atmospheric concentrations of CO_2 and other greenhouse gases required integrating a variety of data, assumptions, and physical and behavioral relationships (see Figure B-1). For this integration, three models were used in this study. The first is a world energy and CO_2 emission model obtained from the Institute for Energy Analysis (IEA) of the Oak Ridge Associated Universities. The second is a regression equation that simplifies a one-dimensional radiative/convective atmospheric temperature model obtained from Dr. James Hansen of the Goddard Institute for Space Studies (GISS). This model also represents heat flux into the ocean and computes sea level rise from thermal expansion of the ocean layers. The third, used in only some scenarios, is a global carbon cycle model obtained from Dr. William Emanuel of the Environmental Sciences Division, of the Oak Ridge National Laboratory (ORNL).

All three models were received from their developers in the form of FORTRAN source programs and were installed on the EPA computer located in North Carolina. Throughout this appendix, the models will be referenced as the IEA, GISS, and ORNL models.

FIGURE B-1

KEY COMPONENTS OF THE ANALYTICAL METHODOLOGY



In addition to changing some of the parameters and operational procedures of both the GISS and ORNL models, additional programs were developed to provide simple interfaces between these two models and to permit more rapid and extensive sensitivity analyses. Separate sections of this appendix describe the individual models and procedures for operating and combining them in the context of this study, as well as the specific assumptions used to run the scenarios.

THE ORGANIZING FRAMEWORK USED

The assumptions, relationships, and models used to estimate sea level rise are shown in Figure B-1. The key variables are described as primary inputs or outputs of the three models or are subsumed in the internal structures of the models.

As shown in Figure B-1, the three models are operated in sequence. The IEA model is first run to generate future energy use and carbon emission scenarios. The ORNL model (or an assumed constant fraction of CO_2 airborne) is next used to translate fossil-fuel carbon emissions into atmospheric CO_2 levels. The GISS model is finally employed to translate increases in CO_2 concentrations into atmospheric temperature increases and sea level rise. (The temperature of the atmosphere at the earth's surface is assumed equal to the temperature of the ocean's top layer.) The GISS model uses a variety of key assumptions as inputs: trace gas growth, thermal sensitivity of the atmosphere, and changes in other forcings.

The process of running the models is not perfectly sequential. The ORNL and GISS models are coupled in an iterative fashion for those analyses where the ORNL model is run. (This is discussed below under the heading "Coupling the ORNL and GISS Models.") Endnote 1 presents the rationale for coupling ORNL and GISS models and compares results using the two basic analytical approaches.

MODEL DESCRIPTIONS

Three models will be described: the IEA world energy model, the ORNL carbon cycle model, and the GISS climate equation ocean heat diffusion model.

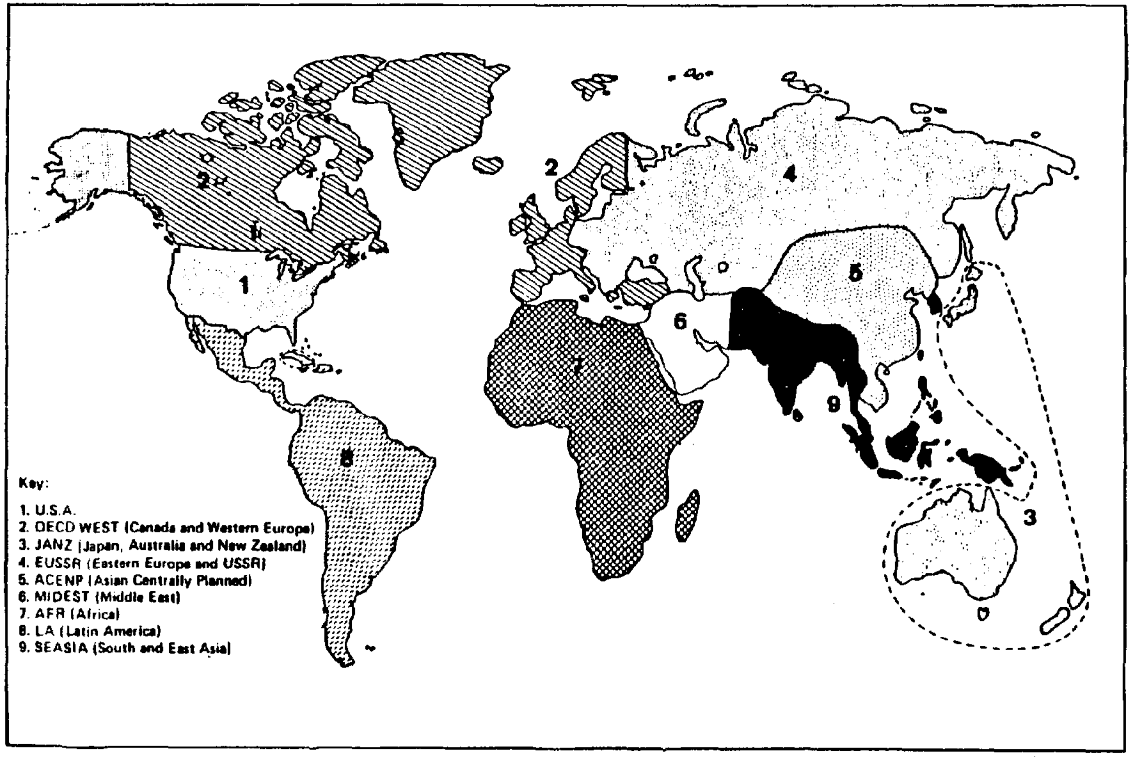
The IEA Long-Term Global Model

The IEA/ORAU model was developed by Jae Edmonds and John Reilly at the Institute for Energy Analysis as an assessment tool for policy analysis.[2] It provides a consistent representation of economic, demographic, technical, and policy factors as they affect energy use and production and CO_2 emissions.

The global model is dissaggregated into nine regions (see Figure B-2). Its time horizon is long-term -- from 1975 to 2100 -- with benchmark years 2000, 2025, 2050, and 2075. Projections beyond 2050 have not been examined in detail for reasonableness of parameters and model structure. Eleven types of primary energy in six major categories are currently considered (see Table B-1). In addition to the supply and demand for energy by region and forecast period, the model also estimates

FIGURE B-2

GEOPOLITICAL DIVISIONS IN THE IEA MODEL



world and regional energy prices consistent with overall global energy balance. The structure, data base, output, and usage of the model are extensively documented.[3]

Energy Demand

Energy demand for each of the six major fuel categories is developed for each of the nine regions separately. Five major exogenous inputs determine energy demand: population, economic activity, technological change, energy prices, and energy taxes and tariffs.

TABLE B-1
PRIMARY FUEL TYPES IN THE IEA MODEL

OIL

- CONVENTIONAL
- UNCONVENTIONAL (ENHANCED RECOVERY, SHALE OIL, AND TAR SANDS)
- SYNTHETIC (FROM COAL AND BIOMASS)

GAS

- CONVENTIONAL
- UNCONVENTIONAL (DEEP WELLS, TIGHT FORMATIONS)
- SYNTHETIC (FROM COAL AND BIOMASS)

SOLIDS

- COAL
- BIOMASS

RESOURCE-CONSTRAINED RENEWABLES

- HYDROELECTRIC

NUCLEAR

SOLAR

- SOLAR ELECTRIC (OTHER SOLAR IS ASSOCIATED WITH CONSERVATION)

An estimate of GNP for each region is used as a proxy for the overall level of economic activity and as an index of income. While the level of GNP is an input to the system, it is derived from assumptions on demographic growth and levels of labor productivity.

World population was assumed to stabilize by 2075, based on work done by Keyfitz et al.[3/] Labor productivity growth for the high scenario was assumed to be 3.2 percent per year in 1980, declining linearly to 2.2 percent per year by 2100.

In the low scenario, labor productivity growth was assumed to start at 2.2 percent per year in 1980 and to decline linearly to 1.7 percent per year by 2100. Both the high and low estimates of productivity growth utilize rates below the average rate of increase around the world in the last thirty years. The mid-range estimate was an interpolation of the two curves.

The energy technology parameter is a time-dependent index of energy productivity, given constant energy prices and real incomes. That is to say, it reflects improvements in energy efficiency beyond those stimulated by increases in real prices or decreases in real income. In the past, technological progress has had an important influence on energy use in the manufacturing sector of advanced economies. The inclusion of an energy technology parameter allows scenarios to be developed which incorporate either continued improvements or technological stagnation as an integral part of energy use scenarios. A constant improvement of 25 percent for each 25-year period was assumed for the industrial sector in all OECD countries (no change was assumed for the other sectors for these countries), and a 10 percent improvement was assumed for the single aggregate sector in other countries.

The final energy factor which influences demand is energy price. Each region has a unique set of energy prices which are derived from world prices (determined in the energy balance component of the model), transportation costs, and region-specific taxes and tariffs. The model can be modified to accommodate non-trading regions for any fuel or set of fuels. It is assumed that no trade is carried on between regions in solar, nuclear, or hydroelectric power, but that all regions trade other types of fuels.

The four secondary fuels (refined oil, refined gas, refined coal, and electricity) are consumed to produce energy services. In the three OECD regions (Regions 1, 2, and 3 in Figure B-2), energy is consumed by three end-use sectors: residential/commercial, industrial, and transportation. In the remaining regions, final energy is consumed by a single aggregate sector.

The demand for energy services in each region's end-use sector(s) is determined by the cost of providing these services, and the levels of income and population. The mix of secondary fuels used to provide these services is determined by the relative costs of providing the services using each alternative fuel.

The price of secondary fossil fuels is a function of the regional price of primary fuels and the cost of refining:

$$P_{jr} = P_{ir}(g_{ij}) + h_j$$

$$P_{ir} = (P_i + TR_{ir})\ TX_{ir}$$

Where: P_{jr} is the price of secondary fuel j in region r; P_{ir} is the price of primary fuel i in region r; g_{ij} is the efficiency of refining i into j; h_j is the nonenergy cost of refining; P_i is the world market price of fuel i; TR_{ir} is the cost of transporting fuel i to region r, and TX_{ir} are taxes on fuel i in region r.

The demand for fuels to provide electric power is then determined by the relative prices of the alternative electricity-generating fuels. Likewise, the demand for synthetic oil and gas from coal and biomass are functions of oil and gas prices. Finally, production levels of primary energy sources are derived from the demand for secondary fuels.

Energy Supply

Three generic energy supply categories are distinguished: resource-constrained conventional energy, resource-constrained renewable energy, and unconstrained energy resources. There are eight different supply modes across these categories, as shown in Table B-2. Production of conventional gas and oil are represented by a logistics curve which reflects historical supply levels and estimates of remaining deposits:

$$\frac{F(t)}{1-F(t)} = \exp(a + bt)$$

Where: F(t) is the cumulative fraction of the total resource exploited by time t, and a and b are empirical parameters.

production rates of these fuels are thus insensitive to price levels.

TABLE B-2

DISTRIBUTION OF IEA FUEL TYPES ACROSS SUPPLY CATEGORIES

Supply Categories

Resource-Constrained Conventional Energy	Resource-Constrained Renewable Energy	Unconstrained Energy Resources
Conventional Oil Conventional Gas	Hydro, Biomass	Unconventional Oil (primarily oil shale) Unconventional Gas (primarily gas) Synthetic Gas (from solids) Synthetic Oil (from solids) Coal Solar Nuclear

Production levels of unconventional oil and gas, nuclear, solar, and solids (coal and biomass) are modeled as "backstop technologies." That is, a base level of production is assumed to be generated over time if real prices remain constant. Shorter-term supply schedules are then superimposed on these long-term trends to reflect the increase or decrease in production due to price rises or declines. If the price falls below a breakthrough price level, then production ceases. These relationships are encompassed in the following general expression:

$$P = a\ [\exp(g/b)^{c}]$$

Where: P is the price of the backstop fuel; a is the breakthrough price; b is a parameter which determines the "normal" backstop price; c is a price-elasticity control parameter; and g is the ratio of output in year t to the base level associated with the backstop price.

Production levels of synthetic oil and gas are driven by the cost of solids, the cost of producing the synthetic fuel, and associated nonenergy costs. The share of coal or biomass allocated to the production of synfuels is specified by a logit share equation, with the relative cost of synfuels versus other sources of gas and oil and the price elasticity of production as key terms.

Resource-constrained renewable fuels are considered constant-flow sources. That is, the rates of energy production are limited by the availability of the resource.

For the high scenario the price of supplying each energy source was the "best guess" of the experts familiar with the respective sources. For the low scenario the cost of nuclear energy was halved starting in 1980.

Energy Balance

The supply and demand modules each generate energy supply and demand estimates based on exogenous input assumptions and energy prices. If energy supply and demand match when summed across all trading regions in each group for each fuel, then the global energy system balances. Such a result is unlikely at any arbitrary set of initial energy prices.

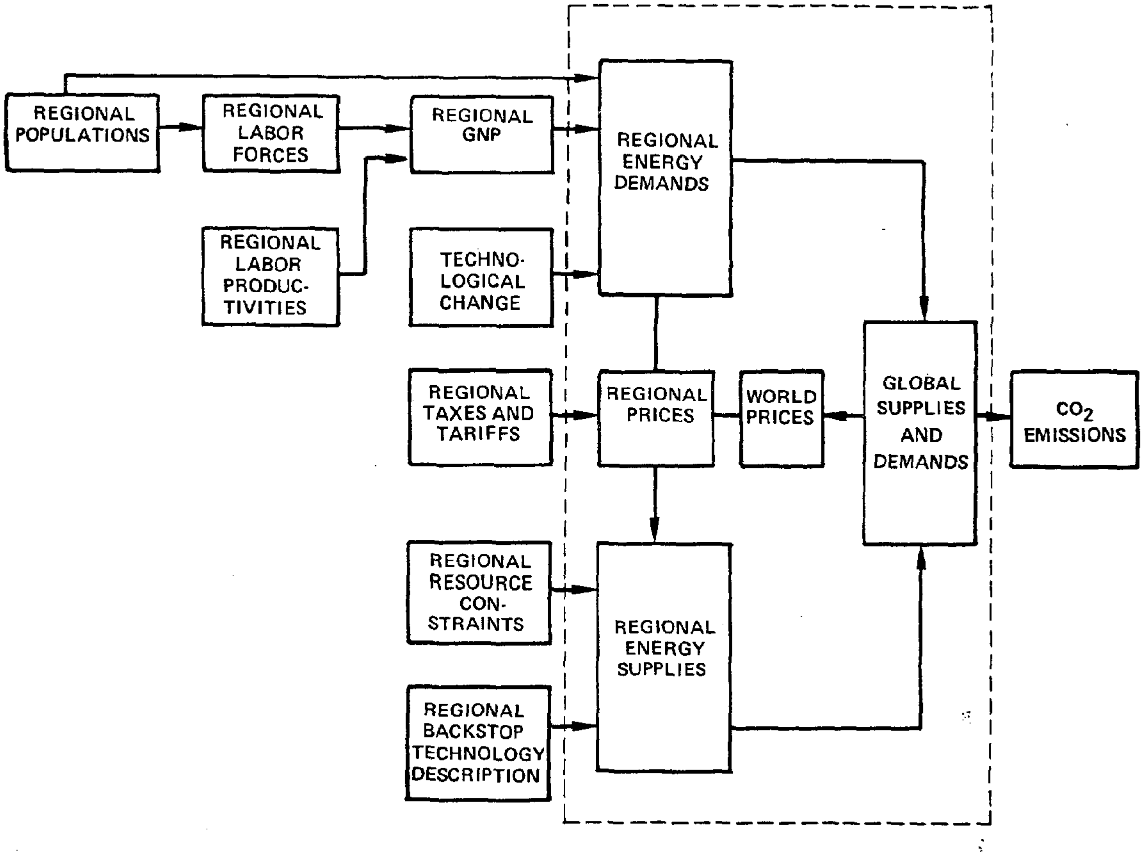
The energy balance component of the model is a set of rules for choosing energy prices which, on successive attempts, brings supply and demand nearer a systemwide balance. Successive energy price vectors are chosen until energy markets balance within a prespecified bound. Figure B-3 displays the interactions necessary to achieve a global energy balance.

CO_2 Release

Given the solution from the energy balance component of the model, the calculation of CO_2 emissions rates is conceptually straightforward. The problem merely requires the application of appropriate carbon coefficients (carbon release per unit of energy) at the points in the energy flow where carbon is released. Carbon release is associated with the consumption of oil, gas, and coal. Large amounts of CO_2 are released from the production of shale oil from carbonate rock and from the production of synthetic fuels from coal. A zero-carbon-release coefficient is assigned to biomass, nuclear, hydro, solar, and conservation. Table B-3 shows the CO_2 emission coefficients used in the IEA model.

FIGURE B-3

SUMMARY OF INFORMATION FLOWS AND PROCEDURES IN THE IEA MODEL TO BALANCE ENERGY SUPPLIES AND DEMANDS



Model Results

Three separate scenarios were examined in conjunction with this study:

1. High economic growth with the more expensive nuclear power production costs produced a 2.345% annual growth in carbon emissions.

2. Slow economic growth with the more expensive nuclear power production costs produced 2.074% annual growth in carbon emissions.

TABLE B-3

CO_2 COEFFICIENTS FOR CARBON-PRODUCING FUELS IN THE CO_2 MODEL

FUEL	CARBON RELEASED (TERAGRAMS OF CARBON PER EXAJOULE)
LIQUIDS	19.7
GASES	13.8
COAL	23.9
CARBONATE ROCK (SHALE) MINING AND PROCESSING	27.9
COAL LIQUIFACTION	18.9
COAL GASIFICATION	26.9

3. Slow economic growth with halved nuclear power production costs produced a 1.674% annual growth in carbon emissions.

The CO_2 emissions used for the three scenarios are depicted in Figure B-4.

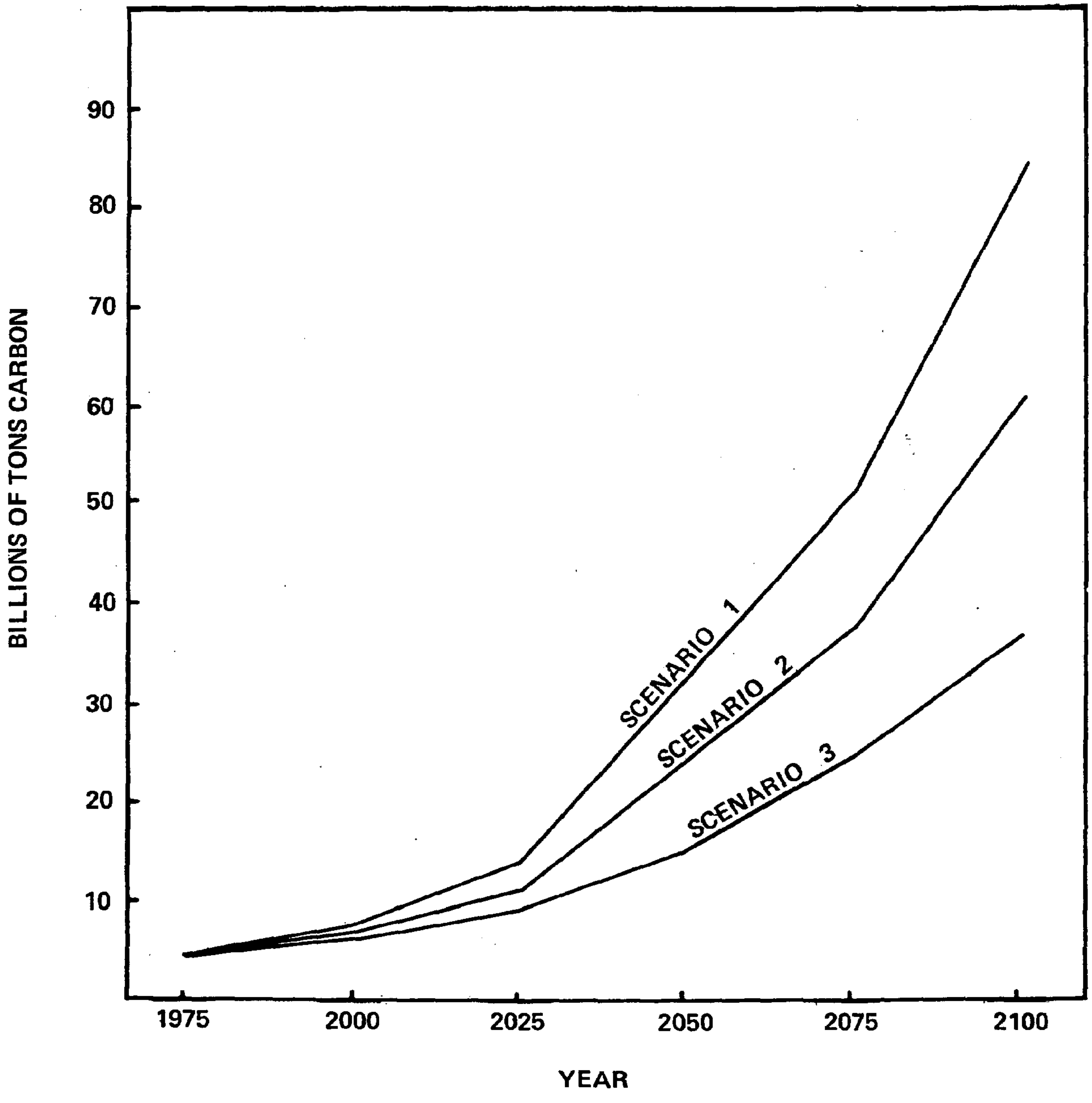
Reasonableness of the Assumptions

The forces that determine emission trends -- long-term population, labor force, and productivity growth, changes in energy supply and demand, additions to the resource base, and the interaction of these factors in a supply-demand framework -- are difficult to project. For example, energy technologies could change much more radically than currently foreseen. Large-scale biomass production might become much more feasible in the next century as an energy source if recombinant DNA and other biotechnologies produce supercrops; large fossil-fuel reserves might be discovered, which would radically decrease fossil-fuels costs;

FIGURE B-4

GLOBAL CO_2 EMISSIONS, 1975-2100

(Billions of Tons of Carbon)



new technologies might be developed that vastly reduce the costs of extracting hydrocarbons from shale or tar sand; or nuclear fusion might become a commercial reality sooner than expected. Any of these "surprises" would alter fuel use and emissions in ways unanticipated by our analysis. Although counting on such surprises would be foolish for a study like this, our conclusions must be tempered by the realization that the future may be very different from the extensive range of possibilities currently envisioned as possible.

With respect to the scenarios generated, the assumption that nuclear energy costs could be instantaneously halved in 1980 is overly optimistic. It was used simply to test the implications of a radical shift in the cost of a major energy source that does not emit CO_2. Other experiments with the model, such as doubling or tripling the cost of fossil fuels, had negligible effects on atmospheric temperatures.[4/]

Although the IEA energy model was designed for long-range policy analysis and satisfies this overriding objective, it does not consider the capital constraints that may limit the rates of substitution among competing fuels. By ignoring potential bottlenecks that could result, the model tends to overestimate the degree to which rapid change in energy supplies is possible. However, since the results of this study (projections of sea level rise) were relatively insensitive to energy projections, this limitation of the IEA model is not critical.

THE ORNL CARBON CYCLE MODEL

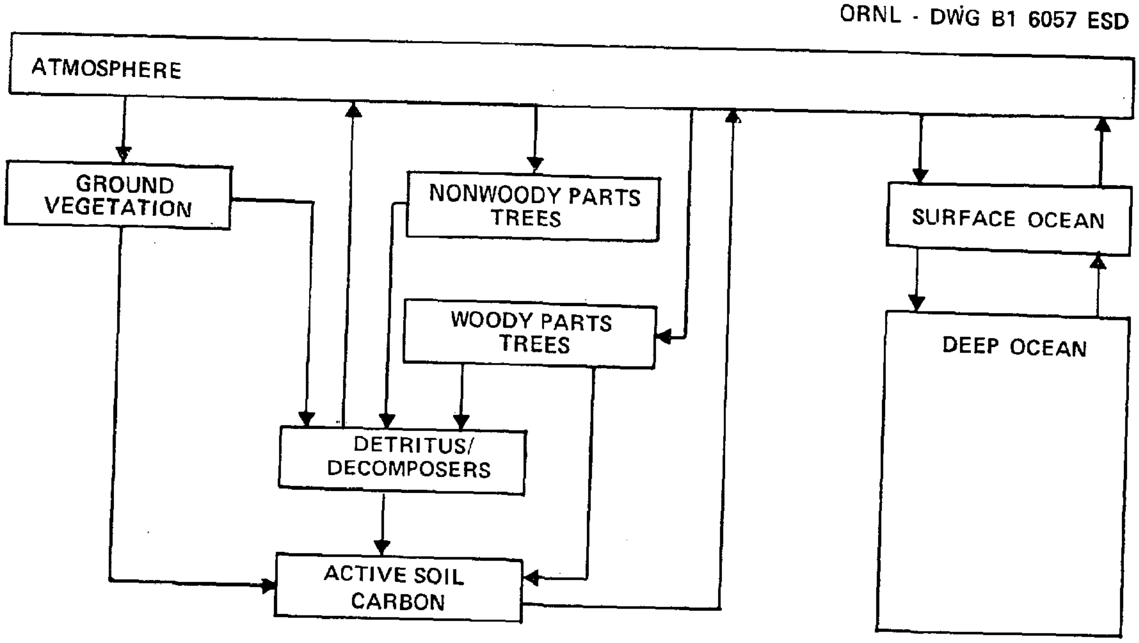
The Oak Ridge National Laboratory carbon cycle model represents flows and stocks of carbon on a global scale.5/ Terrestrial carbon is modeled in considerable detail, while ocean carbon is represented by a simple box-diffusion model. A general overview of the model is presented here.

Figure B-5 depicts the overall structure of the model. Carbon in living material is divided between ground vegetation, the wood parts of trees, and the non-wood parts of trees. Dead organic matter is divided between detritus/decomposer and active soil carbon. Finally, carbon in the oceans is subdivided into surface (less than 260 meters below sea level) and deep layers.

For each of the carbon reservoirs, equations specify maximum stocks of carbon and rates of flow into and out of the reservoirs. In general, terrestrial flows are modeled as linearly dependent on carbon content of the i^{th} donor reservoir ($F_{ij} = a_{ij} C_i$) or as a more complicated logistics function. (Details of the structural equations can be found in Emanuel, et al., 1981.)

The logistic functions for trees include terms for carbon release to the atmosphere from forest clearing. Permanent forest clearing is reflected by reductions in the parameters governing storage capacity. Where clearing is temporary, reestablishment of forests occurs in a delayed exponential fashion. (No future clearing option was assumed in this study.)

FIGURE B-5
STRUCTURE OF THE ORNL CARBON CYCLE MODEL



* THIS FIGURE IS TAKEN FROM AN UPDATED MANUSCRIPT BY W.R. EMANUEL AND OTHER AT OAK RIDGE NATIONAL LABORATORY.

Net uptake of carbon by the oceans is limited by the availability of carbonate ions. The rate at which gaseous CO_2 dissolves in seawater depends on the rate of reaction with CO_3^{--}, which is the first step of a process by which CO_2 is incorporated into various seawater carbonate compounds.

The rate at which carbon flows among the various reservoirs is generally dependent on atmospheric temperatures. Sensitivity to temperature is significant, because a rise in temperature is likely to accompany an increase in atmospheric CO_2. The original version of the ORNL represented this temperature-CO_2 relationship by a simple exponential equation, rather than through a series of heat-flux equations. This portion of the model was replaced by the relatively sophisticated heat-flux relationships in the GISS model, by coupling the two models (see the discussion under "Coupling the GISS and ORNL Models").

The model inputs are estimates of fossil-fuel carbon emissions on a yearly or longer time period basis from 1980 until some future year. (The IEA model estimates are on a 25-year basis. Estimates were provided on a 5-year basis by interpolation of the 25-year estimate.) Outputs are atmospheric CO_2 for 5-year intervals.

The model simulates historical patterns of carbon cycling from 1740 to 1980 on an annual basis. The resulting time trend in CO_2 was modified slightly so that the concentration in 1980 was 339 ppm. This corresponds to the level estimated by the GISS model in 1980, given estimates of fossil fuel carbon emissions in 1975 (the starting point of the IEA model) used in this study. The model was then run to produce estimates of atmospheric CO_2 from 1980 to 2100.

Reasonableness of the Assumptions

The fraction of carbon emissions retained in the atmosphere is the product of a complex biogeochemical cycle that evolves over time. Evidence indicates that as the atmospheric concentration of CO_2 increases, the fraction retained in the atmosphere will also increase. Consequently, using a constant fraction airborne is a very conservative assumption.

The number chosen for the low estimate was 53%, the best estimate of the historical fraction airborne.[6/] A lower number could have been chosen, based on the work of Woodwell et al., which states that past estimates of the biosphere's contribution were too low and thus caused fraction airborne estimates to be too high.[7/]

Lugo and other biologists, along with Broecker and other oceanographers, however, have challenged the Woodwell estimates.[8/] Broecker has shown that the oceans do not have the physical capacity to absorb CO_2 contributions from the biosphere as quickly as Woodwell had originally estimated, and Lugo has shown that Woodwell underestimated tropical forest regrowth, thereby overestimating net forest contributions.

Although it is a strong challenge to the Woodwell estimate, the rebuttal is not absolutely conclusive. Nevertheless, because all carbon cycle models show fraction airborne increasing over time, use of 53 percent probably constitutes a very conservative estimate of retained CO_2 emissions. The ORNL model modifies the fraction airborne over time by taking into account water heating and changes in ocean chemistry as well as temperature-sensitive changes in carbon flows among all compartments.

Even the ORNL carbon cycle model, however, is oversimplified, representing the oceans as a layered vertical column or box, and the biosphere by only a few types of vegetation. Ocean dynamics are far more complex, containing complicated and interdependent vertical and horizontal transports. Ocean chemistry is not well represented in models of the carbon cycle, and sources and sinks may be over- or underestimated.

The impacts of CO_2 and temperature change on photosynthesis and changes in ecosystems are not considered by these models. The inaccuracies produced by such emissions have not been estimated.

INCREASES IN CONCENTRATIONS OF TRACE GASES

Increases in the concentrations of trace gases will add significantly to the warming from CO_2. This report considers four of the most important gases: methane, nitrous oxide, CF_2Cl_2 (CFC-12), and $CFCl_3$ (CFC-11).

Scientific knowledge of these gases is sufficient to separately project emissions and atmospheric residence time only for chlorofluorocarbons. We assume that the half-lives of $CFCl_3$ and CF_2Cl_2 will be 60 and 120 years, respectively. The low, mid-range, and high scenarios assume that emissions will increase annually by 0.7, 2.5, and 3.8 percent of the 1980 level until 2020. Because these emissions will also cause depletion of stratospheric ozone, we assume that additional restrictions will be placed on their use and that emissions will remain constant after 2020. Because of the long residence times for these gases, their concentrations will continue to increase throughout the twentyfirst century in all scenarios. Table B-5 shows the resulting concentrations of these gases in 25-year intervals.

TABLE B-5

CONCENTRATIONS OF CHLOROFLUOROCARBONS
(parts per billion)

	Year						
	1980	2000	2020	2040	2060	2080	2100
Low Scenario							
$CFCl_3$ (CFC-11)	.18	.37	.54	.68	.79	.88	.94
CF_2Cl_2 (CFC-12)	.31	.69	1.06	1.44	1.73	2.00	2.25
Mid-Range Scenario							
$CFCl_3$	.18	.41	.69	.95	1.15	1.30	1.42
CF_2Cl_2	.31	.76	1.34	1.94	2.46	2.91	3.32
High Scenario							
$CFCl_3$	.18	.44	.79	1.14	1.40	1.60	1.76
CF_2Cl_2	.31	.84	1.64	2.51	3.27	3.93	4.51

Existing knowledge of the environmental fates of methane and nitrous oxide did not permit us to model the biogeochemical cycles for these gases. Instead, we projected their concentrations directly. For the low scenario, we assumed that the historical trends in the concentrations of methane and nitrous oxide would continue; for the mid-range and high scenarios, we assumed that they would accelerate. The concentration of nitrous oxide was assumed to increase from the 1980 level (0.3 ppm) geometrically by 0.2, 0.45, and 0.7 percent per year for the three scenarios

(Weiss, 1981). The concentration of methane was assumed to increase annually by 1.0, 1.5, and 2.0 percent for the three scenarios from the 1980 level of 1.6 ppm (Rasmussen, 1981).

SEA LEVEL RISE MODEL AND THE GISS ATMOSPHERIC TEMPERATURE

The GISS model used in this study was based on a one-dimensional radiative-convective (RC) model for estimating temperature increases associated with atmospheric CO_2 rises.[9] A routine for estimating sea level rises in response to temperature fluxes generated by atmospheric forcings was added for this study.

The RC model computes vertical temperature profiles over time from net radiative and convective energy fluxes. Radiative fluxes, in turn, depend on changes in atmospheric gases, especially CO_2, and on the associated feedback effects. The GISS equation used here is based on an empirical fit to the RC model.

The fitted equation, described in Hansen et al., was modified by Lacis for this study to incorporate trace greenhouse gases.

Heat Flux Computations

The heat flux into the earth's surface is estimated by an equation that contains all key temperature-related terms:

$$
\begin{aligned}
F(t) = {} & \frac{2.6\text{x}10^{-5}(\Delta\,\mathrm{CO2})}{[1+.0022(\Delta\,\mathrm{CO2})]^{0.6}} - \frac{5.88\text{x}10^{-3}}{T_e}(\Delta\,T) + \frac{3.685\text{x}10^{-4}}{T_e^{2}}(\Delta\,T)^2 \\
& - \frac{4.172\text{x}10^{-7}}{T_e}(\Delta\,\mathrm{CO2})(\Delta\,T) + 1.197\text{x}10^{-3}(\Delta\,\mathrm{CH4})^{0.5} \\
& + 5.88\text{x}10^{-3}(\Delta\,\mathrm{N20})^{0.6} + 3.15\text{x}10^{-4}(\Delta\,\mathrm{CC3}) + 3.78\text{x}10^{-4}(\Delta\,\mathrm{CC2}) \\
& - 1.197\text{x}10^{-4}(\Delta\,\mathrm{CH4})(\mathrm{N20}) - 2.40\text{x}10^{-2}(\Delta\,V) - 2.10\text{x}10^{-3}(\Delta\,V)^2 \\
& - \frac{1.17\text{x}10^{-3}}{T_e}(\Delta\,T)(\Delta\,V) + 3.184\text{x}10^{-1}(\Delta\,S)
\end{aligned}
$$

Where: F(t) is the heat flux as a function of time in cal min^{-1} cm^{-2}.

Δ CO2 is the change in atmospheric CO_2 from the 1880 value (293 ppm) in ppm.
Δ T is the change in atmospheric temperature (surface level) from the 1880 value in °C
Δ CH4 is the change in atmospheric CH_4 from the 1880 value (1.6 ppm) in ppm.
Δ N20 is the change in atmospheric N_2O from the 1880 value (.300 ppm) in ppm.
Δ CC3 is the change in CCl_3F from the 1880 value (0 ppb) in ppb.
Δ CC2 is the change in CCl_2F_2 from the 1880 value (0 ppb) in ppb.
Δ V is the change in atmospheric optical depth from a baseline level due to volcanic activity in dimensionless units.
Δ S is the change in solar luminosity from a baseline level in fractional units.
Δ T_e is the temperature equilibrium sensitivity -- the assumed temperature rise when CO_2 doubles from the 1880 level (from 293 to 586 ppm).

The heat flux is estimated for time periods ranging from each month to each year (a semimonthly time step was used in this study). The appropriate Δ T value for calculating F(t) in each time period (t=n) is the value estimated for the previous period (t=n-1). For a simple one-layer ocean model, Δ T is obtained by solving the following differential equation:

$$\frac{d \Delta T}{dt} = \frac{F(t)}{C_o}$$

Where: C_o is the heat capacity of the mixed layer of the ocean per unit area (cal cm^{-2}).

Estimates of heat flux from the empirical equation described above were compared by Lacis with the RC model calculations. The two estimates agreed to within one percent for CO_2 values of 0 to 1220 ppm, and to within 5 percent for CO_2 values of 1220 to

1700 ppm.[10] Values for the parameters in the empirical heat-flux equation were obtained as follows:

Δ CO_2: value obtained from the IEA and ORNL models;
Δ CH_4: 1.6 ppm from 1880 to 1980; concentrations after 1980 increase as described in section on trace gases.
Δ N_2O: 0.300 ppm in from 1880 to 1980; concentrations after 1980 increase as described in section on trace gases.
Δ CC_2 and Δ CC3: See Table B-5.

Δ V: constant 0.007 or 0.037 each year for 1980 to 2100

Δ S: 0 for 1880 to 2100; or 0 for 1880 to 1980 and increased or decreased by 0.005% per year for 1980 to 2100.

T_e: 1.5°C, 3.0°C, and 4.5°C.

Changes in Volcano Aerosols and Solar Irradiation

For special cases changes in aerosols and solar luminosity were considered. Aerosols and dust that are produced by volcanoes can lower global temperatures by increasing reflection of incoming energy. A higher estimate of optical depth than the baseline was used as a special case.

Baseline optical depth = .007 each year (dimensionless units)
High optical depth = .037 each year (dimensionless units)

An optical depth of 0.037 is the highest twenty-year average in the last century, while 0.007 is the average over the period 1900-1980. No basis exists for assigning a different value across a whole century. To sustain the high value over the next 120 years would require a continuation of levels of volcanic activity that have been sustained for decades, at most, in recorded history.

Recent evidence indicates some possible shifts in solar luminosity making the term "solar constant" a bit of a misnomer.

Two special case scenarios were considered:

Special Cases: 0.5% increase over 100 years and
0.5% decrease over 100 years

A one-half percent decrease in solar luminosity is much greater than would be likely in the time period under consideration. However, even such an improbably large variation would not overwhelm the greenhouse effect.

Diffusion of Heat in the Ocean

The ocean model consists of a mixed layer of depth $H_m = 100m$ and a thermocline with 62 layers and depth $H = 900m$. The mixed layer temperature is assumed to be independent of depth, while the thermocline temperatures are defined by a diffusion equation with constant thermal diffusivity. The layering is different from that used in the ORNL model, but the difference is not of importance in generating the expansion.

The temperature change in the mixed layer (ΔT_m) is a solution of the equation:

$$cH_m \frac{d \Delta T_m}{dt} = F(t) - F_D(t)$$

where c is the heat capacity of water, H_m is the depth of the mixed layer, F(t) is the heat flux from the atmosphere into the ocean and

$$F_D(t) = - \lambda \left. \frac{\partial \Delta T}{\partial z} \right|_{z=H_m}$$

is the heat flux from the thermocline into the mixed layer.

Note that our z-axis is directed toward the bottom of the ocean. Also, we use g, cm, sec and cal, so the heat conductivity lamda is numercially equal to the heat diffusivity K. Values for diffusivity were set at either 1.18 or 1.9 cm^2/sec. (Special scenarios investigated values of 0.2 and 4.0 cm^2/sec.)

The temperature change in the thermocline (Δ T) is determined by the diffusion equation:

$$c \frac{\partial \Delta T(z,t)}{\partial t} = k \frac{\partial^2 \Delta T(z,t)}{\delta z^2}$$

The boundary conditions for Δ T are:

$$\Delta T = \Delta T_m \quad \text{at } z = H_m$$

and zero heat flux at the bottom of the thermocline:

$$\frac{\lambda \partial \Delta T}{\partial z} = 0 \text{ at } z = H + H_m.$$

Thus it is assumed that no energy escapes through the lower boundary of the thermocline. Note that ΔT_m and ΔT are temperature <u>changes</u> of the mixed layer and the thermocline between the initial time (1880) and time t. It is assumed that in the year 1880 $\Delta T_m = \Delta T = 0$ and thus that the ocean temperature was in a state of equilibrium with the atmosphere at that time.

Required input data are atmospheric CO_2 levels on a yearly or longer time period. Five-year estimates were obtained from the ORNL, or alternatively, by multiplying a fixed-retention factor times the interpolated five-year estimates of carbon emissions from the IEA model. GISS outputs are estimates of ocean temperature increases on a five year basis.

The use of diffusivity coefficients as a surrogate for all circulation processes that transport heat may fail to describe the time paths well, with the downward heat transport in the latter period probably being overestimated because of increasing oceanic stability. Nevertheless this method simplified the problem substantially and a range of different possible coefficients was used to investigate the sensitivity of the overall estimate to the rate of downward heat transport.

These coefficients are:

High: = 1.9 cm^2/sec
Low: = 1.18 cm^2/sec
Special Scenarios: = 0.2 cm^2/sec (minimum)
= 4.0 cm^2/sec (maximum)

The range of coefficients used, 1.18 to 1.9 cm^2/sec is representative of mean oceanwide mixing rates as determined by the NSF-sponsored transient tracer experiment and others. Variation in estimates of the exact value of the data depend on the tracer used and the statistical method of computing the global mean. We tested 0.2 and 4.0 cm^2/sec to account for the possibility of dramatic changes in ocean transports due to deglaciation and climate change.

Sea Level Rise

Given a time trend in ocean temperature rise, the sea level change is estimated as:

$$\Delta H = \int_0^{H_m+H} dz \frac{\Delta a}{a}$$

where a is the specific volume and Δ a is its change due to thermal expansion. For this computation an ocean temperature of 10°C and salinity of 35 per mille are used. In other words, the mixed layer and each of the 62 layers in the thermocline expand to a degree that reflects the average pressure, and the rise in temperature of the layer (as reflected by the change in density). The average global rise in sea level is the output from this component of the model.

Crustal Movements

Systematic changes in the topography of earth's land or oceans can alter apparent sea level. No changes were assumed however, because global variations occur over a vastly longer time scale than the 120 year period considered here. Clark et al. estimated that long-term isostatic adjustment of the earth's surface has caused a worldwide sea level change of 1 meter per 5000 years (2 centimeters per century).[12/] In certain regions, coastal movements can substantially increase or decrease local sea level rise. However, such trends are likely to balance out worldwide.

COUPLING THE ORNL AND GISS MODELS

The general methodology for estimating thermal expansion of the oceans was outlined in Figure B-1. Of the two pathways for translating carbon emissions from fossil fuel combustion into atmospheric CO_2 concentrations (assuming a retention factor and running the ORNL model), this section focuses on the use of the ORNL model. As discussed previously, using the ORNL model to estimate atmospheric concentrations of CO_2 requires the coupling of the ORNL and GISS models and an iterative procedure using the GISS model alone. The discussion in this section emphasizes the sequence of actions employed to couple the two models, and the procedures for iterating within the GISS model.

Calculating Initial Temperature vs. Time Curves

The starting point for the analyses that use the ORNL model is the estimation of a family of temperature-time curves using the GISS model. These curves are employed in the ORNL model to describe a range of future increases in sea surface temperature (in response to rising atmospheric CO_2) which, in turn, will affect the rate of CO_2 exchange among sources and sinks. Essentially, the time trends of temperature, generated by a fairly sophisticated treatment of heat flux in the GISS model, replace the very simple CO_2-temperature relationships in the ORNL model. The treatment of heat flux in the GISS model is still a highly simplified representation of real ocean transports, as discussed above.

To generate the GISS temperature-time curves, it is first necessary to estimate an atmospheric CO_2-time curve, since this is the main driving function for the GISS model. The most straightforward approach is to apply a constant retention factor to the time trend of CO_2 emissions generated by the IEA model. In other words, the first step in this approach appears identical to the other methodological approach. In fact, a modification was employed for these analyses: changing retention factors (from about 0.6 in 1980 to about 0.8 in 2100) were used to generate the preliminary atmospheric CO_2-time curves.

The GISS model was then run with high and low temperature/ CO_2 sensitivity (T_e) values, with and without trace gases, to produce a family of curves of sea-surface temperature versus time. (Values for solar luminosity, volcanic activity, and heat diffusivity were specified in each scenario.) These curves are represented by a quadratic equation of temperature versus time with parameters a and b. The parameter a is the temperature difference between 2100 and 1980; b is the temperature difference between 2040 and 1980 divided by a. These parameters are then used to calculate coefficients for the quadratic equation $T = ct + dt^2 + 293$, where T is the temperature rise after 1980 (°K), and t is the number of years after 1980.

Four new curves reflecting the extreme values observed for a and b were then specified:

		a	
		Highest	Lowest
b	Highest	Case 1	Case 2
	Lowest	Case 3	Case 4

These curves bound all possible changes in temperature, given the time trend in atmospheric CO_2 specified previously. The four combinations of values for a and b are then transmitted to the ORNL model.

Calculating CO_2 v. Time Curves with the ORNL Model

The ORNL model is next employed to estimate future increases in atmospheric CO_2, using the fossil-fuel CO_2 emission scenarios from the IEA model and the four sea-surface-temperature time trends from the GISS model. Since four separate temperature/time curves are employed, four separate CO_2-time curves are generated as output. Each CO_2 curve is represented by estimates of atmospheric CO_2 concentrations in 10-year intervals from 1980 to 2100. Thus, a 4 by 13 matrix of values (corresponding to the four time v. temperature curves and the thirteen inclusive decades between 1980 and 2100) is generated as output.

Estimating Final Temperature v. Time Curves

The four "refined" time projections of CO_2 are returned to the GISS model to obtain a consensus temperature versus time curve. This is accomplished by selecting one of the CO_2 curves as a starting point. (Tests have demonstrated that starting from any one of the four curves will yield the same result.) The GISS model is then run to obtain a corresponding temperature curve from 1980 to 2100. This temperature curve is compared with the four temperature curves originally generated by the GISS model and transmsitted to the ORNL model. The new temperature curve is composed by interpolating among the four previous curves, and a new CO_2 curve is estimated corresponding to the interpolated temperature curve. (In essence, this is a two-way interpolation for each 10-year interval.) The whole process is repeated until two successive temperature curves closely approximate each other. Usually, this takes no more than two iterations.

To check the "accuracy" of such an iterative approach, the final temperature-time curve from GISS was used as input to the ORNL model for a small sample of runs. The resulting CO_2-time curve from ORNL was compared with the final CO_2-time curve in GISS. In all cases, the two agreed within 2 ppm for each 10-year interval.

Estimating the Contribution of Thermal Expansion to Sea Level Rise

Once the final projections of expansion to sea level rise are obtained, the equations in GISS relating ocean volume, temperature, and pressure described previously are employed to estimate thermal expansion. The increase in ocean volume is then translated into global mean sea level rise.

END NOTES TO APPENDIX B

1. The rationale for coupling the GISS and ORNL models in this fashion is based on (a) the sensitivity of many CO_2 uptake and release equations to temperature in the ORNL model, and (b) the more sophisticated treatment of heat flows and temperature changes in response to CO_2 increases in the GISS model. An alternative approach would be to replace the simple temperature equations in the ORNL model with the GISS equations, in essence combining the two models. However, the ORNL model is much more expensive to run than the GISS model. Thus, the coupled approach employed here is a cost-effective way to upgrade the treatment of temperature in the carbon cycle model.

   To illustrate the difference in results between the two basic analytical approaches (fixed-retention factor with the GISS model v. coupled ORNL-GISS modeling), we have listed estimated atmospheric CO_2 levels and sea level rise from 1980 to 2100 in the following table for each approach. Two sets of results are listed for the coupled ORNL-GISS modeling results -- the initial outputs from the ORNL and the final outputs from the GISS model. As shown, the coupled ORNL-GISS approach produces higher estimates than the fixed-retention-factor approach. This is reflected in the retention factor inferred from the ORNL-GISS modeling, which varies from 0.53 in 1980 to 0.72 in 2100.

   A second observation concerns differences between the two sets of ORNL-GISS outputs. The initial ORNL CO_2 (or sea level rise) time curve is higher than the final iteration from GISS, reflecting the fact that the ORNL results represent one of the four extreme temperature-versus-time curves. The final iteration from GISS is a CO_2 time curve interpolated among the extremes, as discussed in the section on coupling the ORNL and GISS models.

ESTIMATED ATMOSPHERIC CO_2 LEVELS AND SEA LEVEL RISE USING THE TWO BASIC ANALYTICAL APPROACHES

(High-Growth Scenario, High-Temperature Sensitivity, No Trace Gases)

	Fixed-Retention Factor (0.53A)*		Coupled ORNL-GISS Modeling			
			Initial ORNL Results		Final GISS Iteration Results	
	CO_2 Level (ppm)	Sea Level Rise (cm)	CO_2 Level (ppm)	Sea Level Rise (cm)	CO_2 Level (ppm)	Sea Level Rise (cm)
1980	339	0	339	0	339	0
1990	354	0.99	359	1.06	356	1.02
2000	370	2.22	382	2.47	375	2.32
2010	392	3.72	412	4.27	401	3.95
2020	420	5.58	451	6.57	436	6.03
2030	457	7.88	502	9.45	482	8.66
2040	511	10.80	578	13.15	555	12.09
2050	584	14.52	681	17.86	654	16.56
2060	676	19.13	814	23.71	784	22.19
2070	787	24.68	979	30.77	947	29.05
2080	919	31.19	1181	39.04	1147	37.16
2090	1083	38.71	1439	48.63	1403	46.62
2100	1281	47.31	1756	59.59	1720	57.48

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* A is a conversion factor to convert tons of carbon retained in the atmosphere into ppm of CO_2. A = 0.472 Gigatons of Carbon per ppm of CO_2.

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APPENDIX C

METHODS OF ESTIMATING SNOW AND ICE CONTRIBUTION

This appendix reviews the results and methods used to generate the estimates of ice melting in the doubled CO_2 experiments with the GISS general circulation model (GCM) and presents the methods used to estimate snow and ice contributions in the scenarios.

GLACIAL MASS BALANCE IN GISS GCM

by Gary Russell
Goddard Institute for Space Studies

The GCM doubled CO_2 experiments imply a sea level rise of 13.5 mm/yr due to melting of land ice. The melting is caused by a mean addition of heat of 3.27 Wm^{-2} to the surface of the land ice. The increment of sea level caused by reduced snow on the continents is insignificant compared to the glacial metling.

The following is a short description of algorithms applied to land ice in the GCM, tables of results from the control run and the doubled CO_2 experiment, and calculations based on those tables.

Precipitation that falls on the ground is calculated from the atmospheric conditions. Precipitation is snow if the first atmospheric layer temperature is below 0°C; otherwise it is rain.

$$\text{EPRCP } (W/m^2) = \begin{cases} 0 \text{ if } T^1 > Q. \\ -\text{PRCP*LHM if } T^1 < 0 \end{cases} \quad [\text{LHM} = 334000 \ (J/kg)]$$

PRCP is the precipitation in kg/m^25

The energy heat flux falling on the ground depends only on the phase of the precipitation, not additionally on the temperature of the rain or snow; this is an inaccuracy, but the error is a relatively small portion of the total flux. Rain over ice immediately runs into the ocean. SNOW (kg/m^2) accumulates on the surface. Over land ice, when the snow exceeds 100 (kg/m^2), some of it is compacted into ice so that the snow depth is reset to 90 (kg/m^2). The compacted ice is accumulated (with a minus sign) in the diagnostic MANDC.

<u>Evaporation</u> is calculated in the surface interaction routine and depends on the surface drag, surface wind magnitude, surface specific humidity, and the ground temperature.

EEVAP (W/m^2) = EVAP * LH

LH = 2500000 (J/kg) over water

LH = 2834000 (J/kg) over ice

EVAP is the evaporation in kg/m^2s

The temperature at which evaporation occurs is ignored.

<u>Runoff</u> over ice is the summation of rain plus melting of snow or ice at the surface, represented by RUNOFF 9kg/m^2s). Runoff carries no energy with it. Over earth, runoff depends on whether the ground is saturated and the energy of runoff is

ERUN (W/m^2) = RUNOFF * T (°C) * SHW [SHW = 4185 (J/kg°c)]

Other Energy Fluxes depend on the ground temperature, the atmospheric situation, the solar zenith angle, and surface albedo.

ESENS (W/m^2)	sensible heating
ESOLR (W/m^2)	net solar heating into the ice
ETHRM (W/m^2)	net thermal heat out of the ice

Net Energy Fluxes into the ground (or ice) are calculated as

$$\text{ENET } (W/m^2) = \text{EPRCP} + \text{ESOLR} - \text{ETHRM} - \text{ESENS} - \text{EVAP} - \text{ERUN}$$

If ENET is negative, the temperature of the ground snow or ice is reduced. If ENET is positive, snow and ice are warmed until they reach 0°C. At that point, snow is melted; after all the snow is melted, the remaining energy melts ice. The melted ice is accumulated in the diagnostic MANDC.

Melting and Compacting of glacial ice is a diagnostic of the GCM called MANDC (kg/m^2s), which is positive for melting. The following equality holds:

$$\frac{d}{dt}\text{ (SNOW + WATER + ICE)} = \text{PRCP} - \text{EVAP} - \text{RUNOFF} + \text{MANDC}.$$

SNOW, WATER, and ICE pertain to the first 4 meters in the ground. MANDC comes from the ice below the first 4 meters. Averaged over an annual cycle in a run which has achieved equilibrium, $\frac{d}{dt}$ (SNOW + WATER + ICE) should be nearly zero. There is energy associated with MANDC.

$$\text{EMANDC } (W/m^2) = \text{MANDC} * [T(°C) * \text{SHI} - \text{LHM}], \; [\text{SHI} = 2060 \; (J/kg°C)]$$

and an equation (for ice).

$$\frac{d}{dt}[(SNOW + ICE) * T * SHI] = ENET + EMANDC.$$

The time derivative was not calculated but is several orders of magnitude smaller than ENET or EMANDC.

Sources of Error

The results of the model should be interpreted in light of the following sources of error:

1. The major source of error is that the climate model uses fractional grid, i.e., each grid box can can contain ocean, sea ice, land ice, and earth. The composite surface albedo is an area-weighted average of the albedos of the separate surface types, but once the composite surface solar absorption is calculated, it is distributed into the surface types uniformly. When ocean ice is replaced by open ocean, the composite albedo will decrease and the increased solar absorption should primarily go into the ocean. However, the model erroneously sends part of the absorbed solar energy into the land ice and ocean ice. Correction of this feature of the model could significantly decrease the estimated melting rate of glaciers.
2. Another aspect of the fractional grid is that sensible heating is proportional to the ground temperature minus the surface air temperature, but the air temperature is a composite of the entire grid box. Because land ice is at a higher altitude than sea ice and the ocean, the sensible heating over land ice is underestimated in both runs. Because the net melting is the

difference between these two runs, the sign of the resulting error is not known.

3. Areas of land ice in the model include Antarctica, Greenland, islands along the Arctic Ocean, and glaciers in southern Alaska. Had alpine glaciers been included as well, the sea level rise from melting would have been somewhat greater.

General Comments on the Tables

1. The hemispheric and global numbers for water and ice were produced with a resolution of hundredths of a mm/day or 3.65 mm/yr. The latitudinal numbers used a resolution of tenths of mm/day or 36.5 mm/yr.
2. The hemispheric and global numbers for energy used a resolution of tenths of $W/.m^2$ except for EMANDC which is know to a hundredth of $W.m^2$. The latitudinal numbers used W/m^2.
3. ENET is calculated by subtracting large numbers and is therefore less accurate. EMANDC is a diagnostic accumulated directly in the GCM and should be much more accurate. (The latter is also true for MANDC).
4. The numbers are based on a 10 year average (years 26-35) of the control run 882 and doubled CO_2 experiment 886.
5. All numbers are per net area [1 (mm/yr) = 1 (kg/m^2yr)]. The associated area is all land area.
6. .0106 (W) added to a square meter of ice will melt 1 (mm) of ice during a year.

7. The 33 (mm/yr) of melting in the difference 886-882 applies to all land. The average melting over land ice is

$$300 \text{ (mm/yr)} = 36 \frac{.291 \text{ (land area)}}{.032 \text{ (land ice area)}}.$$

Similarly, the energy of melting in the difference 886-882 which applies to all land is .36 (W/m^2). Applying this to the land ice only it is 3.27 (W/m^2) $= .36 \frac{.291}{.032}$.

8. The 3 (mm/yr) of melting of land ice in the control run 882 would cause a sea level rise of

$$1.23 \text{ (mm/yr)} = 3 \frac{.291 \text{ (land area)}}{.709 \text{ (water area)}}$$

The 33 (mm/yr) of melting in the difference 886-882 would cause a sea level rise of

$$13.54 \text{ (mm/yr)} = 33 \frac{.291}{.709}$$

9. The sea level rise implied by the reduction of snow on the continents in 886, compared to 882, is

$$1.59 \text{ (mm)} = 3.75 \frac{.291}{.709}$$

This contribution is negligible, because it is a one-time change rather than a rate as in the above cases.

TABLE C-1

Water and Ice Units: (mm/yr)

Control run: 882 Quantities refer to Land

	Glob	NH	SH	82°N	74°N	67°N	59°N	-67°S	-74°S	-82°S	-90°S
PRCP	960	931	1022	329	438	621	694	730	475	183	110
EVAP	719	686	788	73	110	256	402	219	73	37	37
RUNOFF	245	270	190	292	402	475	402	840	73	0	0
$\frac{d\ SNOW}{dt}$	.05	.06	.02	1.1	.2	-.9	.2	.2	-.2	.3	-.4
$\frac{d(WATER + ICE)}{dt}$	-.4	-.6	0	0	0	-.6	-1.8	0	0	0	0
RUN+EV-PR	3	25	-44	36	74	110	110	329	-329	-146	-73
MANDC	3	26	-44	37	73	146	110	329	-329	-146	-73
Land Percentage	29.1	39.4	18.8	15.0	30.6	71.5	57.9	15.4	66.0	100.0	100.0
Land Ice Percentage	3.2	4.3	2.1	13.2	10.7	4.6	1.0	15.4	66.0	100.0	100.0
SNOW (mm)	17.6	15.7	21.6	95	114	61	30	55	82	85	86

TABLE C-2

Water and Ice Units: (mm/yr)

Difference: 886 - 882 Land

	Glob	NH	SH	82°N	74°N	67°N	59°N	-67°S	-74°S	-82°S	-90°S
PRCP	157	131	212	73	110	182	146	146	146	110	73
EVAP	110	95	146	0	0	110	110	-37	0	37	0
RUNOFF	80	55	128	475	255	182	110	1314	219	73	0
$\frac{d\ SNOW}{dt}$	Numbers are nearly 0.										
$\frac{d(WATER + ICE)}{dt}$											
RUN+EV-PR	33	19	62	402	145	110	74	1131	73	0	-73
MANDC	33	21	62	365	146	73	36	1095	73	0	-37
SNOW (mm)	-3.75	-4.8	-1.6	-21	2	-15	-15	-11	-5	-4	1

TABLE C-3

Energy — Units: (W/m^2)

Control Run: 882 — Quanitities Refer to Land

	Glob	NH	SH	82°N	74°N	67°N	59°N	-67°S	-74°S	-82°S	-90°S
ESOLR	154.5	150.2	163.3	32	42	70	96	57	38	38	42
ETHRM	+48.0	+48.0	+48.1	+23	23	30	37	27	30	33	39
ESENS	47.5	45.6	51.6	1	6	14	23	3	2	1	-1
EEVAP	57.3	54.7	62.6	5	8	21	32	16	5	4	4
EPRCP	-1.3	-1.4	-1.2	-5	-5	-3	-3	-7	-5	-2	-1
ERUN	.4	.4	.4	0	0	0.1	0.1	0	0	0	0
ENET	-.07	.17	-.56	-2	-1	1	1	3	-4	-2	-1
EMANDC	-.01	-.29	+.57	0	-1	-1	-1	-3	+4	+2	+1

TABLE C-4

Energy | Units: (W/m^2)

Difference: 886 - 882 | Land

	Glob	NH	SH	82°N	74°N	67°N	59°N	-67°S	-74°S	-82°S	-90°S
ESOLR	0.7	.6	1.2	3	2	-1	-1	3	-1	-2	-3
ETHRM	-4.0	-3.6	-5.0	-2	-2	-4	-4	-4	-3	-2	-3
ESENS	-4.2	-3.3	-6.3	0	0	-5	-5	-1	0	0	0
EEVAP	8.6	7.4	11.4	0	2	7	8	-3	0	0	0
ERPCP	0.1	.3	-.2	-1	-1	0	1	1	-1	-1	-1
ERUN	0.1	.1	.2	0	0	0.1	0.1	0	0	0	0
ENET	.37	.24	.63	4	2	1	0	12	1	0	-1
EMANDC	-.36	-.22	-.64	-4	-1	-1	-1	-12	-1	0	+1

INTERPRETATION OF GISS RESULTS

by John S. Hoffman

The problems with interpreting the GISS model results are twofold:

1. The model looks at the effects of doubled CO_2, while a projection would require looking at the system in transition from current CO_2 levels, to the doubled level and beyond. For the mid-range scenario, temperatures reach 4.1°C in the GISS doubled equilibrium run by 2050. A method needs to be developed to determine melting before this doubling and after it.
2. Melting in situ may not all run off. Some percentage will refreeze, raising the temperature of the ice and changing its physical characteristics. It is undetermined at this time whether those changes cause ice discharges greater than or less than if the melting had resulted in runoff.

These problems are now being analyzed by a team from GISS, NASA, and Lamont-Doherty Geological Observatory, along with several other issues. In the preceeding analysis the results were used only to check the general validity of the numbers developed through our procedure of extrapolating historical ratios, rather than to generate an ice and snow land-to-sea transfer scenario.

THE USE OF THE HISTORICAL METHOD FOR GENERATING SNOW-ICE CONTRIBUTIONS

by John S. Hoffman

A variety of authors have estimated sea level rise in the last century on the basis of tidal gauge stations. The estimates vary between 10 cm and 15 cm. Using historical changes in temperature, Hansen et al. and Gornitz et al. have varied CO_2 increases and the heat absorption capacity of the ocean as represented by the diffusitivity coefficent "K".[1/] For a T_e of 3°C, and a K of 1.2 $cm^2 sec^{-1}$, almost half of the total sea level rise could be accounted for. Sea level rose approximately 5 cm due to thermal expansion; thus, a 10 cm total rise implies 5 cm due to ice and snow transfer from land to sea, assuming changes in other water reservoirs to be negligible. However, if the historical sea level rise was actually 15 cm, then 10 cm was due to ice and snow contributions, giving the higher two-to-one historical ratio. Barnett, the source of the 15 cm estimate, attributes two-thirds of the rise to this source.[2/] The scenarios of future sea level are simply extrapolated past ratios, one to one as the low, two-to-one as the high. This ratio generates estimates within the contribution capacity of the ice sheets, alpine glaciers, and other water sources on land based on a review of several strands of evidence, including the GISS melting estimates.

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