Chapter 3

Estimates of Future Sea Level Rise

John S. Hoffman

INTRODUCTION

Accurate monitoring of atmospheric carbon dioxide began 25 years ago. Since then, sufficient scientific evidence has been developed for two National Academy of Sciences review panels to conclude that sometime in the next century, atmospheric concentrations of C0$_2$ will almost certainly double and raise the atmosphere's mean surface temperature by at least 1.5^{0}C (2.7^0 F) and possibly as much as 4.5^0 C (8.1^0 F) (Charney, 1979)[1]. Such a warming should also raise the global sea level. While adequate knowledge of the various determinants of sea level rise has been developed, until now this diverse knowledge has not been used to estimate possible sea level rise trends.

This chapter presents a range of sea level rise estimates, termed scenarios, that were developed on the basis of knowledge collected from a variety of disciplines, including energy economics, geochemistry, biology, atmospheric physics, oceanography, and glaciology. The most restrictive assumptions from these disciplines were linked together to generate a "conservative" scenario, which projects a sea level rise of 56.2 cm (22 in) by 2100. The least restrictive assumptions were used to generate a "high" scenario, which projects a rise of 345 cm (11.5 ft) by 2100.[2] Two mid-range scenarios were also developed, the mid-range low scenario which projects a rise of 144 cm (4.8 ft) and the mid-range high scenario which projects a rise of 216 cm. (7 ft). In the author's judgment, future sea level rise is most likely to fall in this range.

Although the scenarios span a wide range of sea level rise, they can still be used in analyzing environmental and economic impacts and to evaluate options for preventing or mitigating the adverse effects of this phenomenon. Narrowing the range of estimates of sea level rise would, of course, make these tasks easier. But rapid progress will be made only if funding is increased for key scientific disciplines. Thus, policy makers in government and business may also wish to use the scenarios in making their own assessments of the economic value of developing more precise sea level rise estimates.

THE APPROACH USED FOR ESTIMATING SEA LEVEL RISE

Future global sea level will depend primarily on three factors: the total quantity of water filling the oceans' basins; the temperature of the oceans' layers, which determines the density and volume of their waters; and the bathymetry (shape) of the ocean floor, which determines the water-holding capacity of the basins. A rise in global temperature can, by a variety of physical mechanisms, transfer snow and ice from land to the sea, increasing the quantity of water in the ocean basins, and can raise the oceans' temperatures, causing the thermal expansion of their volumes. Changes in the bathymetry of the oceans' floors occur independently of climate change. Because geological changes in the ocean floor could not raise or lower global sea level by more than a centimeter or two by 2100 (Clark et al., 1978), this factor was not considered in constructing the global scenarios. An evaluation of the impacts of sea level rise at specific coastal sites, however, will require consideration of local uplift or subsidence, which by 2100 could cause changes in land elevation that are large enough to be of significance to local planning (Boesch, 1982).

Projecting sea level rise requires the means to estimate future changes in atmospheric composition, to relate these changes to global warming, and then to determine how the warming can cause land-based snow and ice to enter the sea and the oceans to expand thermally. Figure 3-1 summarizes these relationships and the various alternative assumptions and models used to represent them. Details about these relationships, models, and assumptions are discussed below.

FUTURE ATMOSPHERIC COMPOSITION

This section provides further background on the models and assumptions used to estimate $C0_2$ levels, one of the most important determinants of global temperature. The models and assumptions used to estimate the growth of atmospheric concentrations of trace gases that will influence climate are also discussed.

Estimates Increase in Atmospheric Concentration of CO_2

Although large quantities of carbon circulate between the oceans, atmosphere, and biosphere, before the widespread use of fossil fuels and the removal of forests, the cycling of carbon among these natural compartments had evolved to maintain a more or less stable level of atmospheric $C0_2$. Ice cores, for example, provide evidence that $C0_2$ levels fluctuated no more than 40 ppm for thousands of years (Barnola et al., 1983).

The industrial revolution brought about an enormous change in the carbon cycle, altering its balance dramatically. Machines helped expand the economy to unprecedented levels, allowing much greater amounts of "work" to be done than in pre-industrial economies. In accomplishing this feat, however, enormous quantities of gas and oil had to be used. Combustion of these fuels has grown so large that by 1980, 5 billion metric tons of carbon were being released into the atmosphere every year (Rotty, 1983).

Because this fossil carbon had rested inertly in the ground for hundreds of millions of years (outside the earth's normal cycling of carbon), the sudden injection of $C0_2$ into the atmosphere has greatly overwhelmed the capacity of the biosphere and oceans to absorb $C0_2$. In essence, each year's fuel combustion restores a quantity of carbon to the atmosphere that had taken plants thousands of years to remove. Consequently, atmospheric concentrations Of $C0_2$ have been increasing rapidly: since the 1860s, concentrations are estimated to have risen 20 percent worldwide, while since 1957, monitored data show an increase in atmospheric $C0_2$ concentrations of more than 7 percent (Keeling et al., 1976). Future levels of $C0_2$ will depend on future emissions and on the future capacity of the earth's oceans and biosphere to absorb emissions rather than having them remain in the air-the so-called fraction airborne of $C0_2$.

Table 3-1. Estimated Sea Level Rise, 2000–2100, by Scenario (in cm, with inches in parentheses)

Year	Conservative	*Mid-Range Scenarios*		High Scenario	Historical Extrapolation
		Moderate[a]	*High*		
2000	4.8	8.8	13.2	17.1	2-3
	(1.9)	(3.5)	(5.2)	(6.7)	(0.8-1.2)
2025	13.0	26.2	39.3	54.9	4.5-8.25
	(5.1)	(10.3)	(15.5)	(21.6)	(1.8-3.2)
2050	23.8	52.3	78.6	116.7	7-12
	(9.4)	(20.6)	(30.9)	(45.9)	(2.8-4.7)
2075	38.0	91.2	136.8	212.7	9.5-15.5
	(15.0)	(35.9)	(53.9)	(83.7)	(3.7-6.1)
2100	56.2	144.4	216.6	345.0	12-18
	(22.1)	(56.9)	(85.3)	(135.8)	(4.7-7.1)

Source: From J. Hoffman, D. Keyes, and J. Titus, 1983, *Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs,* 2nd rev. ed., U.S. GPO No. 055-000-00236-3, Washington, D.C.: Government Printing Office.

Note: Scenarios recorded here differ slightly from those in other chapters because of refinements made in the treatment of trace gases in the second revised edition.

[a] Called the low scenario in other chapters.

Figure 3-1 Conceptual basis for estimating sea level rise. High, low, and mid-range assumptions were made or derived from models about each factor that determined atmospheric condition, global warming, thermal expansion, ice and snow discharge, and thus sea level rise. By spanning a full range of estimates for these factors and coupling them on a yearly basis, conservative, mid-range, and high scenarios were generated on a yearly basis to the year 2100.

Future Carbon Dioxide Emissions. Future levels of $C0_2$ emissions will be determined by economic growth and technological change. Economic growth is driven by population and productivity growth. The development of technologies for energy production and use is also the consequence of a complex set of factors. In this analysis, $C0_2$ emissions projected by using a world energy model developed at the Institute for Energy Analysis (IEA) and a series of assumptions gathered from a review of the literature. This model determines fuel use and emissions by simulating market mechanisms. Because many factors about the relevant variables are uncertain, various assumptions about these factors can be run in the model to produce internally consistent estimates of fuel use (Edmonds and Reilly, 1981).

The IEA model desegregates the world into nine regions, balancing the demand and supply of energy in each region by internal production and external trading, in which production and transportation costs determine the costs of satisfying a region's demands. Once fuel use trends are generated, standard emission coefficients are used to estimate $C0_2$ emissions. Model validity was established in a number of ways, including a parametric sensitivity analysis of its various coefficients. The model's outputs were also compared with work done elsewhere, such as that reported in IIASA's (the International Institute for Applied Systems Analysis) *Energy in a Finite World* (Haefle, 1981), and provide consistent, although somewhat lower estimates of energy use than many other efforts.[3] The IEA model, however, has the advantage of being able to test the implications of a wide range of assumptions about energy technologies, policies, and events, as well as the sensitivity of fuel use to other assumptions.

Using this model, a detailed study has been conducted of an array of policies intended to reduce $C0_2$ emissions (Seidel and Keyes, 1983). The study indicates that $C0_2$ emissions are likely to grow regardless of the policies implemented. For example, a tax that quadrupled fossil fuel prices by 2000 reduced $C0_2$ emission growth insufficiently: a 2^0C global warming was delayed by only five years. Thus, the world's capability to displace fossil fuels in an effective manner appears quite limited.

Some of the assumptions used in this effort were quite conservative, even for the high scenario. For example, for population growth, a single demographic projection was used: all regions of the world were assumed to reach zero population growth by 2075. Many demographers would regard such an assumption as optimistic. Nonetheless, based upon the work of Keyfitz et al. (1983) and others, it seemed reasonable.

For productivity growth, two assumptions were made:

For the high scenario, world labor productivity growth was assumed to start at 3.5 percent per year and decline linearly to 2.2 percent by 2100.

For the low scenario, world labor productivity growth was assumed to start at 2.2 percent and decline linearly to 1.7 percent by 2100.

Both the high and low assumptions are below the rate of productivity growth achieved in the world in the last 30 years.

Next, the energy used for production had to be estimated. This use will depend on the mix of goods and services produced in the world's economies and the technologies utilized to meet those needs. For all scenarios, the energy use per unit of output was assumed to decline with economic growth, reaching 40 percent of its current level by 2100. This assumption was based on the expectation of increasing conservation and the tendency of societies growing more affluent to shift output toward less energy intensive products (Edmonds and Reilly, 1981).

The selection of future energy sources to meet total energy demand was based on the comparative costs of satisfying the energy needed, which depends on the availability of resources, the costs of transporting fuels, and on available energy extraction and use technologies. Three sets of assumptions were made regarding these areas.

For the high scenario, a best guess based on current research was made about the future costs of various energy technologies. Progress was assumed for emerging technologies such as solar, but no unprecedented breakthroughs were assumed.

For the mid-range scenarios, emissions were assumed to be halfway between the conservative and high scenarios.

For the conservative scenario, the cost of nuclear energy was halved, starting in 1980, from current levels, thereby increasing the comparative attractiveness and use of this form of energy. Such an assumption obviously is unrealistic, but by lowering the cost of a nonfossil fuel energy so quickly, it created a more restricted fossil fuel growth.

The IEA model, of course, was used to integrate these different assumptions and produce various emissions trends.

Fraction Airborne Assumptions. A precise accounting of all the sources and sinks of carbon has not yet been achieved. This alone makes precise specification of the fraction of $C0_2$ that will remain airborne impossible. In addition, many of the biogeochemical processes that control the exchange of carbon may be somewhat influenced by climate and rising $C0_2$, thus making estimation of the future fraction airborne even more difficult.

Nevertheless, knowledge of the carbon cycle is sufficient to make some reasonable limiting assumptions. Oceans (the primary sink for emissions), for example, will have limited capacity to absorb $C0_2$, and the implication is that the percentage of future emissions absorbed by that sink will decline (Broecker et al., 1980). Three assumptions were used to represent the future evolution of the fraction airborne.

For the conservative scenario, the best estimate of the historic fraction airborne was used (53 percent) as an estimate of its future value.

For the high scenario, a carbon cycle model that considers some, but not all, of the factors that will cause the fraction airborne to rise was used to generate an evolving and rising fraction airborne (from 61 percent to 80 percent by 2100).

For the mid-range scenarios, the fraction airborne was assumed to rise as in the carbon cycle model.

The choice of 53 percent as the most restrictive assumption, rather than a lower estimate advocated by few researchers (e.g., 40 percent), can be justified for two reasons. First, the fraction airborne will almost certainly rise, making it almost certain that over the time period of concern that the fraction airborne would actually rise above the low estimate. Second, evidence has accumulated that makes earlier claims of large amounts of deforestation (Woodwell, 1978) seem to high. A higher estimate of deforestation implies greater CO_2 emissions and thus more CO_2 remaining airborne to produce the observed increase in atmospheric concentrations. Biologists (Lugo, 1980) have shown that early estimates of forest contribution ignored forest regrowth (which would recycle the carbon back into biomass), while oceangraphers (Broecker et al., 1980) have shown that the ocean could not physically absorb amounts of CO_2 required by the deforestation estimates. Thus, while some doubt still persists about the best estimate of the historical fraction airborne, the use of a constant 53 percent for the future fraction airborne probably will, in any case, be a conservative assumption of its future level. If, however, Woodwell turns out to be correct, from 1990 to 2050, the additional CO_2 resulting from deforestation will compensate for the lower fraction airborne, and the scenarios discussed here will be valid. After 2050, however, forests would be exhausted and global heating and sea level rise would not increase as quickly as predicted (Keyes et al, 1984).

While the model of the carbon cycle developed by Emmanuel and Killough of Oak Ridge National Laboratories (ORNL) predicts a fraction airborne that rises in the high scenario, it does not represent the highest plausible level of CO_2 remaining in the air. The model simulates the exchange of carbon from oceans, biota, and the terrestrial features of the earth and the atmosphere at a highly aggregate level and in a simplified manner (Killough and Emmanuel, 1981). As such, the model represents some of the carbon cycle such as the oceans' limited capacity to absorb CO_2 that could raise the fraction airborne. The model does not, however, consider possible changes in oceanic circulation that could be induced by warming. As the surface layers of the ocean warm, circulation could decrease, further from reducing the oceans' capacity to absorb $C0_2$. Thus, although the model's outputs were used as the high assumption, the ORNL model appears to be a more realistic assumption for the fraction airborne than the historical estimate and was used in the mid-range estimates.

Increases in Atmospheric Concentrations of Trace Gases

During the 1970s the trace gases methane, nitrous oxide, and chlorofluorocarbons began to be monitored more accurately. Observed increases in the concentrations of these gases appear to have had between 50 and 100 percent of the warming effect of the rise in $C0_2$ in that decade (Lacis et al., 1981). Unfortunately, atmospheric concentrations of the trace gases could not be projected in the same manner as concentrations of $C0_2$. With the exception of the chlorofluorocarbons, our knowledge of man-made and natural sources and sinks of these gases, the biogeochemical exchange mechanisms between their storage compartments, and the atmospheric chemistry that governs their chemical form in the atmosphere has not yet advanced to the point that their future concentrations can be meaningfully projected by estimating emissions and fraction airborne separately. Thus, for methane and nitrous oxides, direct historical observations of the concentrations of these trace gases in the atmosphere were used as a basis for estimating future concentrations; for chlorofluorocarbons, emissions were projected and a simple model of their expected residence time in the atmosphere was used.[4]

For the low scenario, atmospheric concentrations chlorofluorocarbons were assumed to increase based on 60 year and 120 year half-lives for $CFCl_3$ (R-11) and CF_2Cl_2 (R-12), respectively, and on the assumption that emissions increase at 0.7 percent of the 1980 level every year until they are capped in 2020 (Gibbs, 1983); nitrous oxide concentrations were assumed to grow at 0.2 percent per year (Weiss, 1981); and methane concentrations were assumed to grow at 1 percent per year (Rasmussen,1981).

For the mid-range scenarios, chlorofluorocarbon emissions were assumed to grow annually by 2.5 percent of the 1980 level until they are capped in 2020 (Gibbs, 1983); the concentrations of atmospheric nitrous oxide were assumed to grow by 0.45 percent per year (Weiss, 1981); and the concentrations of methane were assumed to grow by 1.5 percent per year (Rasmussen, 1981).

For the high scenario, chlorofluorocarbon emissions were assumed to grow annually by 3.8 percent of the 1980 level until they are capped in 2020 (Gibbs, 1983); nitrous oxide concentrations were assumed to grow 0.7 percent per year (Weiss, 1981); and methane concentrations were assumed to grow 2.0 percent per year (Rasmussen, 1981).

The possibility exists that new sinks or new sources of methane and nitrous oxide could arise, either as a result of climatic change or human activity. For example, global warming could result in methane hydrates located on northern continental shelves becoming a source of methane emissions (McDonald, 1982). Rising $C0_2$ could cause changes in plant and soil interactions (through the fertilization effects Of $C0_2$), making soils a greater source of nitrous oxide (Lemon, 1983). Similarly, the possibility exists that current sources or sinks may become exhausted. If either of these situations arises, the resulting change in the biogeochemical cycle could radically alter the growth of atmospheric concentrations of these gases. Unfortunately, without a significant increase in research in these areas, it will be difficult to improve projections of the future concentrations of these gases.

FUTURE GLOBAL TEMPERATURE

Global surface temperature is determined by the radiation received from the sun (mainly in the visible part of the spectrum), the reflectivity of the earth's surface and atmosphere, and the amount of outgoing invisible infrared radiation that the atmosphere traps. Without the atmosphere's greenhouse constituents, the thermal balance (temperature) of the earth would be relatively straightforward to estimate: the outgoing infrared radiation would balance incoming visible radiation at an effective temperature of approximately-18° C (0° F) (Hansen et al., 1983).

Fortunately for the existence of life on earth, the atmosphere has greenhouse gases, such as H_20, $C0_2$, methane, chlorofluorocarbons, N_20, and other trace gases, which trap some of the escaping infrared radiation, thereby raising the earth's temperature. These gases are called greenhouse gases because they allow sunlight to pass unimpeded to the earth's surface but absorb the infrared radiation given off by the earth. After absorbing the infrared energy, the gases warm, and then re-radiate the energy, half of which goes downward to the planet's surface. With the earth's current concentrations of greenhouse gases, enough energy is trapped to raise the earth's surface temperature to 33° C (58° F) (Hansen et al., 1983).

Increasing concentrations of atmospheric $C0_2$ and other infrared-absorbing gases will cause more radiation to be trapped and raise temperatures. The temperature rise associated with the radiative effect of rising concentrations of greenhouse gases would not be difficult to estimate if the warming did not further alter the composition of the earth's atmosphere or change the earth's reflectivity: a doubling of $C0_2$ would raise the average surface temperature 1.2° C. In reality, however, the radiative forcing (that is, the initial warming) will change the atmospheric composition and surface reflectivity of the earth in ways that amplify the warming. Determining the magnitude of amplification is difficult, thus adding uncertainty as to the effect of rising $C0_2$ (or other greenhouse gases).

The Amplification of Initial Warming Effects

The initial warming will cause water vapor to evaporate; as the evaporated water enters the air, it will trap more infrared radiation, thereby causing further temperature increases. The initial warming will also melt snow and sea ice, thereby reducing the sunlight reflected back into space and causing even further warming. Other feedbacks also exist; changes may occur in cloudiness or cloud height, for example, which, depending on how they occur, could raise or lower the amplification. Unfortunately, at this time, scientific understanding of all the relevant climatic processes is insufficient to determine the total amplification with precision. The best the scientific community has been able to do is to conclude that the total amplification will be at least 25 percent (Chamey, 1979).

In building the scenarios, uncertainties about the response of the various parts of the climate system were encompassed by using a wide range of the estimates of thermal sensitivities (or thermal equilibrium responses) made by the National Academy of Sciences (NAS) after two thorough analyses of the evidence.[5]

For the low scenario, a 1.5° C temperature rise was assumed for a doubling of $C0_2$ concentrations.
For the mid-range scenarios, a 3.0° C rise was assumed for a $C0_2$ doubling.
For the high scenario, a 4.5° C rise was assumed for a doubling of $C0_2$.

Other Forcings

Two other forcings can influence the earth's thermal balance in the time frame under consideration: changes in particulates and volcanic aerosol levels and changes in solar irradiation. Shifts in solar irradiation would be caused by shifts in the output of energy from the sun or by alterations of the earth's orbit or axis. These latter changes occur far too slowly and are not relevant within the time frame under consideration (Hays et al., 1976). Thus, the possibility of an ice age driven by the Milankovitch effect may be ruled out; the time frame for such a cooling would be much longer than the 120 years considered in this effort.

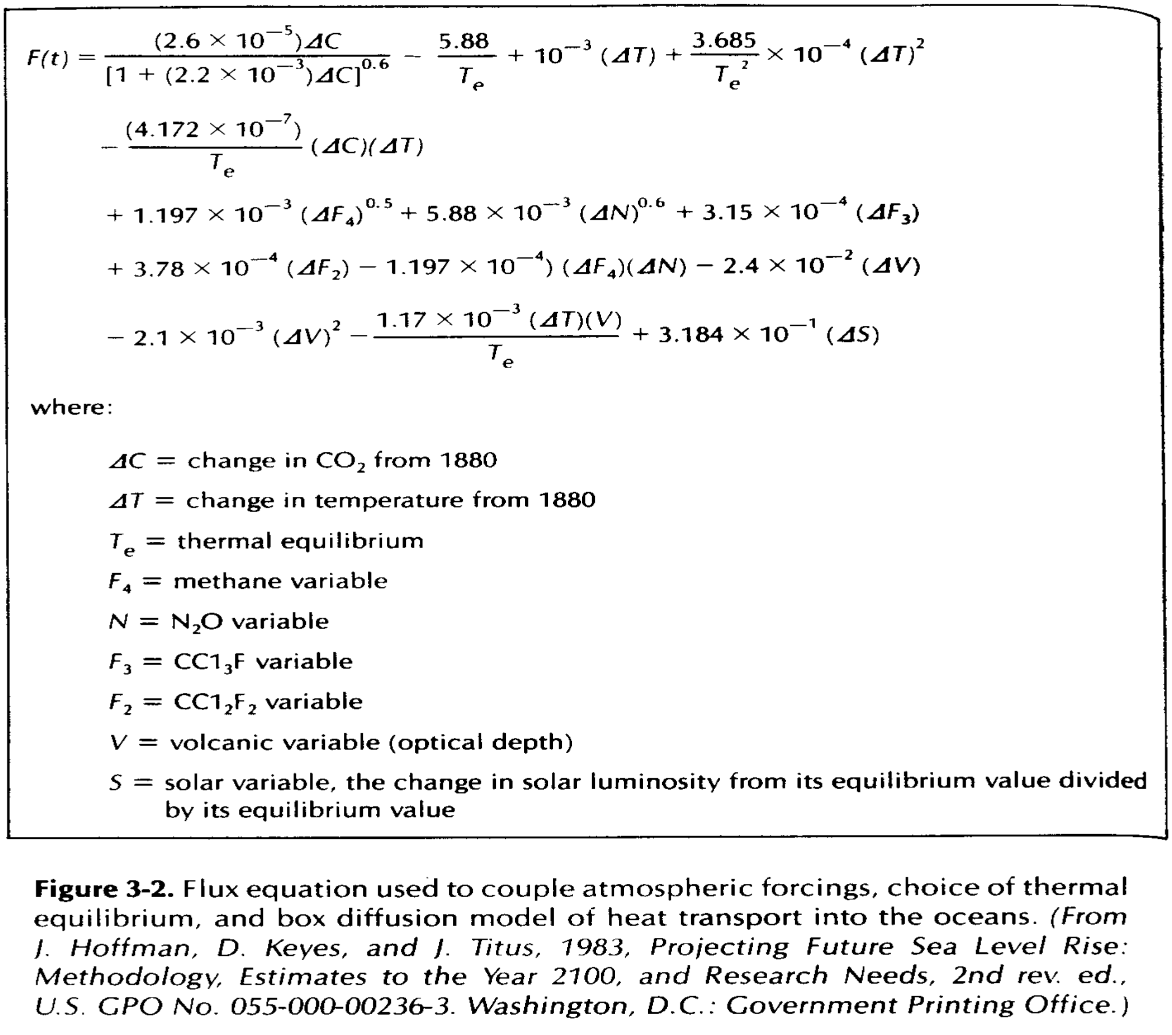
Preliminary evidence from NASA and other astronomical observations, however, indicates that yearly changes in solar irradiation could be large if the changes recorded to date continue in a single direction for long periods of time (Wilson, 1982). However, no evidence for any systematic unindirectional change exists at present (Wilson, 1982).

Shifts in concentration of tropospheric particulates can be produced by economic activity. The warming or cooling effects of these particulates, however vary with their physical nature and their geographic distribution (Bach, 1981). At this time, it appears that both their positive and negative thermal effects should cancel out (Bach, 1981). Therefore, tropospheric particulates were assumed to have no net effect. Volcanic eruptions, however, can transport aerosols to the stratosphere, which will lead to a cooling effect. Agung, a large Indonesian volcano, exploded in 1963, for example, decreasing global temperatures for the following year (Hansen et al, 1978).

Because of their potential influences, changes in volcanic activity and solar irradiation were considered in several “special case” scenarios. In one scenario it was assumed that throughout the next 100 years, the optical opacity of the atmosphere (the factor that volcano aerosols increase) would remain at the level it reached during the two decades of the last century when optical opacity was highest. Changes in solar irradiation were also tested in several special case scenarios. In some of these scenarios, a linear increase to a total of 0.5 percent was assumed over the next 100 years, while in other scenarios, solar irradiation was assumed to decrease linearly by that same amount. Evidence supporting either of these two shifts, however, is lacking and these scenarios should not be looked upon as accurate predictors.

Atmospheric Composition and Temperature Sensitivity

A complex climate model was not used to incorporate the temperature effects of the forcings on yearly global temperature. Instead, an equation was used (see Figure 3-2) that had been empirically fit to a one-dimensional radiative convective climate model (Hansen et al,. 1981). This equation allowed the various changes in the independent factors, or forcings (e.g., changes in atmospheric composition or solar irradiation), to be related to changes in atmospheric composition and to assumptions about thermal equilibrium, the levels of the aerosols, and solar irradiance. The equation had been coupled to a box-diffusion model of the ocean so that it actually generates a heat flux to the ocean, the size of the flux depending on the difference in temperatures between the air and the ocean’s surface. In this way, the various forcings and responses of the climate system were integrated with an “oceans model” that simulates the delays that will occur in atmospheric warming as a result of the ocean's capacity to absorb heat. The heat flux is generated on a year-by-year basis, as atmospheric concentrations of greenhouse gases change. Thus, atmospheric and oceanic temperatures rise slowly, with heat gradually being passed to lower layers of the ocean.



$$F(t) = \frac{(2.6\times 10^{-5})\Delta C}{[1+(2.2\times 10^{-3})\Delta C]^{0.6}} - \frac{5.88}{T_e} + 10^{-3}(\Delta T) + \frac{3.685}{T_e^{2}}\times 10^{-4}(\Delta T)^2$$

$$- \frac{(4.172\times 10^{-7})}{T_e}(\Delta C)(\Delta T)$$

$$+ 1.197\times 10^{-3}(\Delta F_4)^{0.5} + 5.88\times 10^{-3}(\Delta N)^{0.6} + 3.15\times 10^{-4}(\Delta F_3)$$

$$+ 3.78\times 10^{-4}(\Delta F_2) - 1.197\times 10^{-4})(\Delta F_4)(\Delta N) - 2.4\times 10^{-2}(\Delta V)$$

$$- 2.1\times 10^{-3}(\Delta V)^2 - \frac{1.17\times 10^{-3}(\Delta T)(V)}{T_e} + 3.184\times 10^{-1}(\Delta S)$$

where:

ΔC = change in CO_2 from 1880
ΔT = change in temperature from 1880
T_e = thermal equilibrium
F_4 = methane variable
N = N_2O variable
F_3 = $CC1_3F$ variable
F_2 = $CC1_2F_2$ variable
V = volcanic variable (optical depth)
S = solar variable, the change in solar luminosity from its equilibrium value divided by its equilibrium value

Figure 3-2. Flux equation used to couple atmospheric forcings, choice of thermal equilibrium, and box diffusion model of heat transport into the oceans. *(From J. Hoffman, D. Keyes, and J. Titus, 1983, Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs, 2nd rev. ed., U.S. GPO No. 055-000-00236-3. Washington, D.C.: Government Printing Office.)*

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FUTURE OCEAN AND GLACIAL RESPONSES TO GLOBAL WARMING

The effects of global warming on sea level also depend on how that warming influences the oceans and ice sheets of the world. This section describes the models and assumptions used to produce the scenarios.

Ocean Response

As discussed, increases in global temperature will not raise the average temperature of all the oceans' various layers immediately. The temperature of the surface waters will respond most quickly, essentially increasing in synchrony with atmospheric temperature. The transport of heat downward, however, will be slower (Charney, 1979). Furthermore, as an atmospheric warming occurs, the circulation of ocean waters will probably decrease, slowing the formation of deep cold water at the poles and thus the upwelling of cold water elsewhere. Changes in circulation could ultimately alter the rate of oceanic heat absorption, especially toward the end of the next century. Because the speed at which these circulation changes will occur is not clear, however, this possibility was not considered in creating the scenarios. The effects of such a change on thermal expansion would in any case be ambiguous. A decline in heat absorption would tend to slow thermal expansion, but this tendency would be counteracted the fact that global warming would occur faster.

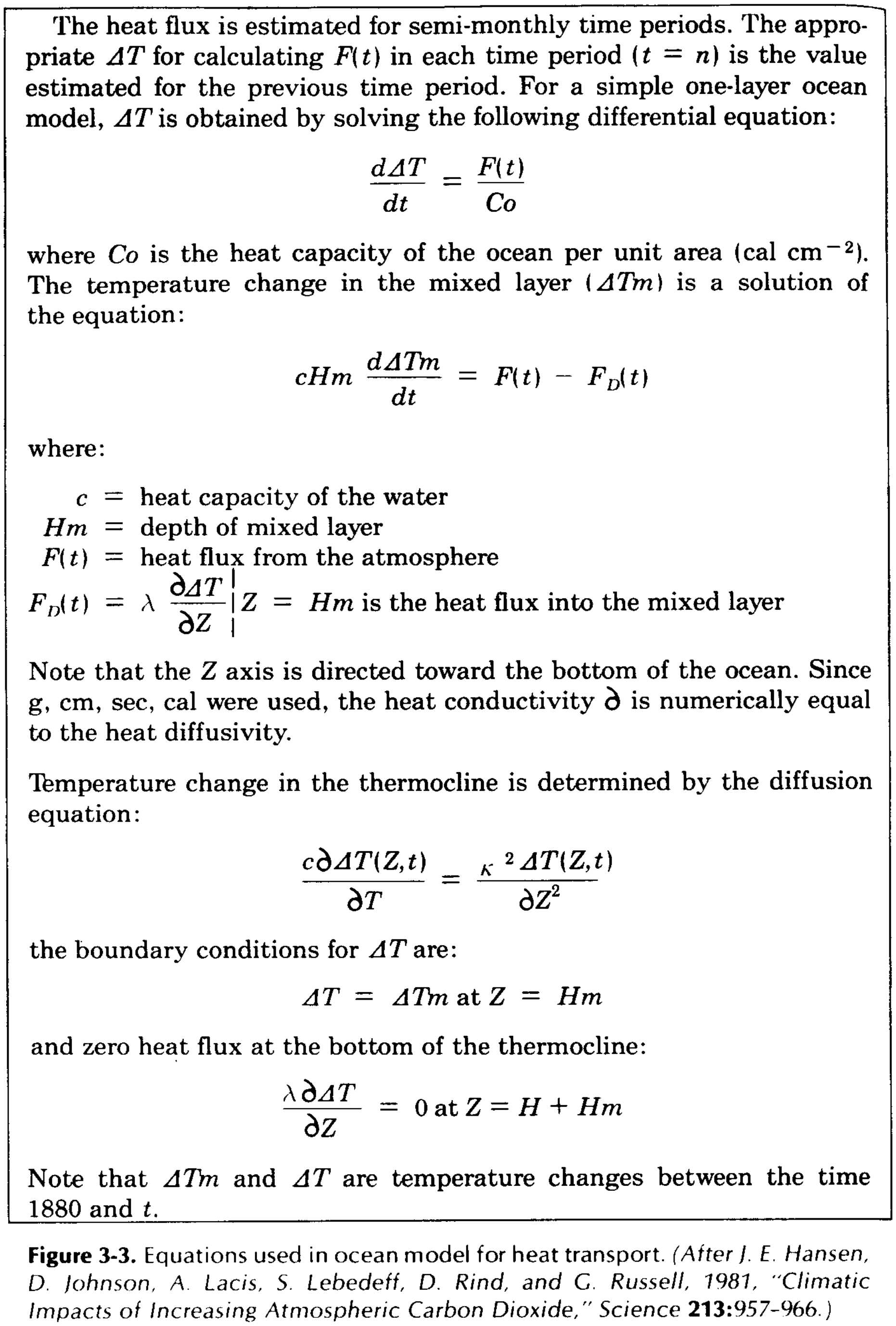
The ocean model assumes that a column of water can be used to represent the oceans and that heat can be transported downward like a passive tracer. (Figure 3-3 shows the equations used.) The estimate of the rate of heat diffusion downward uses data from various studies of radioactive and chemical tracers. Heat was not assumed to be transported below the mixed layer of the ocean (Hansen et al., 1981). In the model used, the mixed layer has a depth of 100 m (328 ft) and the thermocline has a depth of 900 m (2,952 ft). The mixed layer temperature was assumed to be independent of depth. A diffusion equation with a constant thermal conductivity determines the thermocline's temperature.

For the low scenario, the diffusion coefficient assumed was 1.18 cm^2 sec^{-1}.
For the mid-range scenarios, the diffusion coefficient was assumed to be 1.54 cm^2 sec^{-1}.
For the high scenario, the diffusion coefficient assumed was 1.9 cm^2 sec^{-1}.

The thermocline has a depth of 900 m (2,952 ft). The mixed layer temperature was assumed to be independent of depth. A diffusion equation *with* a constant thermal conductivity determines the thermocline's temperature.

For the low scenario, the diffusion coefficient assumed was 1.18 cm^2 sec^{-1}.
For the mid-range scenarios, the diffusion coefficient was assumed to be 1.54 cm^2 sec^{-1}.
For the high scenario, the diffusion coefficient assumed was 1.9 cm^2 sec^{-1}.

This range of diffusion coefficients assured that neither too little nor too much heat was absorbed by the oceans. Thermal expansion was calculated by using mean temperatures, salinities, and pressures for each layer in the water column, so that for each layer a standard coefficient of expansion could be used once the change in temperature was ascertained. This estimating approach slightly mis-estimates actual thermal expansion because actual ocean temperatures and fluxes vary latitudinally. An analysis of this averaging error, however, indicates that it is not large.[6] The approach generates a good first order estimate of thermal expansion.



The heat flux is estimated for semi-monthly time periods. The appropriate ΔT for calculating $F(t)$ in each time period $(t = n)$ is the value estimated for the previous time period. For a simple one-layer ocean model, ΔT is obtained by solving the following differential equation:

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

where Co is the heat capacity of the ocean per unit area (cal cm^{-2}). The temperature change in the mixed layer (ΔTm) is a solution of the equation:

$$cHm\,\frac{d\Delta Tm}{dt} = F(t) - F_D(t)$$

where:

c = heat capacity of the water
Hm = depth of mixed layer
$F(t)$ = heat flux from the atmosphere
$F_D(t) = \lambda \left.\frac{\partial\Delta T}{\partial Z}\right| Z = Hm$ is the heat flux into the mixed layer

Note that the Z axis is directed toward the bottom of the ocean. Since g, cm, sec, cal were used, the heat conductivity ∂ is numerically equal to the heat diffusivity.

Temperature change in the thermocline is determined by the diffusion equation:

$$\frac{c\partial\Delta T(Z,t)}{\partial T} = \frac{\kappa\,{}^{2}\Delta T(Z,t)}{\partial Z^{2}}$$

the boundary conditions for ΔT are:

$$\Delta T = \Delta Tm \text{ at } Z = Hm$$

and zero heat flux at the bottom of the thermocline:

$$\frac{\lambda\partial\Delta T}{\partial Z} = 0 \text{ at } Z = H + Hm$$

Note that ΔTm and ΔT are temperature changes between the time 1880 and t.

Figure 3-3. Equations used in ocean model for heat transport. *(After J. E. Hansen, D. Johnson, A. Lacis, S. Lebedeff, D. Rind, and G. Russell, 1981, "Climatic Impacts of Increasing Atmospheric Carbon Dioxide," Science* **213:**957-966.*)*

Figure 3-3. Equations used in ocean model for heat transport. (After *J. E.. Hansen, D. Johnson, A. Lacis, S. Lebedeff, D. Rind, and G. Russell, 1981, "Climatic* Impacts of Increasing Atmospheric Carbon Dioxide," Science **213:**957-966.)

Snow and Ice Contribution to Sea Level

The amount of water locked on land areas in the form of snow and ice will change as global temperatures increase. Large amounts of such snow and ice exist on Greenland and Antarctica. Because polar temperatures are expected to rise more than the global average (Manabe, 1983), the direct effects of warming on increased melting, evaporation, and sublimation will be great; a less direct effect will be the influence of warming on deglaciation. The net effects of these decreases in land-based snow and ice will be reduced somewhat by increases in snowfall that can be expected in polar areas. Warmer air will tend to carry more moisture and snow to extreme latitudes.

It is difficult at this time to determine with certainty the net effects of increased melting and increased snowfall on mass balance. An initial examination of doubled $C0_2$ experiments using the general circulation model developed at the Goddard Institute for Space Studies (GISS)the time reveals that in situ melting (for an equilibrium temperature at $C0_2$ doubling) could be the equivalent of 10.5 to 16.5 mm (0.4 to 0.6 in) per year of sea level rise. These estimates are subject to some overestimation for a number of reasons (Hoffman et al., 1983). For example, not all melt-water will run off; some will percolate into the ice sheets. This meltwater will cause additional crevassing and ice softening, which, in turn, could accelerate the deglaciation of the ice sheets.

Deglaciation is likely because large parts of the East and West Antarctic icefields are grounded below sea level, and thus are subject to rapid collapse. With the reduction of sea ice and the warming of the polar oceans, these areas are much more likely to experience future deglaciation. Some of these icefields, notably in the West Antarctic, are held in place by pinning grounded below sea level. At present, these pinnings prevent the glaciers from moving rapidly seaward. Warmer oceanic waters may melt, and remove the pinnings, soften the ice, and thus lead to a much more rapid movement of the ice. Ultimately, large portions of the land-based ice sheets could enter the ocean. The speed of deglaciation, if it occurs, will depend upon many things: ocean currents, the frictional coefficients of the "surging" ice, and the specific topography of pinnings and outlet channels (Bentley, 1983; Hughes, 1983).

Evidence exists that the West Antarctic completely disappeared during previous global warmings, raising sea level by 5-6 m (16-20 ft) 120,000 years ago (Mercer, 1978). Unfortunately, little scientific effort has been expended to determine the rate of deglaciation in the near future. Two estimates have been published that speculate that the earliest time of the total collapse of the West Antarctic icefields would be 200 and 500 years from now (Hughes, 1983; Bentley, 1983). Unfortunately, neither researcher made interim estimates of deglaciation. For icefields in East Antarctica or Greenland, no estimates of deglaciation have been made at all, despite their potential vulnerability.

Given the absence of studies, it was impossible to use process models of icefields to estimate the deglaciation that global warming could cause. EPA is now supporting very limited research in this area for the second round of sea level scenarios, due to be completed in late 1984. That effort will use process models to examine key physical processes, boundary conditions, parameters and their potential evolution, in order to create better scenarios of glacial contributions under various scenarios of global temperature rise. In the present effort, however, methods that are far less reliable had to be used.

One possibility was to assume that the meltwater estimated by the GISS model for a $C0_2$ doubling will produce an equivalent sea level rise through either of two mechanisms: either by directly entering the sea as runoff or by indirectly causing faster deglaciation as the refreezing process changes ice flow characteristics. Because the GISS model output provides estimates of melting only for the equilibrium warming (4.1° C) for a doubling of $C0_2$, estimates of the total melting that would take place over the next century, when temperatures would at first be lower and then warmer than the doubled temperature, could not be made directly from the model output. A relationship between global temperatures and the melting thus had to be assumed. Assuming proportionality of melting to global warming, a sea level rise of roughly 75-112 cm (2.5-3.7 ft) can be forecast by 2100 (assuming no error in the GISS estimates).

Another method for predicting the contribution of snow and ice transfer from land to sea is to assume a continuation of the past association between thermal expansion and total sea level rise. Because part of the historical sea level rise can be attributed to thermal expansion, estimates of the ratio of thermal expansion to snow/ice are possible. By extrapolating that ratio into the future, scenarios of snow/ice contributions can be generated. Since different estimates of past sea level rise exist, this approach requires generating both a high and conservative snow/ice thermal expansion ratio.

The sea level rise estimates used in this process were based on work by Barnett (1983) and Gornitz et al. (1982), who estimated historical sea level rises of 10-15 cm (4-6 in). The Gornitz group also estimated that thermal expansion accounted for 5cm (2 in) of the rise; thus, depending on whose global sea level rise estimate is used, there is either a 5 or 10 cm (2 or 4 in) residual. This latter approach was the one actually used to generate the scenarios. Using these values, two assumptions were made:

For the low scenario, the ratio of future snow/ice contribution to future thermal expansion was assumed to be " one to one."
For the high scenario, a "two to one" ratio was assumed.
For the mid-range-low scenario, the low snow and ice assumption was used; for the mid-range-low scenario, the high snow and ice assumption was used.

The ratio approach has serious flaws. At best, it has a weak physical basis. It relies on estimates of past temperature change that are somewhat uncertain. Furthermore, it also extrapolates a constant ratio of snow and ice to thermal expansion. If alpine glaciers were the source of sea level rise not explained by thermal expansion, the possibility exists that these sources may become exhausted towards the end of the forecast period, reducing the ratio over time. If deglaciation were the source, its many nonlinear features could lead to underestimates by the end of the forecast period. Clearly, more research is needed on this problem; the responses of land- based ice should be made on the bases of direct projections of snow and ice contributions with process models of deglaciation melting, and run off from all snow and ice fields. Nevertheless, the flaws in the estimating approach are not egregious to invalidate the effort. The approaches used to estimate sea level rise constitute an attempt to address the source of sea level rise in a reasoned manner and appear to be a far better choice than ignoring the possible contribution of snow and ice resting on land, particularly given the clear importance these sources should have future sea level rise. The estimating procedure while less than perfect, at least starts to utilize the existing base of knowledge to estimate sea level rise.

FUTURE SEA LEVEL RISE

Considering only changes in greenhouse gases (not the special case scenarios that deal with other forcings), sea level could rise as much as 345 cm (136 in) and as little as 56.2 cm (22 in) (Hoffman et al., 1983) by 2100. Neither of these extreme estimates is likely, however, since the probability of all the conservative or all the high assumptions turning out to be true is very small. The moderate thermal expansion scenario, because it assumes either the middle ground for all assumptions or the assumption that appeared most realistic, constitutes a much more likely trend for this component of sea level rise. Two scenarios were produced for snow and ice contribution. For the moderate scenario, the low snow and ice ratio was assumed. For the mid-range-high scenario (not discussed in other chapters), the high snow and ice ratio was used. The moderate scenario produces a rise of 144.4 cm (4.8 ft) by 2100, while the mid-range-high scenario produces a rise of 216 cm (7 ft) by 2100.

Table 3-1 summarizes the changes by quarter century, for the conservative, moderate, mid-range-high and high scenarios. Extrapolations of the historical rate of rise are included for comparison. Table 3-2 summarizes some of the special case scenarios that considered changes in volcanic activity and solar irradiation.

REDUCING UNCERTAINTIES

In all foreseeable circumstances, sea level is likely to rise by amounts considerably greater than this past century's rise. The most conservative assumptions used in this analysis lead to an accelerating sea level rise and a total rise that is 400 percent greater than that of the last 100 years. Nevertheless, many uncertainties exist about the rate of rise. The very high scenario has over seven times the sea level rise of the conservative scenario. Part of the variance between scenarios may be an artifact of the relatively crude methods used for estimating sea level rise, rather than a lack of insight into its physical mechanisms. That part of the uncertainty can probably be eliminated in the next two years if more resources are to devoted to the estimating effort. However, even those improvements may not provide more precise estimates.

In order to improve substantially the estimates of future sea level rise and to narrow the range of scenarios, more time and more scientific research will be needed. Merely waiting for observations will, however, be the slowest way to learn more about sea level's future rise. To maximize the value of future observations, the theoretical base and models used to interpret the relevant data must be improved. Rapid progress can be made by accelerating the research aimed at improving our basic understanding of the processes that underlie climatic change and sea level rise.

Unfortunately, a serious acceleration of research will require additional resources. The present shortage of federal funds has already reduced research in many of the areas of greatest concern. Therefore, three demonstrations need to be made to justify changing this situation and accelerating research.

First, a demonstration of the value to society of speeding the development of better information must be made. This need is documented in other chapters and will not be discussed here. Second, the possibility of speeding research to narrow the range of sea level rise and the probable progress under different funding levels must be demonstrated. Finally, it must be demonstrated that the appropriate organizational and management processes can be used to ensure that research is effective and accomplishes what is theoretically possible. Since these last two areas are closely linked to the scenario-generating process itself, they will be given a brief review here.

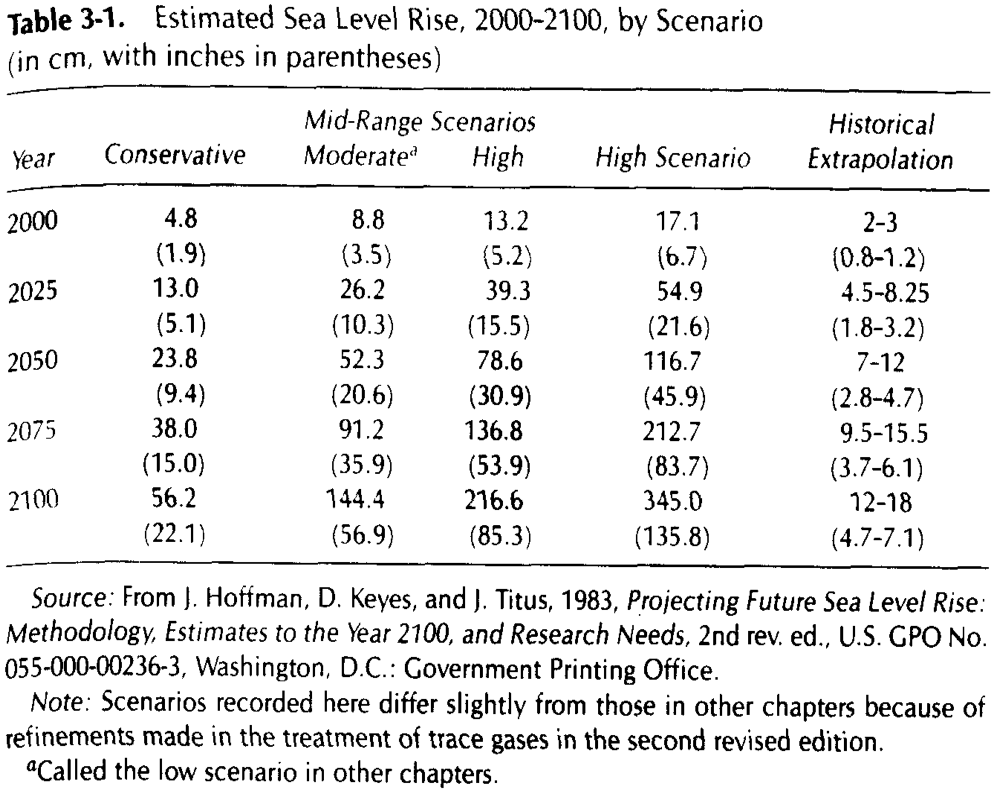


Table 3-1. Estimated Sea Level Rise, 2000-2100, by Scenario (in cm, with inches in parentheses)

		Mid-Range Scenarios			*Historical*
Year	*Conservative*	*Moderate*[a]	*High*	*High Scenario*	*Extrapolation*
2000	4.8	8.8	13.2	17.1	2-3
	(1.9)	(3.5)	(5.2)	(6.7)	(0.8-1.2)
2025	13.0	26.2	39.3	54.9	4.5-8.25
	(5.1)	(10.3)	(15.5)	(21.6)	(1.8-3.2)
2050	23.8	52.3	78.6	116.7	7-12
	(9.4)	(20.6)	(30.9)	(45.9)	(2.8-4.7)
2075	38.0	91.2	136.8	212.7	9.5-15.5
	(15.0)	(35.9)	(53.9)	(83.7)	(3.7-6.1)
2100	56.2	144.4	216.6	345.0	12-18
	(22.1)	(56.9)	(85.3)	(135.8)	(4.7-7.1)

Source: From J. Hoffman, D. Keyes, and J. Titus, 1983, *Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs,* 2nd rev. ed., U.S. GPO No. 055-000-00236-3, Washington, D.C.: Government Printing Office.

Note: Scenarios recorded here differ slightly from those in other chapters because of refinements made in the treatment of trace gases in the second revised edition.

[a] Called the low scenario in other chapters.

Table 3-1. Estimated Sea Level Rise, 2000-2100, by Scenario *(in* cm, with inches in parentheses)

Source: From J. Hoffman, D. Keyes, and J. Titus, 1983, *Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs,* 2nd rev. ed., U.S. GPO No. 055-000-00236-3, Washington, D.C.: Government Printing Office.

Note: Scenarios recorded here differ slightly from those in other chapters because of refinements made in the treatment of trace gases in the second revised edition.

[a] Called the low scenario in other chapters.

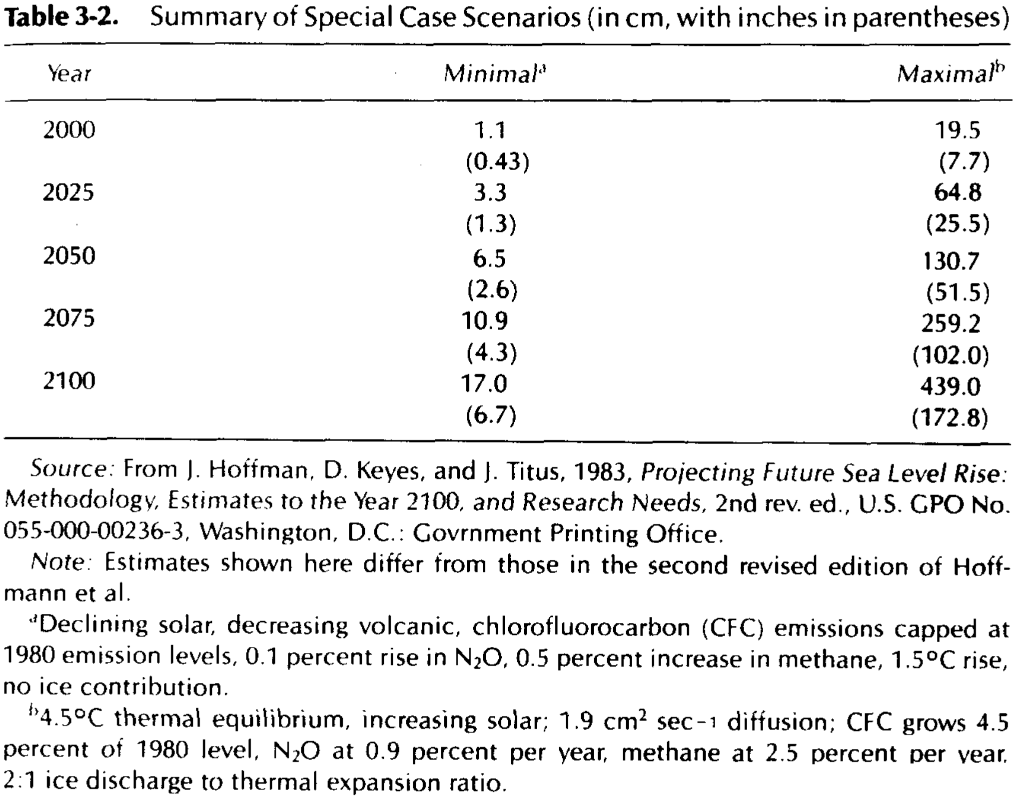


Table 3-2. Summary of Special Case Scenarios (in cm, with inches in parentheses)

Year	*Minimal*[a]	*Maximal*[b]
2000	1.1 (0.43)	19.5 (7.7)
2025	3.3 (1.3)	64.8 (25.5)
2050	6.5 (2.6)	130.7 (51.5)
2075	10.9 (4.3)	259.2 (102.0)
2100	17.0 (6.7)	439.0 (172.8)

Source: From J. Hoffman, D. Keyes, and J. Titus, 1983, *Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs,* 2nd rev. ed., U.S. GPO No. 055-000-00236-3, Washington, D.C.: Govrnment Printing Office.

Note: Estimates shown here differ from those in the second revised edition of Hoffmann et al.

[a] Declining solar, decreasing volcanic, chlorofluorocarbon (CFC) emissions capped at 1980 emission levels, 0.1 percent rise in N_2O, 0.5 percent increase in methane, 1.5°C rise, no ice contribution.

[b] 4.5°C thermal equilibrium, increasing solar; 1.9 cm^2 sec-1 diffusion; CFC grows 4.5 percent of 1980 level, N_2O at 0.9 percent per year, methane at 2.5 percent per year, 2:1 ice discharge to thermal expansion ratio.

Table 3-2. Summary of Special Case Scenarios(in cm, with inches in parentheses)

Source: From J. Hoffman, D. Keyes, and J. Titus, 1983, *Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs,* 2nd rev. ed., U.S. GPO No.055-000-00236-3, Washington, D.C.: Government Printing Office.

Note: Estimates shown here differ from those in the second revised edition of Hoffmann et *al.*

[d] Declining solar, decreasing volcanic, chlorofluorocarbon (CFC) emissions capped at 1980 emission levels, 0.1 percent rise in N_20, 0.5 percent increase in methane, 1.5°C rise, no ice contribution.

[b] 4.5°C thermal equilibrium, increasing solar; 1.9 cm^2 sec -1 diffusion; CFC grows 4.5 percent of 1980 level, N_20 at 0.9 percent per year, methane at 2.5 percent per year, 2:1 ice discharge to thermal expansion ratio.

Opportunities for Narrowing the Range of Estimates

The range of scenarios can be narrowed through a series of short- and long-term projects. There are a number of possibilities for short-term projects during the next two years that utilize existing knowledge to make better projections.

In the area of atmospheric composition, existing information on trace gases could be accumulated and used to generate more realistic scenarios. Parametric models that allowed sensitivity testing could be used that join sinks, sources, and exchanges to generate better low and high scenarios for these gases. Carbon cycle models could also be parametrically extended to look at major uncertainties in ocean uptake and photosynthesis.

For thermal responses, transient (year-by-year) runs could be made using general circulation models (GCMs). This would allow better estimates of temperature increases and thermal fluxes through time on a geographically disaggregated basis. Net ablation due to melting, evaporation, sublimation, and additional snowfall in polar regions could be tracked in these runs.

Scenarios of the deglaciation of icefields could be constructed using models that represent physical processes. Critical parameters, relationships, and boundary conditions would be varied, thus generating a first good estimate of the plausible ranges of deglaciation contribution.

Together, these efforts would greatly increase the total confidence in the scenarios, although they might not narrow the range very much.(Whether they would or not depends almost totally on the output of the glacial research.)

In the longer term, improving scenarios and narrowing the estimates of future sea level rise must be based on research that produces greater knowledge, observations, and modeling capabilities useful for simulating the future evolution of the relevant natural systems. Opportunities for speeding the development of knowledge exist for all systems that determine sea level's future rise.

Most critically, more research needs to be conducted on trace gases, including monitoring and modeling. Current funding efforts in this area are relatively small and dispersed through many federal agencies. Better observational systems and better models of atmospheric composition can be developed and refined, greatly increasing our confidence in predictions of future trace gas concentrations.

For climate response, several areas of improvement can be targeted. First, and of paramount importance, dynamic ocean models must be integrated into general circulation models (GCMs). This task will require a much larger effort than the resources currently devoted to this task. Yet until this is done, it will be impossible to have an accurate understanding of the geographic distributions of future precipitation and temperature changes that will be critical to better projections of snow accumulation and melting. Second, cloud responses need to be modeled better in GCMs and validated with observational data. Such efforts would appreciably reduce uncertainty about the thermal equilibrium. Third, larger computers and more computer time should be provided to run general circulation models. At present, the number of runs (experiments), their geographical scale, and the representation of processes in models are severely limited by lack of computational support. Last, albedo, sea ice, and hydrological processes need to be modeled more carefully in large climate models. Improvements in these areas would improve the accuracy in projecting global warming, and provide information on the accumulation/melting of snow and ice and on the conditions critical to projecting deglaciation.

Of greatest importance to improving sea level rise estimates, however, will be development of a better understanding of snow/ice responses. Three primary areas regarding ocean-glacial response can be improved. First, observational programs to track the mass balance of all icefields and sea level throughout the world could be undertaken to refine the basis for validating models. Second, for each icefield, models could be developed that can realistically consider changes in conditions predicted by climate models, as well as the actual geography of fields. Field work will be needed to provide data to these efforts. This would yield much better estimates of deglaciation. Last, selected experiments could be conducted, such as pulling icebergs to waters of appropriate temperature, to learn the true value of certain critical parameters.

These lists of research opportunities represent a partial description of possibilities to accelerate the acquisition of knowledge of sea level rise. Existing funding by various federal agencies "supports" the accomplishment of all these goals to a very limited degree. Unfortunately, many projects that are critical to the timely accomplishment of these goals are not being funded, or are being funded at insufficient levels, or with inadequate guarantees of long-term support. For example, many opportunities to observe natural systems and collect data are being lost, disrupting or delaying the construction of time series and geographical data sets that are critical to improving or validating models. And no major effort to model oceans and incorporate these models into climate models has been undertaken. Present funding levels could significantly delay the date at which more precise and reliable estimates of sea level rise are available.

Management of Research

The research undertaken to improve estimates of sea level rise must consider the need for secure, long-term commitments of funding. Major interdisciplinary scientific teams, not just individual or group projects, will be needed to address most of the scientific issues that are blocking more precise estimates of sea level rise. The development and maturation of research efforts depends on steadily increasing the funding of teams that are directed by well-respected scientists capable of integrating the efforts of forcefully independent scientists.

Success in scientific research can never be guaranteed-those at the frontier cannot necessarily predict what is beyond or how fast they will be able to proceed. Success can be thwarted, however, by failing to sustain the conditions needed for performing solid basic research. In the case of sea level rise, the challenges to progress are great, in part, because of the interdisciplinary nature of the efforts required. The opportunities for progress that exist can be successfully pursued only if interested parties decide that the value of accelerating research justifies the costs. The question is not whether we can do better, but whether we have the will to do so.

NOTES

1. J. Charney, chairman, Climate Research Board, 1979, Carbon *Dioxide and Climate: A Scientific Assessment*, Washington, D.C.: NAS Press. This panel made a major review of the evidence. After looking for factors that might diminish the warming to negligible proportions, the panel concluded that a significant rise in temperature was almost certain. A second panel reviewed the work done since the initial assessment and concurred with its results: J. Smagorinsky, chairman, Climate Research Board, 1983, Carbon *Dioxide: A Second Assessment,* Washington, D.C.: NAS Press.
2. The estimates of scenarios used in this chapter are based upon results contained in J. Hoffman et al. (1983). They differ from the scenarios used in other chapters of this book in having a slightly lower high scenario, a higher conservative scenario, and higher mid-range scenarios. These estimates, based on later computer runs using more realistic estimates of trace gas growth, should be used for future analyses until they are improved upon by the next generation of scenarios, due to be published by EPA in winter 1985.
3. Estimates made by Lovins et al. (1981) provide an interesting counterexample in which radically slower energy use rates are assumed. The feasibility of these estimates is in doubt, however.
4. The choice of these growth rates depends on the beliefs one has about sinks and sources. Sinks can become saturated and sources exhausted. New sources or sinks can develop with a climate change. Any projection of future levels of trace gases implies some combination of changes in sources and sinks. To the degree that reality is different, the projections will be wrong. For a discussion of these gases, see Chamberlain., Joseph W., Henry M. Foley, Gordon J. MacDonald, and Marvin A. Ruderman. 1982. "Climatic Effects of Minor Atmospheric Constituents." In W.Clark, ed., *Carbon Dioxide Review.* New York: Clarendon Press, pp. 253-277.
5. While the NAS has estimated between 1.5°C and 4.5^0C as the equilibrium response to doubled CO_2, no major

modeling effort has yielded an estimate below 2^{0}C. Recently, results from the Goddard Institute for Space Studies and the National Center for Atmospheric Research have yielded results of around 4^{o}C (pers. comm.).

6. Personal communication with Dr. Gary Russell on his estimate of thermal expansion with heat fluxes made for multiple columns at different temperatures.

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