Chapter 1

An Overview of the Causes and Effects of Sea Level Rise

James G. Titus and Michael C. Barth

with contributions by

Michael J. Gibbs, John S. Hoffman,
and Murray Kenney

INTRODUCTION

The average person's view that sea level is constant is not shared by everyone, and for good reason. Petroleum companies and their geologists find oil on dry land once covered by prehistoric seas, and paleontologists find marine fossils on desert plains. Nevertheless, within the period of time relevant to most decisions, the assumption that sea level is stable has been appropriate. Only in a few cases have local changes in relative sea level due to land subsidence and emergence been large enough to have important impacts.

Recently, however, the view that current sea level changes are unimportant has been called into question. Coastal geologists are now suggesting that the thirty centimeter (one foot) rise in sea level that has taken place along much of the U.S. coast in the last century could be responsible for the serious erosion problems confronting many coastal communities.' Furthermore, according to the National Academy of Sciences, the expected doubling of atmospheric carbon dioxide and other greenhouse gases could raise the earth's average surface temperature 1.5-4.50C (3-80F) in the next century. Glaciologists have suggested that the sea could rise five to seven meters (approximately twenty feet) over the next several centuries from the resulting disintegration of the West Antarctic ice sheet.

A more immediate concern is that the projected global warming could raise the sea as much as one meter in the next century by heating ocean water, which would then expand, and by causing mountain glaciers and parts of ice sheets in West Antarctica, East Antarctica, and Greenland to melt or slide into the oceans. Thus, the sea could reach heights unprecedented in the history of civilization. Until this effort, no one had attempted to forecast sea level rise in specific years or determine its importance to today's activities.*

A rise in sea level of even one meter during the next century could influence the outcomes of many decisions now being made. In the United States, thousands of square miles of land could be lost, particularly in low-lying areas such as the Mississippi Delta, where the land is also subsiding at approximately one meter per century. Storm damage, already estimated at over three billion dollars per year nationwide, could also increase, particularly along the well-developed and low-lying Atlantic coast. Finally, a rising sea will increase the salinity of marshes, estuaries, and aquifers, disrupting marine life and possibly threatening some drinking water supplies. Fortunately, the most adverse effects can be avoided if timely actions are taken in anticipation of sea level rise.

Although action may be taken to limit the eventual global warming from rising atmospheric CO_2, the warming expected in the next sixty years and the resulting rise in sea level are not likely to be prevented. Most CO_2 emissions are released by burning fossil fuels. Because these fuels are abundant and relatively inexpensive to produce, a voluntary shift to alternative energy sources is very unlikely. Regulatory action that would effectively limit CO_2 concentrations is also unlikely. Such actions by any one nation, even the

---

*Editors' note: After the submission of this manuscript, the NAS released a projection that sea level could rise seventy centimeters by 2080, not including the impact of Antarctica (see Revelle, 1983).

United States, could delay the effects of increasing concentrations of CO_2 by a few years at most, while imposing competitive disadvantages on the nations industries. Emissions of other trace gases (such as chlorofluorocarbons and methane) could add significantly to the projected global warming. Furthermore, the uncertainties surrounding the impacts on climate currently make it impossible to determine whether preventing the global warming would provide a net benefit to the world or to individual nations. Finally, even if emissions are curtailed, global temperatures and sea level will continue to rise for a few decades as the world's oceans and ice cover come into equilibrium.

Although preventing a global warming would require a worldwide consensus, responding to its consequences would not. Communities can construct barriers or issue zoning regulations; companies and individuals can build on higher ground; and environmental agencies can take measures to reserve dry lands for eventual use as biologically productive wetlands.

To meet the challenge of a global warming, society will need accurate information concerning the likely effects of sea level rise. Unfortunately, communities, corporations, and individuals do not by themselves have sufficient resources or incentives to undertake the basic scientific research required to reduce existing uncertainties. This responsibility falls upon national governments throughout the world. Only their efforts can provide the information that decision makers will need.

This book is based on interdisciplinary efforts that the United States Environmental Protection Agency (EPA) initiated to encourage the development of information necessary to adapt to sea level rise. In the spring of 1982, EPA organized a project aimed at developing methods to study the effects of sea level rise and estimate the value of policies that prepare for this rise. The project proceeded in the following steps, as illustrated in Figure 1-1.

Available scientific research was used to project conservative, low, medium, and high scenarios of global sea level rise through 2100.
The scenarios were adjusted for local trends in subsidence to yield local sea level rise scenarios through 2075 for two case study sites-Galveston, Texas, and Charleston, South Carolina.
Economic and environmental scenarios were developed for the two case study sites, assuming no rise in sea level.
The physical effects of sea level rise for the case study areas were estimated.
The economic effects of sea level rise if it were not anticipated were estimated,
Options for preventing, mitigating, and responding to the effects of sea level rise were developed.
The economic effects of sea level rise if it were anticipated were estimated.
The value of anticipatory actions and better projections of sea level rise was assessed.

Given the broad range of disciplines encompassed in this effort and the range of individuals to whom it might be of interest, this introductory chapter provides an overview of the entire project, written for the general reader. Chapters 2 through 10 explore the issues in more detail.

Chapter 2 summarizes the scientific evidence on the relationship between rising $C0_2$ concentrations and global temperatures.

Chapter 3 sets forth the range of estimates for sea level rise that underlie the remainder of the analysis.

Chapter 4 presents the method and results of an analysis of the effects of sea level rise on the Charleston area. The chapter projects the two causes of shoreline retreat, inundation and erosion, as well as changes in flood levels and salt intrusion into aquifers.

Chapter 5 presents an analysis similar to that in Chapter 4, using somewhat different methods for the Galveston Bay area.

Chapter 6 catalogues the potential engineering responses to sea level rise, their costs, and their potential effectiveness.

Chapter 7 presents the methods, data, and results of an economic impact analysis of the physical effects of sea level rise at the two case study sites as well as an analysis of the benefits of anticipating the rise in terms of reducing adverse impacts.

Chapter 8 examines policy options for resort communities adapting to sea level rise and the decisions that property owners on Sullivans Island, South Carolina, would face after a major storm.

Chapter 9 indicates how sea level rise may affect existing hazardous waste facilities and implications for the regulation of proposed facilities.

Chapter 10 presents the reactions of six potential users of this information delivered to a conference on sea level rise in Washington, D.C., on March 30, 1983. In the first comment, Dr. Sherwood Gagliano discusses Chapters 4, 5, and 6, as well as his experience with relative sea level rise in Louisiana. The other comments present a broad range of views on the technical and social implications of sea level rise.

Progress in understanding sea level rise and the most appropriate ways to respond will require discussions within and between diverse disciplines including biology, climatology, economics, engineering, geology, geography, hydrology, meteorology, and urban planning. The most important needs are: less uncertainty in the range of sea level rise estimates; better methods to assess the physical effects of sea level rise; better methods to estimate economic impacts on specific communities and private-sector firms; assessments of the actions that could be taken in response to, and in anticipation of, sea level rise; greater awareness on the part of potentially affected parties; and better estimates of the potential savings from anticipating sea level rise.

We have only begun to determine the degree to which research should be accelerated to produce better forecasts of sea level rise. Such an assessment is necessary to ensure that government efforts to address sea level rise are allocated a level of resources commensurate with the potential benefits of such efforts. The case studies reported here indicate that Charleston and Galveston could save hundreds of millions of dollars by preparing for sea level rise. If additional analyses are consistent with the findings of the case studies, then the value of better forecasts would easily justify the substantial costs of developing them. More research should be undertaken to confirm our findings; because of the time it will take to improve sea level rise estimates, an evaluation of the appropriate priority for such research should not be delayed.

This book provides a framework for understanding the importance of sea level rise. The methods developed and applied to Galveston and Charleston can be used for other jurisdictions. They can also be used by corporations, municipalities, or states to evaluate individual project decisions in the coastal zone. Parties that could be affected by sea level rise should determine whether the impacts will require changes in their operations and the importance of better forecasts.

We hope that this book proves to be more than a collection of useful scientific papers. We believe that it raises important policy issues that warrant the attention of all citizens, not just those who allocate research budgets, issue government regulations, and make investment and locational decisions. Responding to the challenge of a rising sea will require better assessments and public awareness of the future rate of sea level rise, the likely effects, and options for slowing the rise or adapting to it. Our goal is to accelerate the process by which these issues are resolved.

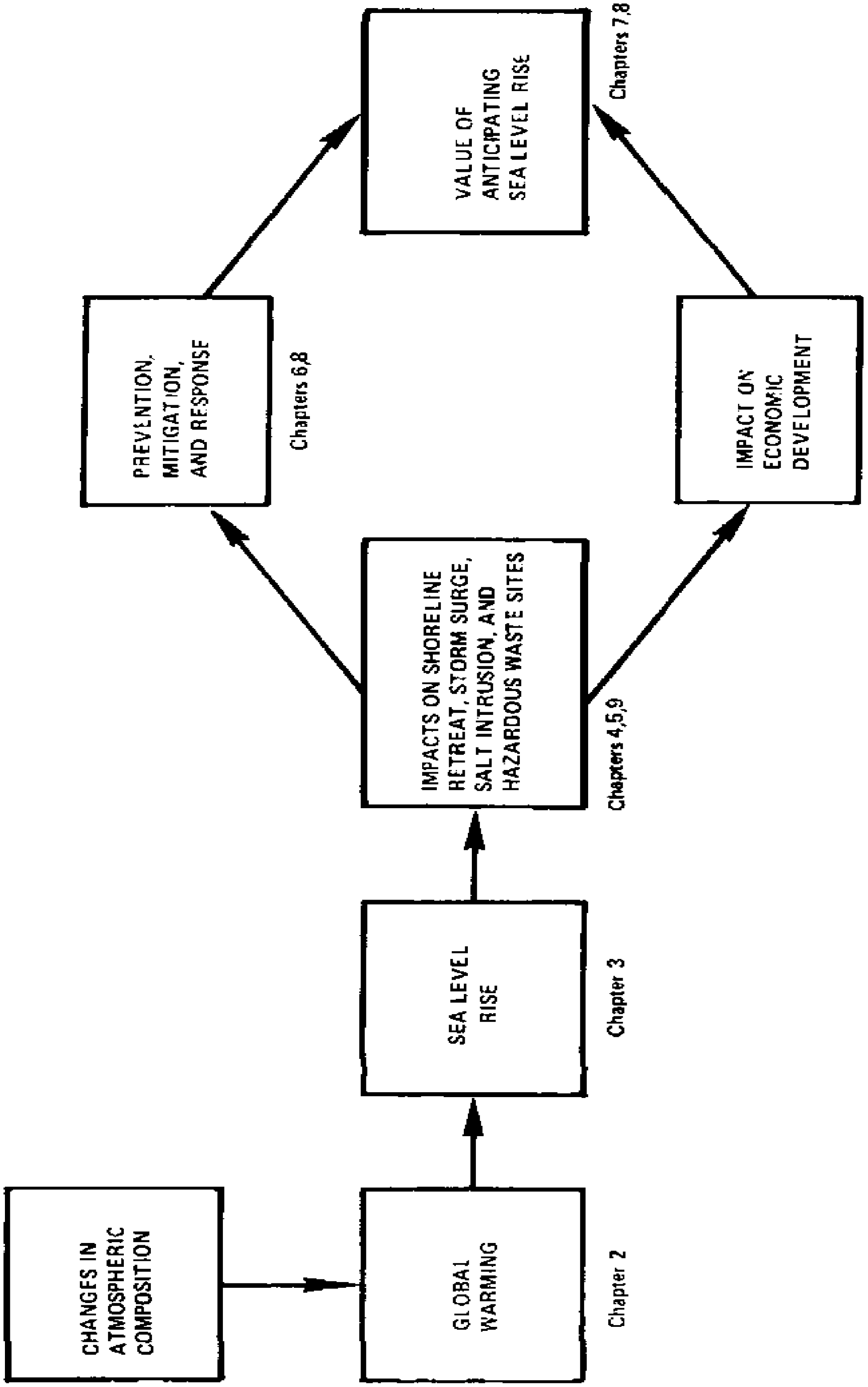

Figure 1-1. Overview.

SEA LEVEL, CLIMATE, AND CARBON DIOXIDE EMISSIONS

The rise and fall of sea level is influenced by both geological and climatic factors. Changes in mid-ocean ridge systems may have been responsible for a drop in sea level of three hundred meters (one thousand feet) over the last eighty million years (Hays and Pitman, 1973).[2] Even today, emergence and subsidence of land can have a noticeable effect on local sea level. For example, Louisiana is currently losing over one hundred square kilometers (approximately fifty square miles) of land per year, largely because of subsidence estimated at one meter per century (Boesch, 1982). In contrast, emergence has caused difficulty for Finnish port authorities facing progressively shallower harbors.

Geological events affecting sea level are, however, generally slow and unlikely to accelerate. Although this has generally been true for climatic changes in the past, the future may be different. This section looks at the relationship between sea level and climate, explaining how rising atmospheric concentrations of carbon dioxide can raise the earth's average surface temperature and thereby dramatically change both climate and sea level.

The Relationship between Climate and Sea Level

Climate influences sea level in two ways: by moving the earth's water between glaciers resting on land and the oceans and by changing the temperature of the ocean water and thus its volume. If all the glaciers in Antarctica and Greenland melted, sea level would rise more than seventy meters (over two hundred feet). In the past, enough ocean water has accumulated in glaciers to lower sea level about one hundred and fifty meters (five hundred feet).

Although complete melting of land-based glaciers would take thousands of years, partial melting could raise sea level as much as a meter in the next century. Furthermore, glaciers grounded under water could disintegrate more quickly. Two leading glaciologists have estimated that the entire West Antarctic ice sheet (the largest marine-based glacier) could enter the oceans in two hundred years (Hughes et al., 1979) and five hundred years (Bentley, 1980) raising sea level five to seven meters (about twenty feet). Although a complete disintegration of this marine based glacier will not occur in the near future, parts of it and other icefields, as well as mountain glaciers, could be vulnerable in the next century.

Because water expands when heated, a warmer climate could raise the sea even without any contribution from glaciers. Although a warming of the entire ocean would take several centuries, the upper layers could warm and raise sea level as much as a meter by 2100. This shorter-term effect of a global warming is frequently overlooked.

Past Trends in Climate and Sea Level

For the last two million years and probably longer, sea level and climate have fluctuated together in cycles of 100,000 years. These cycles are caused by changes in solar irradiance due to cyclic changes in the tilt of the earth's axis. During ice ages, the earth's average temperature has been about 5EC (9EF) colder than at present, with glaciers covering major portions of the continents. During the Last Glacial (12,000-20,000 years ago), sea level was approximately one hundred meters (over three hundred feet) lower than today. During previous ice ages it may have been one hundred and fifty meters lower (Donn et al., 1962).

During the warm interglacial periods, temperatures and the sea have risen to approximately the levels of today. There is no evidence that the land-based glaciers in Greenland and Antarctica have ever completely melted in the last two million years. However, glaciologist J. H. Mercer (1972) has suggested that the West Antarctic ice sheet has completely disappeared, with sea level rising five to seven meters above its present level, probably during the last interglacial (115,000 years ago). From the end of the Last Glacial until about six thousand years ago, sea level rose approximately one meter per century.

In the last century, tidal gauges have been available to measure sea level at specific locations.

Studies combining these measurements to determine trends in worldwide sea level have concluded that it has risen ten to fifteen centimeters (four to six inches) in the past century (Fairbridge and Krebs, 1962; Gutenberg, 1941; Lisitzin, 1974; Barnett, 1983; Gomitz et al., 1982). At least part of this rise can be explained by the warming trend of 0.4EC in the last century and the resulting thermal expansion of the upper layers of the ocean (Gornitz et al., 1982). The remainder may be due to a small amount of glacial melting and a delayed response of deep-ocean waters to longer-term warming trends.

The Greenhouse Effect and the Prospect of Global Warming

Although climate and sea level have been relatively stable in recent centuries, the next century may be very different. In the past, the delicate balance of the global climatic system has evolved slowly as its various determinants shifted. Current activities, however, are altering this balance.

Man is reversing millions of years of natural evolution by putting back into the atmosphere carbon that had been sequestered over the ages as fossil fuels. Atmospheric concentrations of CO_2 are likely to double, and possibly triple, by 2100. Because no historical precedent exists, reasonable expectations about future climate must be based on scientific evidence, not geological records. After evaluating the available evidence, the National Academy of Sciences concluded that a doubling of atmospheric concentrations of CO_2 would warm the earth's average surface temperature 1.5-4.5EC (2.7-8.1EF) (Charney, 1979; Smagorinsky, 1983).

The greenhouse effect of the atmosphere has never been doubted. Most of the sun's radiation is visible light, which passes through the atmosphere largely undeterred. When the radiation strikes the earth, it warms the surface, which then radiates the heat as infrared radiation. However, atmospheric CO_2, water vapor, and some other gases absorb the infrared radiation rather than allow it to pass undeterred through the atmosphere to space. Because the atmosphere traps the heat and warms the earth in a manner somewhat analogous to the glass panels of a greenhouse, this phenomenon is generally known as the "greenhouse effect."? Without this effect, the earth would be 33EC (60EF) colder than it is currently.

The extent to which CO_2 absorbs heat has been known for almost a century (Arrhenius, 1896). In Chapter 2, Hansen et al. show that a doubling of atmospheric $C0_2$ would raise the average temperature 1.2EC (2.OEF) if nothing else in the earth's climatic system changed. However, many parts of the climate will change, amplifying the direct impact of $C0_2$. Because these changes are not completely understood, the total warming is difficult to estimate. The current uncertainty surrounding the impact of $C0_2$ on average temperature is centered around these climatic "feedbacks," not the direct warming from $C0_2$. Evidence of some of these feedbacks is so strong that the National Academy of Sciences has concluded that the warming will be at least 1.5EC.

The most important feedback will result from the warmer atmosphere's ability to retain more moisture. Because water vapor also absorbs infrared radiation, additional heating will result. Hansen et al. estimate that doubled $C0_2$ would increase the atmosphere's water vapor content 30 percent, heating the earth an additional 1.4EC.

Another important positive feedback concerns the impact of snow and ice cover on the earth's albedo, the extent to which it reflects sunlight. Ice and snow reflect most of the sun's radiation, while water and soil absorb it. An increase in surface temperatures would melt snow cover on land and floating ice and thereby allow the earth to absorb energy that would otherwise be reflected back into space. Hansen et al. estimate an additional warming of 0.4EC from the albedo effect.

A feedback that is less understood is the impact of a global warming on clouds, which also reflect sunlight into space. The effects of clouds on the earth's albedo depend on their heights and other properties, as well as the extent of cloud cover. Thus, the impact of a global warming on clouds is somewhat uncertain. Nevertheless, with somewhat less confidence, Hansen et al. estimate a 2 percent reduction in cloud cover and a resulting warming of 0.5EC. They also estimate that increases in cloud height would result in an additional warming of 0.5EC, for a total impact of 1.0EC from clouds.

Although the increase in the average temperature of the earth is a convenient shorthand description

Of $C0_2$-induced climatic change, it masks important regional implications. Most researchers agree that polar temperatures would increase two to three times the earth's average increase. The world's climate depends largely on circulation patterns by which the atmosphere and the oceans transport heat from warm to cold regions. As a result, any significant change in the difference between equatorial and polar temperatures could dramatically affect climatic patterns. A particularly important effect of these changes will be shifts in annual and seasonal precipitation and evaporation, with some areas gaining and others losing. Furthermore, because hurricanes require an ocean temperature of 27EC (80EF) or warmer, a global warming could allow hurricanes to form at higher latitudes and during a greater part of the year. Although these changes could be important to coastal communities, they have not been examined in this study.[4]

Increasing Atmospheric Concentrations of Carbon Dioxide and Other Greenhouse Gases

Although the climatic change that would result from $C0_2$ emissions is poorly understood, there is complete agreement that $C0_2$ concentrations are increasing. The measured concentration of $C0_2$ in the atmosphere increased from 315 parts per million in 1958 to 339 ppm by 1980 (Keeling, 1982). Estimates from tree rings suggest that the concentration was approximately 280 ppm in 1860.

Approximately one-half the $C0_2$ released by combustion of fossil fuels has remained in the atmosphere. It is generally believed that most of the remaining $C0_2$ has dissolved into the oceans. Although tropical deforestation and cement production also result in $C0_2$ emissions, their contributions have been and will continue to be much less important.

In the next few decades, $C0_2$ emissions are unlikely to be curtailed, either voluntarily or by regulation. The world's infrastructure is built around fossil fuels. The cost of using coal, gas, and oil is low compared with nuclear and solar power, and this relative cost advantage is expected to continue. Therefore, a voluntary reduction in $C0_2$ emissions is unlikely.

The only governmental action that could successfully reduce $C0_2$ emissions would be to curtail the use of fossil fuels. Emission controls (scrubbers) for $C0_2$ from power plants would at least quadruple the cost of electricity (Albanese, 1980). For smaller users of fossil fuels, such as homes and motor vehicles, control is not even feasible. Other plans, such as sequestering carbon in massive tree plantings, are even less plausible (Greenberg, 1982).

Even if political leaders decide to take drastic actions to limit worldwide consumption of fossil fuels, it is probably already too late to prevent significant rises in global temperatures and sea level. A recent study by EPA investigated the impact of drastic energy policy changes on the expected timing of a greenhouse warming (Seidel and Keyes, 1983). The authors concluded that such policies could have important impacts by 2100, but would not substantially delay the 2EC warming expected by 2040. They estimated that a 300 percent tax on fossil fuels would delay the 2EC warming by only five years, and that even a worldwide ban on coal, shale oil, and synthetic fuels would delay the warming by only twenty-five years, if implemented by 2000. Furthermore, such a ban would delay the rise in sea level expected through 2040 by only twelve years.[5]

The political feasibility of instituting such a ban by 2000 is also doubtful, because only a worldwide agreement to curtail emissions could be successful. Any individual nation that curtails its own emissions will delay the day when $C0_2$ concentrations double by a few years at most. (This delay would be even less if the resulting drop in energy prices induced other nations to increase their own consumption.)[6] Furthermore, because energy costs would increase for any nation that curtailed its emissions, that nation's industries would be placed at a competitive disadvantage compared with those of the rest of the world. The failure of most other nations to follow the United States' lead in banning chlorofluorocarbons in spray cans, where the costs were very minor, indicates that reaching a worldwide consensus on curtailing emissions is extremely difficult. Finally, political leaders would require proof that such a policy would be more beneficial than adapting to higher $C0_2$ levels. Such proof will probably remain impossible to provide for the foreseeable future.

Several other gases emitted by human activities also absorb infrared radiation, and would thus contribute to a global warming. The most significant of these trace gases are methane, nitrous oxide, and chlorofluorocarbons. As Hansen et al. discuss in Chapter 2, emissions of these gases added 50-100 percent to the greenhouse effect from $C0_2$ Although less is known about the future importance of these gases, emissions of some of them, particularly chlorofluorocarbons, may grow much faster than $C0_2$ (Palmer et al., 1980).

The impact of increasing concentrations of greenhouse gases will almost certainly be an unprecedented global warming. Some people have suggested that this warming may be offset because the earth would otherwise be entering a cool period. However, a natural cooling would take place over tens of thousands of years and is thus unlikely to significantly offset the global warming in the next century. Even a drastic increase in volcanic activity would offset less than 10 percent of the projected rise in sea level (Hoffman et al., 1983).

Estimating the Magnitude of the Greenhouse Effect

In the last few decades, mathematical models have been developed to estimate the impact of $C0_2$ on climate. Two of the most complete climate models, those of Hansen et al. and Manabe and Stouffer (1980), estimate the warming from doubled $C0_2$ to be 4EC and 2EC, respectively.[7] In Chapter 2, Hansen et al. discuss the differences between these models, and other evidence supporting estimates of the magnitude of the greenhouse effect. They conclude by estimating that in the 1990s the warming from the greenhouse effect will exceed the fluctuations that have occurred in this century, laying to rest any remaining doubts about the importance of the greenhouse effect.

One of the most important differences between the two models is that Manabe and Stouffer assume that the behavior of clouds would not change, while the Hansen et al. model predicts it to be an important positive feedback. The former model also assumes that less sea ice exists and therefore that the albedo effect will be less significant. Finally, the Manabe and Stouffer model assumes that the atmosphere transports all heat from equatorial to polar regions, while Hansen et al. assume that ocean currents also transport heat. These differences cause Manabe and Stouffer's estimate to be lower than that of Hansen et al.

Hansen et al. identify three types of evidence that support estimates of the magnitude of the greenhouse effect: temperatures on other planets, recent global temperature trends, and long-term climate cycles. Compared with the earth, Mars has lower concentrations and Venus higher concentrations of $C0_2$ and other greenhouse gases. Hansen et al. show that temperature differences between these planets are well-explained by the greenhouse effect, not merely by their distances from the sun. For example, without the greenhouse effect, Venus would be approximately the same temperature as the earth. However, because the planet's atmosphere is mostly $C0_2$ and traps infrared radiation more than one hundred times as efficiently as the earth's atmosphere, Venus is 400EC hotter.

Hansen et al. show that their model's predictions are also consistent with historical evidence. In the past century, global temperatures have increased 0.4EC, with 0.1EC fluctuations from decade to decade. Hansen et al. show that much of the variation in temperature can be explained by their model when the impacts of $C0_2$ and volcanoes are considered. Another type of historical evidence is the ability of the models to explain climatic periods from long ago. Over the last 18,000 years, the earth's average temperature has increased 4EC as the ice covering much of North America, Europe, and Asia retreated. Hansen et al. show that the changes in ice cover used by their model to predict the warming from $C0_2$ is consistent with the changes in ice cover that have occurred in the last 18,000 years.

SEA LEVEL RISE SCENARIOS

Faced with the consequences of a global warming, coastal decision makers would like to have a precise projection of sea level rise. Unfortunately, because of the large degree of uncertainty in many of the factors influencing sea level, available scientific knowledge is inadequate to generate a precise forecast.

Nevertheless, in Chapter 3, Hoffman argues that available knowledge is sufficient to estimate the likely range of sea level rise in the next century. For each of the factors influencing sea level rise, he consulted the experts and the literature to determine conservative and high estimates. He then linked various combinations of these estimates to produce scenarios of worldwide sea level rise ranging from conservative to high.

Scenario Building

Figure 1-2 illustrates the relationships among the factors influencing sea level rise that Hoffman considered. Several different models representing these components were used to generate over 90 scenarios. From these, a conservative, a mid-range low, a mid-range high, and a high scenario were identified.

The major factors influencing sea level that Hoffman considered were: $C0_2$ emissions; fraction airborne (the fraction of $C0_2$ emissions that remains in the atmosphere); concentrations of other trace gases; climate sensitivity (global warming resulting from increases in atmospheric concentrations of $C0_2$ and trace gases); thermal expansion of ocean water; and snow and ice contributions.

For the first five factors, Hoffman specified a conservative, a mid-range, and a high assumption. For snow and ice contributions, he used only a high and a low assumption.

Carbon Dioxide Emissions. The World Energy Model of the Institute for Energy Analysis was run under a variety of assumptions regarding population growth, economic activity, and the relative costs of various sources of energy to produce scenarios of $C0_2$ emissions (Institute for Energy Analysis, 1982). Based on the work of Keyfitz et al. (1983), all scenarios assumed that world population achieved zero growth by 2075. The high scenario assumed that per capita economic growth decreased from 3.5 percent per year in 1980 to 2.2 percent by 2100. These rates are lower than experienced by the world economy in the last thirty years. For the conservative scenario, growth will diminish from 2.2 percent in 1980 to 1.7 percent in 2100. All scenarios assumed that energy efficiency improves, and the conservative scenario also assumed that the cost of producing nuclear power was reduced 50 percent in 1980. As a result of these assumptions, $C0_2$ emissions would grow at average rates of 1.7 percent, 2.0 percent, and 2.3 percent per year from 1980 to 2100, for the conservative, mid-range, and high scenarios, respectively.

Fraction Airborne. Two methods were used to determine the percentage of carbon emissions that remain in the atmosphere (i.e., the fraction airborne). In the conservative scenario, the historical average of 53 percent was used. In the mid-range and high scenarios, the Carbon Cycle Model of the Oak Ridge National Laboratories (ORNL) was used (ORNL, undated). This model simulates the movement of carbon among the biosphere, oceans, and atmosphere, taking into account decay, oxidation and other biochemical actions. Largely because the upper layers of the ocean would approach saturation as warmer surface temperatures reduced vertical mixing of the oceans, the model predicted that the rate of atmospheric retention of $C0_2$ would grow from 60-80 percent by 2100. As a result, atmospheric concentrations of $C0_2$ would double by 2055 in the high scenario and by 2085 in the conservative scenario.

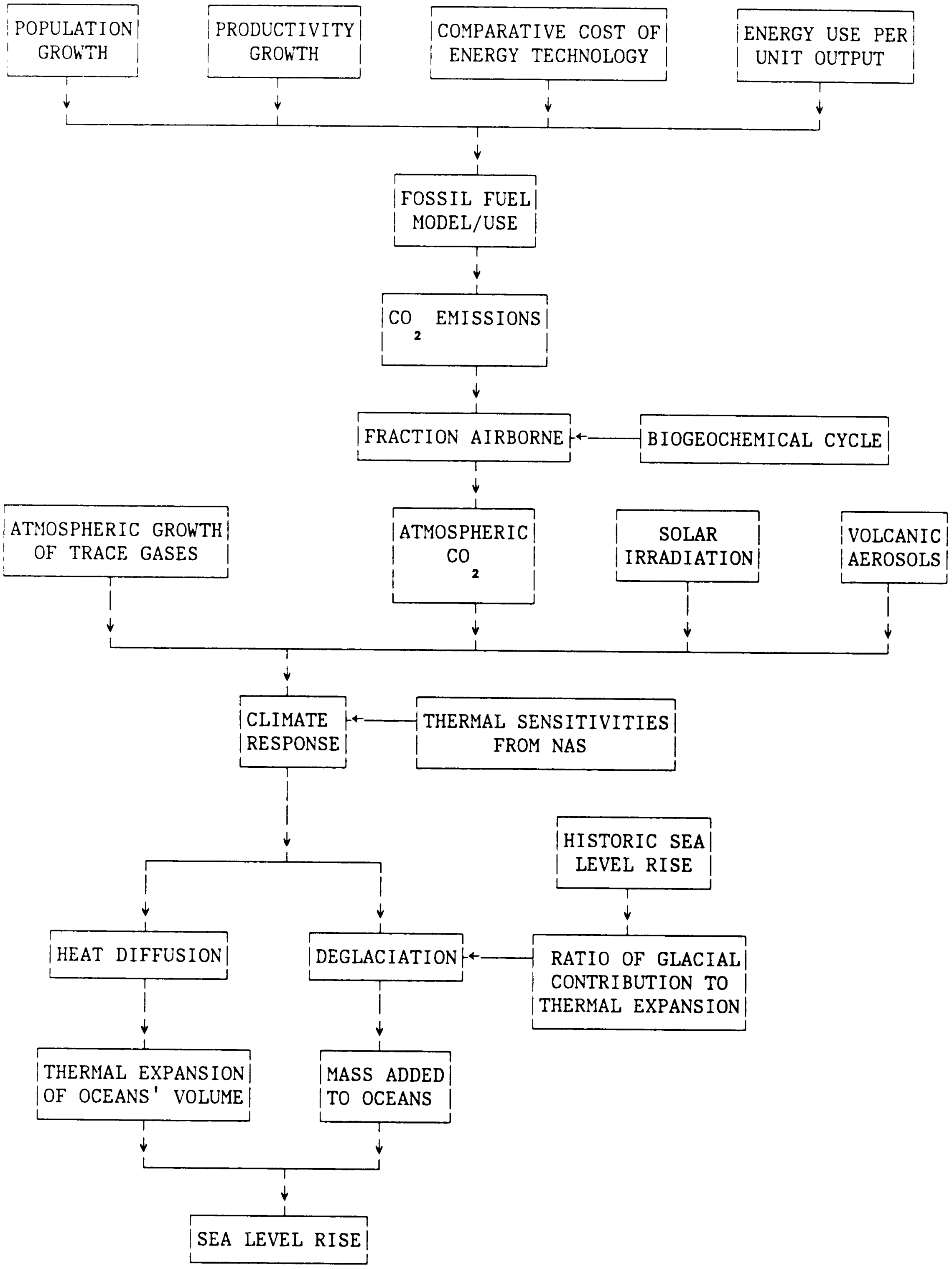

Figure 1-2. Basis for scenarios. For each factor or relationship, high and low assumptions were developed using the published literature.

Concentrations of Other Greenhouse Gases. Knowledge of the origins and fates of other gases that absorb infrared radiation is insufficient to project their atmospheric concentrations in the same manner as was done for $C0_2$. Hoffman only considered four of the most important trace gases: methane, nitrous oxide, and two chlorofluorocarbons, $CFCl_3$ (R-11) and CF_2Cl_2 (R-12).

Because of the ozone depletion potential from chlorofluorocarbons, all scenarios assumed that emissions would not increase after 2020. From 1980 until that date, the conservative, mid-range, and high scenarios assumed that emissions of these gases would increase linearly by 0.7, 2.5, and 3.8 percent of the 1980 level, respectively, each year. Concentrations of these gases were calculated by assuming the half-lives of $CFCl_3$ and CF_2Cl_2 to be 60 and 120 years, respectively. For nitrous oxide and methane, Hoffman projected atmospheric concentrations directly. The three scenarios assumed that methane concentrations would increase geometrically by 1.0, 1.5, and 2.0 percent per year, and that nitrous oxide concentrations would increase by 0.2, 0.45, and 0.7 percent per year.

Climate Sensitivity. Hoffman used the National Academy of Sciences' estimated range of the impact of a $C0_2$ doubling on average surface temperature (Charney, 1979; Smagorinsky, 1982). The conservative scenario assumed that the average surface temperature would increase 1.5EC (2.7EF), the mid-range scenarios assumed 3.0EC (5.4EF), and the high scenario used 4.5EC (8.1EF). Given these assumptions about the impact of a doubling, Hoffman projected year-by-year increases in temperature using the increases in greenhouse gases with an equation fit to the results of a climatic model that includes heat transfer from the atmosphere to the oceans. [8]

Thermal Expansion of Oceans. Although surface waters would warm quickly with rising global air temperatures, the downward transport of heat into deeper ocean layers would warm them much more slowly. Hoffman employed an ocean model that uses diffusion as a surrogate for all heat transport processes to estimate heat transported into the top one thousand meters (3,200 feet) of the ocean. All scenarios used coefficients based on interpretation of data on ocean tracers.[9] Because glacial melting and climate change might alter ocean currents drastically, special-case scenarios were also developed. [10] These extreme assumptions did not have large effects on the resulting projections of sea level rise. The expansion of water was computed at each depth using standard coefficients of expansion for the temperature, pressure, and salinity of a globally averaged column of water.

Snow and Ice Contributions. Very little work has been done concerning the impact of a global warming on deglaciation. As a result, Hoffman acknowledges that his assumptions about the impact of global warming on glaciers constitute the weakest part of the analysis. He notes that in the last century, a global warming of 0.40C (0.70F) would be sufficient to explain a 5 cm (2 in) rise in sea level from thermal expansion. However, various authors have estimated that the actual rise was 10-1 5 cm (4-6 in). Therefore, factors other than thermal expansion - most likely snow and ice contributions from land-accounted for the other 5-10 cm rise. Given the absence of glacial process models. Hoffman assumed that this relationship would persist.

Therefore, the conservative and mid-range low scenarios assumed that the rise in sea level from deglaciation would equal the contribution from thermal expansion, while the mid-range high and high scenarios assumed that it would be twice the contribution. Hoffman notes that these assumptions were consistent with estimates of melting derived from Hansen et al. three-dimensional global climate model, which simulates world climate on an hour-by-hour basis in a manner very close to observed conditions. Nevertheless, he argues that this aspect of the scenarios should be improved as soon as possible by using glacial process models*.

---

* Editors' Note: Subsequent analysis had led Hoffman to conclude that the mid-range low scenario is more likely than the mid-range high scenario.

Results of Sea Level rise Scenarios

Table 1-1 illustrates Hoffman's results for global sea level rise through 2100. Under the high scenario, sea level will rise about 17 cm (6.7 in) by 2000, 117 cm (3.8 ft) by 2050, and 345 cm (11.3 ft) by 2100. Under the conservative scenario, sea level will rise about 17 cm (6.7 in) by 2000, 117 cm (3.8 ft) by 2050, and 345 cm (11.3 ft) by 2100. Under the conservative scenario, sea level will rise 4.8 cm (2 in) by 2000, 24 cm (9.4 in) by 2050, and 56 cm (22 in) by 2100. Because of local subsidence, most of the Atlantic and Gulf coasts of the United States can expect the sea to rise 15-20 cm more in the next century than these figures indicate.

Tables 1-2 and 1-3 show the sea evel rise scenarios that Kana et al. And Leatherman used in the Charleston and Galveston case studies. These scenarios differ from Hoffman's scenarios for several reasons. First, Hoffman made several improvements in his scenarios after Kana et al. And Leatherman had completed their chapters. [11] Second, Kana et al. And Leatherman adjusted the global scenarios to account for local conditions. Third, instead of using the conservative scenario, the case studies used a basline scenario calculated by extrapolating past trends of global sea level rise and using judgment regarding local trends. Finally, the "mid-range low" scenario is called "low" and the "mid-range high" scenario was replaced by a "medium" scenario equal to the average of the high and low scenarios.

Research Necessary to Reduce Uncertainty

Opportunities are available for substantially reducing the major uncertainties regarding sea level rise. However, better knowledge will require considerably greater research expenditures than are currently being made. Moreover, a mission-oriented management will be needed to induce the necessary coordination between researchers who normally work apart in such diverse fields as climatology, oceanography, glaciology, and biogeochemistry.

Of the major factors considered in Hoffman's scenarios, insufficient research is currently being undertaken on concentrations of trace gases, deglaciation, and incorporation of the oceans into climate models. Although there is a modest amount of ongoing research to determine the likely impact of $C0_2$ emissions on average global temperatures, these activities are not driven by a sense of urgency that is based on the need to produce year-by-year estimates that are useful for decision makers.

In researching trace gases, the short-term priority should be to identify all the sources and sinks, both current and future, that will influence concentrations of chlorofluorocarbons, methane, nitrous oxide and other important gases neglected in this study. Over the longer term, biogeochemical models that accurately represent the atmospheric, oceanic, and terrestrial processes that control the levels of these gases need to be developed.

Climate models that incorporate realistic geography, realistic heat uptake and transport by the oceans, and the feedback effects of melting, evaporation, sublimation, and snowfall in polar regions should be run on a year-by-year basis as soon as possible in order to provide estimates of the time path and geography of climate change. A major effort to include better ocean models should be the highest long-term priority. A better representation of polar processes in global climate models is also necessary.

The response of glaciers to a global warming is the least understood of the major factors that will determine sea level rise. In the short run, global climate modelers, southern ocean oceanographers, and glaciologists can produce scenarios of meltwater runoff and deglaciation that complement the scenarios of thermal expansion developed by Hoffman. In the longer term, a greater data collection will be needed. Without the better observations necessary to build and validate models, it will be impossible to provide reliable and precise estimates. In the next decade, more complete models of icefields should be developed, based on the specific topography of each field. Experiments such as towing icebergs into warmer water could also be undertaken to provide additional insights into the behavior of glaciers under radically different conditions. Observational programs using satellite data to track the advance and retreat of glaciers should also be undertaken. Together, these efforts can greatly improve the precision of estimates of snow and ice

Table 1-1. Worldwide Sea Level Rise Scenarios, 1980-2100
(in cm and ft above 1980 levels)

Scenario	*2000*	*2025*	*2050*	*2075*	*2100*
Conservative	4.8 (0.16)	13.0 (0.43)	23.8 (0.78)	38.0 (1.2)	56.2 (1.8)
Mid-range Low	8.8 (0.29)	26.2 (0.86)	52.3 (1.7)	91.2 (3.0)	144.4 (4.7)
Mid-range High	13.2 (0.43)	39.3 (1.3)	78.6 (2.6)	136.8 (4.5)	216.6 (7.1)
High	17.1 (0.56)	54.9 (1.8)	116.7 (3.8)	212.7 (7.0)	345.0 (11.3)

Table 1-2. Sea Level Rise Scenarios for Charleston, 1980-2075
(in cm, with ft in parentheses)

Scenario[a]	*Year*		
	1980	*2025*	*2075*
Baseline	0	11.2 (0.4)	23.8 (0.8)
Low	0	28.2 (0.9)	87.6 (2.9)
Medium	0	46 (1.5)	159.2 (5.2)
High	0	63.8 (2.1)	231.6 (7.6)

Source: Global sea level rise scenarios are from Chapter 3, modified to reflect local conditions based on the historical trend for Charleston. (S. D. Hicks et al., 1983, *Sea Level Variations for the United States, 1855-1980,* technical report, Rockville, Md., NOAA, Tides and Water Levels Branch)

[a] Baseline scenarios for each year reflect present trends. Other scenarios reflect accelerated sea level rises at various rates.

Table 1-3. Sea Level Rise Scenarios for Galveston, 1980-2075
(in cm, with ft in parentheses)

Scenario	*Year*		
	1980	*2025*	*2075*
Baseline	0	13.7 (0.45)	30.0 (0.98)
Low	0	30.7 (1.0)	92.4 (3.0)
Medium	0	48.4 (1.6)	164.5 (5.4)
High	0	66.2 (2.2)	236.9 (7.8)

Source: See Chapter 5.

contributions to sea level rise. Finally, models of thermal expansion that consider longitude and latitude should replace the one-dimensional model Hoffman used. Over the longer run, models of ocean circulation capable of considering the impacts of global warming and deglaciation on ocean mixing, and thus heat uptake, should be developed.

The challenge of advancing our knowledge will require careful management of research. Only if sustained long-term support is given to interdisciplinary scientific teams can accelerated research speed the development of necessary information and narrow the range of plausible sea level rise scenarios. The sporadic stop-and-start efforts and the support of individuals or groups working in isolation that have characterized many recent efforts are not likely to be sufficient for this challenge.

EFFECTS OF SEA LEVEL RISE

This section describes the physical and environmental effects of sea level rise, and the activities that can be undertaken to prevent or adapt to these effects.

The Physical Consequences of Sea Level Rise

The physical consequences of sea level rise can be broadly classified into three categories: shoreline retreat, temporary flooding, and salt intrusion. The most obvious consequence of a rise in sea level would be permanent flooding (inundation) of low-lying areas. A sea level rise of a few meters would inundate major portions of Louisiana and Florida, as well as beach resorts along the coasts. Marshes and low-lying flood plains along rivers and bays would also be lost.

Many coastal areas with sufficient elevation to avoid inundation would be threatened by a different cause of shoreline retreat: erosion. In fact, the current trend of sea level rise may be causing the serious erosion that is taking place in many coastal resorts (New Jersey, 1981; Pilkey et al.,1981). The constant attack of waves causes beaches to take a particular profile, which fluctuates seasonally. Winter storms erode the upper beach and deposit sand offshore, and the calmer spring and summer waves redeposit the sand and restore the beach. However, a rise in sea level alters the relationship of the shore profile to the water level (see Figure 1-3). Because the water near the beach is deeper than before, more energy is required to move the offshore sand back to the beach. Consequently, some of the material deposited offshore by winter storm waves remains offshore, and a portion of the beach is lost (Bruun, 1962; Schwartz and Fisher, 1979).

Another cause of beach erosion from sea level rise is overwash and the resulting landward migration of coastal barriers (Massachusetts, 1981; U.S. Department of Interior, 1983). Many American beach resorts lie on narrow islands and spits (peninsulas with the ocean on one side and a bay on the other). Rather than erode them in place, overwash processes cause the islands and spits to migrate landward in a fashion similar to a tank tread. These processes take place during storms and raise islands as well as move them landward. Although this process may protect the barrier itself, property on the seaward side may be totally lost.

Increased storm damage is an economically important result of sea level rise. Wind and low pressure during hurricanes and other storms cause the water level in an area to rise temporarily, sometimes by several meters. The Federal Emergency Management Agency classifies these storms in terms of both their frequency and the magnitude of the elevation in water level -the latter phenomenon is known as storm surge. Regions with 1 percent and 10 percent chances of flooding in a given year are designated as 100-year and 10-year flood zones, respectively. Existing development is often predicated on the basis of these flood frequencies. An increase in sea level would increase the water level during a flood by approximately the amount of sea level rise, bringing new areas into the flood zones. Higher water tables also exacerbate flooding by decreasing the ability of land to drain stormwaters. Finally, erosion and deeper water could subject new areas to damaging storm waves.

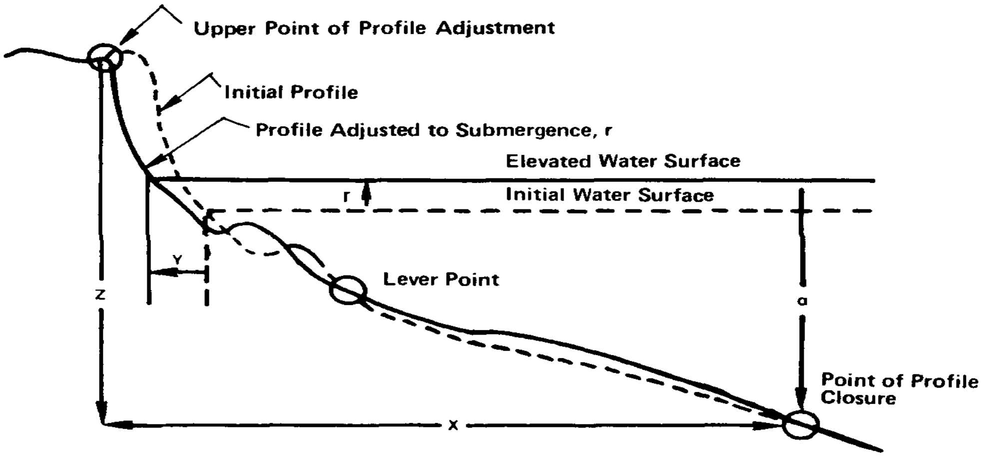

Figure 1-3. Concept of profile adjustment to increased sea level. Given a shore profile at equilibrium and a rise in water level, Bruun's Rule (1962) states that beach erosion occurs in order to provide sediments to the shore bottom so that the shore bottom can be elevated in proportion to the rise in water level (a). The volume of sediment eroded from the beach (V) is equal to the volume of sediment deposited on the shore bottom *(V). (Source: after E. B. Hands, 1981. Predicting Adjustments in Shore and Offshore Sand Profiles on the Great Lakes. CERC Technical aid 81-4, Ft. Belvoir, Va.: Coastal Engineering Research Center)*

Sea level rise also causes the salt content of aquifers and estuaries to migrate landward. In coastal aquifers, a layer of freshwater floats on top of the heavier saltwater. The saltwater generally forms a wedge such that the farther inland (the higher the water table), the farther below ground is the boundary between fresh and saltwater. Where sea level rise results in a landward movement of the shoreline, this boundary will move inland as well. Because the level of the water table is itself determined by sea level, a rise in sea level causes the freshwater/saltwater boundary to rise. The landward and upward shift of this boundary implies that certain freshwater wells may become salty. Overpumping of coastal aquifers also has resulted in salt intrusion, however, and in many instances this problem dwarfs the possible impact of sea level rise.

A rise in sea level also would increase the salinity of rivers and estuaries. Since the last ice age, as sea level rose approximately one hundred meters (several hundred feet), such freshwater rivers as the Susquehanna have evolved into estuaries like the Chesapeake Bay. A decrease in the flow of a river or an increase in the volume of water allows salt to migrate upstream. An increase in sea level of only thirteen centimeters (five inches) could result in salt concentrations in the Delaware River migrating two to four kilometers (one to two miles) upstream (Hull and Tortoriello, 1979). A rise of one meter could cause salt concentrations to migrate over twenty kilometers, possibly enough to threaten part of Philadelphia's water supply during a drought. Because some rivers recharge aquifers, some aquifers might become salty as well.

The impacts of storm damage and salt intrusion may be exacerbated or mitigated by the impacts of an enhanced greenhouse effect on climate. For example, possible increases in hurricane frequencies would further increase storm damage, while reductions in the severities of northeasters could reduce it. Flohn (1981) has suggested that in the mid-latitudes less precipitation might result, which would amplify salinity increases. Because these possibilities are still very tentative, they are not included in the analyses presented here.

Impacts on Today's Decisions

The costs associated with the physical effects of sea level rise could be very high. Although the worst effects would not begin to be felt until 2025, low-lying areas and beach resorts could be seriously affected before then. Furthermore, a wide variety of decisions made in the next decade will significantly influence the extent of the damages from sea level rise in the next century.

A popular convention used in evaluating large-scale projects is to assume that the project has a lifetime of thirty years. For many purposes, this convention is useful. Unfortunately, it has also led some managers to view the future beyond thirty years hence as completely irrelevant, even for projects that last much longer. Although machinery may only last ten years, many factories last fifty to one hundred years. Although pavement may last only ten years, a road lasts and channels land development for centuries. The location and layout of most major cities in the eastern United States were determined by decisions made before 1800. Houses, bridges, port facilities, airports, utilities, cathedrals, and office buildings constructed in the next decade may be useful for the next century or longer.

Sea level rise could affect all of these projects. Buildings could be destroyed by erosion and storms. Federal government programs that aid victims of natural disasters could become much more costly. Roads could be destroyed, and the costs to localities of maintaining infrastructures could increase. Bridges, docks, and aids to navigation would have to be reconstructed. Communities with high water tables would have to redesign drainage systems, and basement flooding could become more severe. Salt intrusion could necessitate constructing expensive desalinization facilities or relocating water intakes. Existing riparian rights and pacts to distribute water between municipalities might become unfair.

Environmental Impacts of Sea Level Rise

Like the physical effects, the environmental impacts of sea level rise fall into the categories of shoreline retreat, salt intrusion, and increased flooding. Perhaps the most serious environmental consequence would be the inundation and erosion of thousands of square miles of marshes and other wetlands. Wetlands (areas that are flooded by tides at least once every 15 days) are critical to the reproductive cycles of many marine species. Because marsh vegetation can collect sediment and build upon itself, marshes can "grow" with small rises in sea level. But for faster rates of sea level rise, the vegetation will drown. Its resulting deterioration may significantly erode land previously held together only by the marsh vegetation. Relative sea level rise of one meter per century is eroding over one hundred square kilometers (about fifty square miles) per year of marshland in Louisiana.

Salt intrusion is a threat to marine animals as well as vegetation. Many species must swim into fresher water during reproduction. In response to sea level rise, fish might swim farther upstream, but water pollution could prevent such an adaptation from succeeding. Some species, on the other hand, require salty water, such as the oyster drill and other predators of oysters. Consequently, salinity increases have been cited for the long-term drop in oyster production in the Delaware Bay (U.S. Fish and Wildlife Service, 1979; Haskin and Tweed, 1976), as well as recent drops in the Chesapeake Bay. Salt intrusion could also be a serious problem for the Everglades.

Flooding could have a particularly important impact on environmental protection activities. As Chapter 9 indicates, regulations for hazardous waste sites promulgated under the Resource Conservation and Recovery Act currently impose special requirements for sites in 100-year flood zones. Another EPA program, Superfund, has responsibility for abandoned waste sites, some of which are in low-lying areas such as Louisiana and Florida that could be inundated.

There are over one thousand active hazardous waste facilities in the United States located in 100-year floodplains (Development Planning and Research Associates, 1982) and perhaps as many inactive sites. Sea level rise could increase the risk of flooding in these hazardous waste sites. For example, if a hazardous waste facility is subjected to overwash by strong waves or simply to flooding that weakens the facility's cap, the wastes can be spread to nearby areas, thus exposing the population to possibly contaminated surface water. Moreover, by intruding into clay soils (which are often used as liners for hazardous waste disposal) saltwater can increase leaching of wastes.

RESPONSES TO SEA LEVEL RISE

We briefly review here the numerous methods that are available to prevent, mitigate, and respond to erosion, flooding, and salt intrusion from sea level rise. Sorensen et al. provide more detail in Chapter 6.

Communities and individuals must decide whether to attempt to protect themselves from the consequences of sea level rise or adapt to them. Generally, prevention will be economically justifiable only at valuable locations, such as population centers, defense installations, historical sites, and areas of environmental importance such as habitats of endangered species. Other areas would have to adjust to the consequences.

Prevention of erosion requires keeping waves from attacking the shore. This is generally achieved by intercepting the waves offshore or by armoring the beach itself. Offshore breakwaters limit the size of incoming waves. Revetments armor the beach itself and can be useful for moderate size waves.

Several means of preventing inundation and storm surge also serve to limit erosion. Seawalls, levees, and bulkheads are vertical wall structures made of materials of various strengths, depending on the size of the waves. New Orleans and other low-lying communities are protected by levees, while Galveston is protected by a seawall. With a rising sea, however, these structures may require protection themselves. Shoreline retreat in Galveston, for example, threatens the seawall's foundations. Accurate forecasts of future sea level rise could enable engineers to determine the heights and best design of these structures so that their initial construction is appropriate and cost-effective for their entire lifetime.

Because beaches and waves are important to resort communities, structures are not always an acceptable response to erosion, inundation, and storm surge. A popular but expensive option is artificial beach nourishment, that is, pumping sand from offshore or dredging a nearby channel. Because it would increase the amount of sand required, a rise in sea level could significantly increase the cost of such activities. In Chapter 8, however, Titus argues that the substantial real estate values would justify beach nourishment in many resorts, provided the sand was available.

Restoring other mechanisms of natural systems can also protect against erosion and storm surge. For example, dunes can provide a reservoir of sand to slow erosion and act as a levee against storm surges. Also, some marshes are supplied with sufficient sediment during floods to keep up with sea level rise. Where dunes have been destroyed or rivers levied to prevent flooding, restoring these natural mechanisms may be cost effective.

Adjustment to the physical consequences of sea level rise may sometimes be more appropriate than prevention. In anticipation of erosion, some communities may prohibit construction in the most hazardous areas, and abandonment may even be necessary. In Chapter 8, Titus suggests that in the aftermath of a devastating storm, low-density communities might require development to retreat landward by fifty meters (one to two hundred feet). Such a policy could prevent subsequent losses to erosion and storms and help preserve a recreational beach. In the case of barrier islands, he recommends that communities consider imitating natural overwash processes by pumping sand to the bay side to preserve total acreage. Marsh systems could be maintained by identifying and reserving higher ground for migration, and later, by planting marsh vegetation.

Communities could adapt to increased storm damage by using measures already required in many hazard-prone areas. Houses can be elevated on pilings, waterproofed, and designed so that the first floor is a carport or utility area. Orienting structural walls parallel to the prevailing wave direction can protect them from destruction by storm waves. Commercial buildings can be designed so that the most valuable equipment is above future flood levels.

Adaptation to erosion and storm damage requires more advanced warning of sea level rise than building protective structures. For example, once completed, a building frequently is used for fifty to one hundred years; a highway influences development even longer. In contrast, protective structures and beach restoration can be accomplished in only a few years.

As with erosion, inundation, and flooding, individuals may either prevent or adapt to salt intrusion. In rivers, salt migrates upstream from both sea level rise and droughts. Therefore, preventive methods that currently focus on droughts could be extended to incorporate sea level rise. The Delaware River Basin Commission has responded to salt intrusion by constructing reservoirs that release water during droughts, maintaining a minimum flow. Areas that rely on rivers for drinking-water supplies can also maintain the flow by restricting consumption during droughts. Smaller communities can respond by moving intakes upstream or shifting to alternative supplies.

Most marine species can respond to salt intrusion by migrating upstream. Although sessile species such as oysters cannot move upstream fast enough to respond to salinity increases from droughts, the gradual rise in sea level would probably be slow enough to accommodate a migration. Because water pollution from urban areas upstream might make such a migration impractical, additional water pollution controls might be necessary.

The most frequent response to salt intrusion into a coastal aquifer is to seek alternative water supplies, such as wells farther inland. However, valuable aquifers, such as the Potomac-Raritan-Magothy aquifer system in southern New Jersey, might warrant engineering solutions. Freshwater can be injected near the salty body of water that is recharging the aquifer, forming an injection barrier that reverses the flow of water back into the saltwater body. Extraction of the intruding salt water, physical barriers, and increasing the amount of freshwater available to recharge the aquifer are other options. However, all of these options are expensive and have had only limited application.

The increased risk of flooding hazardous waste sites could be addressed by strengthening existing programs, particularly as they apply to closed and abandoned sites. As Chapter 9 discusses, EPA regulations already require operating waste sites in 100-year floodplains to ensure that wastes do not escape and contaminate surrounding areas during floods. With a rise in sea level, the 100-year flood boundary would shift inland, and these regulations would require more sites to undertake flood mitigation measures as the risks increase4. However, existing regulations provide no similar protection against contamination from closed or abandoned sites. Regulations governing the closure of waste sites in the future could be modified to ensure that the sites are secure in the event of sea level rise.

METHODS USED IN THE CASE STUDIES

The case studies were innovative approaches to problems that previously had not been explored. Because in many instances there was little or no research on which to build, we adopted the case study approach so that our efforts would produce methods as well as results.

Each analysis required inputs from the previous analysis. Using the projections of sea level rise, Kana et al. and Leatherman projected the shoreline retreat and storm surge that would result if no additional protective measures were implemented. Using this information, Gibbs projected the economic impacts of sea level rise, both for the cases where sea level rise is and is not anticipated. In both cases, he used the analysis of Sorensen et al. to develop possible structural responses to sea level rise. The difference between these impacts (i.e., with and without anticipation of sea level rise) provides a measure of the value of policies that anticipate sea level rise. Titus used Gibbs's estimates of economic impacts to explore homeowners' decisions of whether to rebuild oceanfront houses destroyed by a major storm.

Choices of Study Areas

Several factors were considered in choosing our case study sites. We wanted to represent different coasts and different tidal and erosion patterns. We wanted commercial and industrial development patterns to vary. The costs of obtaining data covering both natural phenomena (such as the National Weather Service's Storm Surge Model) and socioeconomic variables had to be within the study's budget. The availability of expert coastal scientists with extensive experience in that particular study area was also considered important.

In response to these considerations, Galveston and Charleston were chosen as study areas. Galveston's history of subsidence and the availability of maps dating back to 1850 provided a record of the impact of relative sea level rise on the area. The two areas have different tidal patterns, Galveston Bay being *microtidal* (tide ranges average less than two feet) and Charleston being mesotidal (tide ranges average five to six feet).

Charleston and Galveston also exhibit different industrial development, resources, amenities, and protective approaches to storm threats. The most highly developed part of the Galveston study area is directly exposed to the ocean, with extensive protective structures throughout the area. Charleston lies behind a string of barrier islands and has few coastal works other than a seawall guarding the tip of the peninsula. Charleston's extensive historic district poses special economic and environmental challenges, while Texas City, in the Galveston study area, boasts one of the country's largest petrochemical and refinery complexes. Growth within the Galveston area is limited by land subsidence and groundwater shortages, while parts of Charleston will experience rapid build, growth over the next two decades. The National Weather Service's new storm Surge Model was available for the Galveston area. Finally, Leatherman (for Galveston) and Kana et al. (for Charleston) had extensive experience in coastal research and mapping of their respective areas.

Projecting Shoreline Retreat

Sea level rise causes shorelines to retreat both because land lying below future sea level will be permanently inundated and because erosion of nearby land will increase. The particular method appropriate for estimating shoreline retreat at given points on the coastline depends upon topography, beach composition, wave climate, sediment supply, and available historical data.

A theoretical model for estimating the impact of sea level rise on shoreline retreat is provided by the Bruun Rule (see Figure 1-3). This rule assumes that after a rise in sea level, the beach profile that existed prior to the rise will be restored through wave action eroding away the upper part of the beach and redepositing the material on the bottom. Essentially, the Bruun Rule says that shoreline retreat should be predicted using the average slope of the entire beach system from the dune crest to an area several thousand feet out to sea, rather than the slope of the portion of the beach immediately above sea level.

Despite its importance as a conceptual tool, the Bruun Rule is insufficient to predict shoreline retreat. If a certain percentage of sediment is likely to be carried away, the method must be adjusted by using an estimate of the percentage of material lost. Furthermore, estimating the offshore limit of the beach system can be difficult and involves an element of judgment. Finally, the Bruun Rule only estimates shoreline changes caused by sea level rise, while our analysis requires estimates of all factors influencing shoreline location. Therefore, even where the Bruun Rule can estimate shoreline retreat due to sea level rise, it may be necessary to rely on other methods to account for shoreline changes caused by other factors.

In the Galveston case study, Leatherman used an empirical model for determining shoreline retreat and concluded that the model was consistent with results obtained from applying the Bruun Rule. Using maps dating back to 1850, he determined that the local relative sea level rise (global sea level rise plus subsidence, which has been of major importance in the Galveston area) of forty centimeters (sixteen inches) was the only major cause of the shoreline retreat that had been observed. Because the area has a constant slope, he assumed that another forty-centimeter rise would result in the same amount of shoreline retreat as had been observed in the past. Therefore, Leatherman predicted shoreline retreat by an empirical formula that says, essentially, that each centimeter of future sea level rise will result in a shoreline retreat equal to one-fortieth the retreat that has occurred since 1850.

Determining the impact of sea level rise on the Charleston area presented a more difficult problem. First, the record for shoreline change was available only for the last 40 years, during which relative sea level rose only ten centimeters (four inches). Equally important, because the three rivers that converge to form Charleston Harbor deposit significant amounts of sediment and much of the shore had actually advanced, historical sea level rise has been only one of many factors responsible for historical shoreline change. Furthermore, because Charleston Harbor is narrower than Galveston Bay, the waves are smaller. Therefore, wave-induced erosion (predicted by the Bruun Rule) would not be as significant. On the other hand, a rise in sea level would slow river currents and alter the amount of resulting shoreline change. Finally, while most of the case study area was in the harbor, the area also included a barrier island (Sullivans Island).

Kana et al. generated a baseline shoreline by extrapolating past trends, making allowances for the probable rediversion of the Santee River, which would reduce sediment supply. Their projections of shoreline change due to sea level rise within the harbor assumed that all shoreline changes would be due to inundation (i.e., no erosion would result from sea level rise within the harbor). For Sullivans Island, Kana et al. used the Bruun Rule to predict erosion due to sea level rise until the island reached a critical width. At that point, they assumed that the island would migrate landward at a rate of six meters per year, on the basis of experience with other barrier islands in "overwash mode" in the region. All existing development on the island would be destroyed as the island migrated by approximately its own width.

For protected shorelines, both case studies assumed that the protective structures would halt all erosion up to the point where they were overtopped. Leatherman, however, points out that earthen levees in Texas City would erode before being overtopped unless they were reinforced.

Storm Surges

Storm surge refers to the superelevation of water associated with hurricanes and northeasters. Predictions of storm surge elevations are generally based on historical records of previous storms. The Galveston Bay area was one of the first areas modeled by the National Hurricane Center using the SLOSH (Sea, Lake, and Overland Surges for Hurricanes) model, which Leatherman used to estimate existing storm surge frequency. SLOSH simulates wind speeds and storm surges based on the probabilities of various combinations of tides, meteorological conditions, topography above and below the water, and existing coastal structures. The model estimates the frequency of flooding and maximum surge. Because this model was not yet available for Charleston, a previous analysis based on the National Oceanic and Atmospheric Administration's SPLASH (Special Program to List Amplitudes of Surges from Hurricanes) model was used to predict storm surge frequencies and magnitudes given existing sea level.

Both case studies estimated the new storm surge levels for areas already in flood zones by adding the amount of sea level rise to the amount of flooding predicted by SPLASH and SLOSH under current conditions. Both assumed that the floodplain boundaries would move inland to the point where the resulting increase in elevation of the boundaries was equal to the rise in sea level. (This assumption of no attenuation of the flood surge would not be appropriate for very flat areas, such as Florida and the Mississippi Delta.)

For protected areas, Kana et al. and Leatherman assumed that there would be no flooding unless surges were great enough to overtop seawalls. Although sea level rise would subject some barriers to greater stresses than they were designed to withstand, Kana et al. and Leatherman assumed they would remain intact. Both assumed that once a barrier was overtopped, the water level on the protected side would rise to the level to which it would have risen without the seawall. Although a barrier should provide some protection, Leatherman believes this assumption to be reasonable for Texas City because of the city's small size. In the case of Galveston, flooding would occur from the bay side before the seawall was overtopped.

Salt Intrusion

The two case studies considered only the salt intrusion into aquifers, not surface waters. The "Ghyben-Herzberg relation" was used to estimate the present location of the freshwater/saltwater boundary. This principle states that the depth of the saltwater/freshwater interface is forty times the elevation of the water table above mean sea level. This is conservative in that the boundary has undoubtedly moved landward due to overpumping. Sea level rise was assumed to shift the water table and freshwater/saltwater boundary upward by the amount of sea level rise and landward in accordance with shoreline retreat.

Admittedly, more sophisticated models might have been used. However, we did not believe that salt intrusion into aquifers warranted additional investigation because the salt intrusion from overpumping in the Charleston area dwarfed all impacts from sea level rise, and Galveston-Harris County prohibits additional pumping of groundwater because of historical problems with subsidence.

Economic Impacts

Gibbs's economic analysis in Chapter 7 proceeds in two steps. First, he defines and measures the economic value of the land affected by shoreline movement and storm surge. The economic impact estimates are measured in terms of the real resource costs to society caused by sea level rise. Then, he analyzes the value of anticipating sea level rise. Gibbs's analysis does not, however, consider the impacts of salt intrusion or the impacts (positive or negative) on parties outside the study area.

Real economic losses fall into three categories: (1) the direct losses of economic services from land and capital caused by shoreline retreat and storm damage; (2) the cost of protection, mitigation, and response measures taken to reduce these losses; and (3) lost opportunities due to sea level rise. Gibbs encompassed these three consequences with a single measure called "net economic services." This measure is the value of all services produced minus the costs of producing them (costs include expenditures for new investment, maintenance, and protection and mitigation actions). Because structures remaining at the end of the time period analyzed will continue to produce economic services, their value must also be considered.

To compute net economic services, Gibbs simulated investment, the damages from storms and erosion, and prevention, mitigation, and response measures for each decade. Because human behavior is difficult to predict, Gibbs examined the sensitivity of the economic analysis to various parameters and assumptions. For example, he varied the behavioral assumptions that determine development patterns and the choice of protective actions, with different responses to the same experience and information being tested.

Expectations will play a key role in determining future damage. By considering behavioral responses, the analysis explicitly accounted for the effects of expectations of sea level rise on future decisions. For example, if no one anticipates sea level rise, certain areas could be developed, only later to face the threats of shoreline retreat and storm damage. In this instance, the costs of storm damage (and possibly of protective measures needed later) would increase. If sea level rise were anticipated, however, such areas might be developed differently or not at all, reducing adverse impacts. Three types of community response action are used in the analysis: stop or reduce the rate of shoreline movement through the use of revetments, levees, or other means; eliminate the threat of storm surge (up to a given elevation) through the use of seawalls and levees; and reduce or prohibit investment in given areas by promulgating land use regulations.

In computing net economic services, the lost opportunities associated with less development and the cost of building protective structures were subtracted.

The Value of Anticipating Sea Level Rise

The value of anticipating sea level rise and its consequence depends on how much people change their behavior to avoid the resulting economic losses. Gibbs estimated this value using a variety of assumptions about how people would change their behavior. Changes in both private investment and community planning were considered. Private investment was simulated to be reduced in areas of increasing hazard due to sea level rise. Changes considered in community actions include forgoing development of areas that would be lost because of sea level rise and taking more timely and effective protective measures.

Gibbs did not examine impacts on environmental amenities. Later analyses will need to consider these impacts. For example, sea level rise could destroy the marsh habitat of an endangered species, and advanced planning could save the marsh. The value of saving the marsh would include such disparate consequences as savings to the fishing industry and preventing a species from becoming extinct.

CASE STUDY RESULTS

This section summarizes the impacts of sea level rise on the Charleston and Galveston areas. The physical impacts of sea level rise are summarized in terms of the area of land lost and changes in the areas subject to flooding. (Chapters 4 and 5 present detailed maps showing these effects.) Because salt intrusion into groundwater from sea level rise was not projected to be significant, this impact is discussed only briefly. Finally, we summarize Gibbs's estimates of the economic impacts of sea level rise and the extent to which these impacts could be reduced by policies that anticipate this rise.

Before discussing the results of the case studies, we strongly emphasize that these results should be viewed with extreme caution, particularly the projections for specific neighborhoods. The case study Chapters 4, 5, 7, and 8 are initial applications of methods developed for this book. Although the methods use realistic assumptions and rely as much as possible on empirical evidence, none of the authors can be certain that all major factors were adequately considered. Therefore, the results should be viewed as approximations to illuminate our understanding of sea level rise, not as precise forecasts of the fates of particular city blocks. This caution applies most of all to the Chapter 8 analysis of Sullivans Island. We also remind the reader that we expect the actual rise in sea level to be between the low and medium scenarios. Although we investigated the high scenario, we believe it to be very unlikely.

Charleston Study Area

Description. The Charleston study area consists of the land around Charleston Harbor, which is formed by the confluence of the Cooper, Ashley, and Wando Rivers (see Figure 1-4). The study area includes all of Charleston and parts of North Charleston, Mount Pleasant, Sullivans Island, and James Island. The shores of the harbor are dominated by fringing salt marshes and tidal creeks. Lower Charleston peninsula, in the center of the study area, has a maximum elevation of only six meters (eighteen feet) and includes several low-lying areas that have been reclaimed from the harbor. North Charleston, on the upper part of the peninsula, has elevations up to ten meters (thirty feet). West Ashley, to the west of the peninsula, is a relatively flat area fronted by extensive marshes along the shores of the harbor and the tidal creeks, with elevations of three meters or less. Mount Pleasant, while also flat, is generally higher, with elevations between three and ten meters. Sullivans Island, in the northeast portion of the study area, is a narrow barrier island whose average elevation is less than three meters above sea level.

Because of the harbor's funnel shape, tides range up to two meters (about six feet). Although the Charleston area does not have a history of extensive hurricane damage, the tides and the extensive network of tidal creeks expose parts of the peninsula, West Ashley, and Sullivans Island to periodic flooding. The Cooper River has recently been responsible for a large amount of sedimentation, which has led to the accretion of shorelines in the marshy areas within the harbor.

The only major protective structure in Charleston is the Battery, a six foot seawall located at the tip of Charleston Peninsula. Even today, 100-year storm would overtop the Battery.

The Charleston study area had a population of approximately 120,000 in 1980. Charleston Peninsula, with over 70,000 people, is the economic and population center for the study area. The southern end of the peninsula has a densely populated historic district and other residential, commercial, and port areas; the central peninsula consists of industrial parks and marshland; and the upper peninsula (North Charleston) has a combination of residential areas and heavy industry, including a very large naval reservation.

Because most of the peninsula is already highly developed, the potential for the Charleston area to grow is limited. Undeveloped land is scarce, and although some growth may take place in the northern portion or elsewhere through shifts to more high-density land uses, the long-term growth rate for population and employment has been estimated at 0.8 percent per year for the next fifty years.

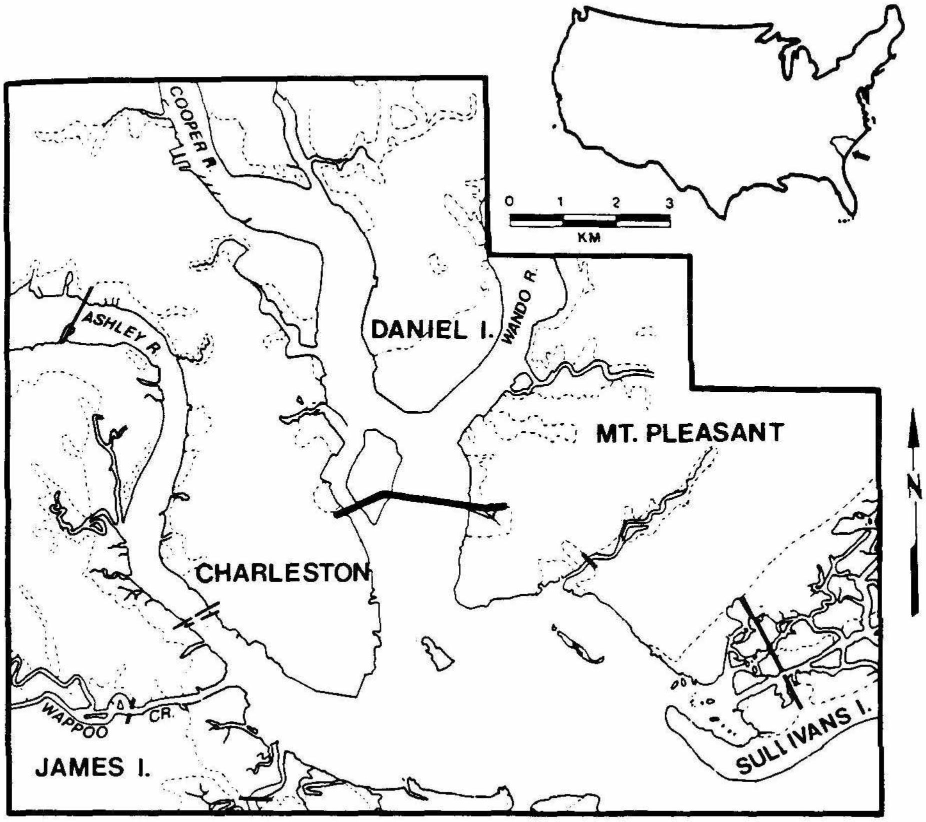

Figure 1-4. Charleston study area.

West Ashley and James Island (population 8,500 within the study area), on the mainland to the west of the peninsula, consist mostly of low-density single-family housing. Portions of these communities lie within the city limits of Charleston. Future development will be mostly single-family housing on currently vacant land.

Mount Pleasant (population 21,800) is a residential commuter town with attendant commercial development. It has the greatest potential for growth of any community in the study area. Most of this growth will be in the form of additional housing, but extensive industrial development will probably take place to the north, near the new South Carolina Port Authority terminal and the planned expressway.

Sullivans Island (population 10,000) is a residential and resort community located to the east of Mount Pleasant along the coast. The island itself has been extensively developed with single-family homes, with high-rise and condominium construction currently prohibited by zoning regulations. Changes in those regulations would be a prerequisite to any substantial growth on Sullivans Island. Because of sediment supply and a jetty that protects Charleston Harbor, much of the island is currently accreting.

The Charleston study area has five hazardous waste facilities in the current 100-year floodplain, and six outside the floodplain. Of the hazardous wastes stored, treated, or disposed of at these sites, carcinogens and ecotoxins probably present the greatest risks to human health and the environment in the event of a release. The types of hazardous wastes at these facilities include cadmium, arsenic, benzene, beryllium, chromium VI, nickel, and vinyl chloride.

Impacts of Sea Level Rise. The analysis by Kana et al. concludes that up to one-half of the Charleston area could be permanently flooded if no response actions were taken. Gibbs concluded that taking anticipatory actions could save the area as much as $1.5 billion.

Table 1-4 summarizes the impacts of sea level rise on shoreline retreat and on the 10- and 100-year floodplains for the years 2025 and 2075 under the low, medium, and high scenarios, as well as an extrapolation of current trends. In general, the impacts of the high scenario in 2025 are slightly less than the impacts of the low scenario in 2075. Even if only current trends continued, the study area would lose 4 percent of its land by 2075, mostly on Sullivans Island and in the marshes along Charleston Harbor. Under the low scenario, 5.2 percent of the land would be lost by 2025 and 15 percent by 2075. Under the high scenario, 14 percent of the area would be lost by 2025 and 45 percent by 2075.

Tables 1-A through 1-C in the appendix provide similar estimates of the impacts on specific communities. In the medium scenario, Sullivans Island could lose the first one or two rows of houses along the ocean by 2025 and would migrate landward by its own width by 2075, destroying virtually all existing development. Developed portions of Charleston Peninsula would not be threatened under the low scenario, partly because of existing seawalls and bulkheads. However, these protective structures would not prevent inundation of one-quarter and one-half of the peninsula by 2075 for the medium and high scenarios, respectively. The West Ashley/James Island area would be even more vulnerable, and Mount Pleasant would be the least affected.

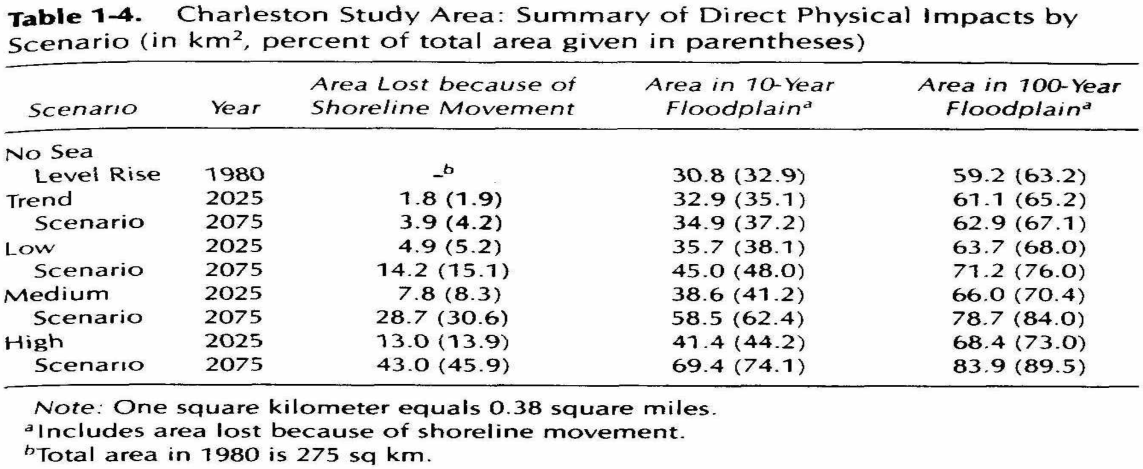

Table 1-4. Charleston Study Area: Summary of Direct Physical Impacts by Scenario (in km^2, percent of total area given in parentheses)

Scenario	*Year*	*Area Lost because of Shoreline Movement*	*Area in 10-Year Floodplain*[a]	*Area in 100-Year Floodplain*[a]
No Sea Level Rise	1980	–[b]	30.8 (32.9)	59.2 (63.2)
Trend	2025	1.8 (1.9)	32.9 (35.1)	61.1 (65.2)
Scenario	2075	3.9 (4.2)	34.9 (37.2)	62.9 (67.1)
Low	2025	4.9 (5.2)	35.7 (38.1)	63.7 (68.0)
Scenario	2075	14.2 (15.1)	45.0 (48.0)	71.2 (76.0)
Medium	2025	7.8 (8.3)	38.6 (41.2)	66.0 (70.4)
Scenario	2075	28.7 (30.6)	58.5 (62.4)	78.7 (84.0)
High	2025	13.0 (13.9)	41.4 (44.2)	68.4 (73.0)
Scenario	2075	43.0 (45.9)	69.4 (74.1)	83.9 (89.5)

Note: One square kilometer equals 0.38 square miles.
[a] Includes area lost because of shoreline movement.
[b] Total area in 1980 is 275 sq km.

Table 1-4 also shows that by 2075 in the medium scenario, a 10-year storm would cause as much flooding as a 100-year storm would inflict today. About one-third of the study area is currently in the 10-year floodplain, and about two-thirds is within the 100-year floodplain. By 2075 under the low scenario, almost one-half the study area would be in the 10-year floodplain, and three-quarters within the 100-year floodplain. Under the high scenario, 75 percent of the study area would be within the 10-year floodplain by 2075, and almost 90 percent of the study area, including five additional hazardous waste sites, would be in the 100-year floodplain.

Kana et al. found that the freshwater/saltwater interface could shift up to sixty meters (two hundred feet). They concluded that this impact would be negligible, compared with the impact of overpumping on salt intrusion.

Shoreline retreat and additional storm flooding could inflict heavy economic losses. Gibbs estimated the economic impacts of sea level rise for two assumptions about how individuals and communities would address sea level rise: (1) people would have no foresight and would adapt only in response to the observed effects of sea level rise; and (2) people would use foresight to adapt in anticipation of these impacts. The value of anticipating sea level rise would be the difference between these two impacts. Table 1-5 displays Gibbs's estimates of economic impact for each of the sea level rise scenarios. This table combines results shown for storm surge and erosion damages in table 1-C in the appendix. The assumptions used to calculate these results are presented in detail in Chapter 7.

The cumulative economic impact in the Charleston study area would range from $280 million in the low scenario through 2025 to $2.5 billion in the high scenario through 2075, if sea level rise were not anticipated.[12] These impacts range from 5 percent to 35 percent of the total economic activity that would take place in the study area in the absence of sea level rise.

Gibbs concluded that the impacts could be reduced by 43-65 percent by anticipating sea level rise. Anticipation of sea level rise was represented by reducing private investment in areas of increasing hazard and more timely implementation of community responses, such as the construction of seawalls and levees.

Although Gibbs assumes that most options would be implemented after 2000, Titus concludes in Chapter 8 that by 1990 sea level rise may be a critical issue to Sullivans Island, a barrier resort. His conclusion was based on the data underlying Kana's projection that the first or second row of houses could be eroded by 2025 under the high scenario and on Gibbs's unreported result that a 100-year storm would devastate much of the island. Titus concludes that unless the community plans to pump increasing amounts of sand onto the beach for the foreseeable future, perhaps 20 percent of the houses should not be rebuilt in their original locations after a storm in 1990 if the high scenario is expected.

Galveston Study Area

Description. The Galveston study area includes the northern third of Galveston Island, the top of Bolivar Peninsula, and the nearby mainland areas of Texas City, La Marque, and San Leon (see Figure 1-5). The land throughout the study area is primarily a gently sloping coastal plain broken by estuaries and lagoons along the shores of Galveston Bay. Most of the study area is less than five meters above sea level. Tides in the area range from fifteen centimeters in Galveston Bay to sixty centimeters in the Bolivar Road inlet.

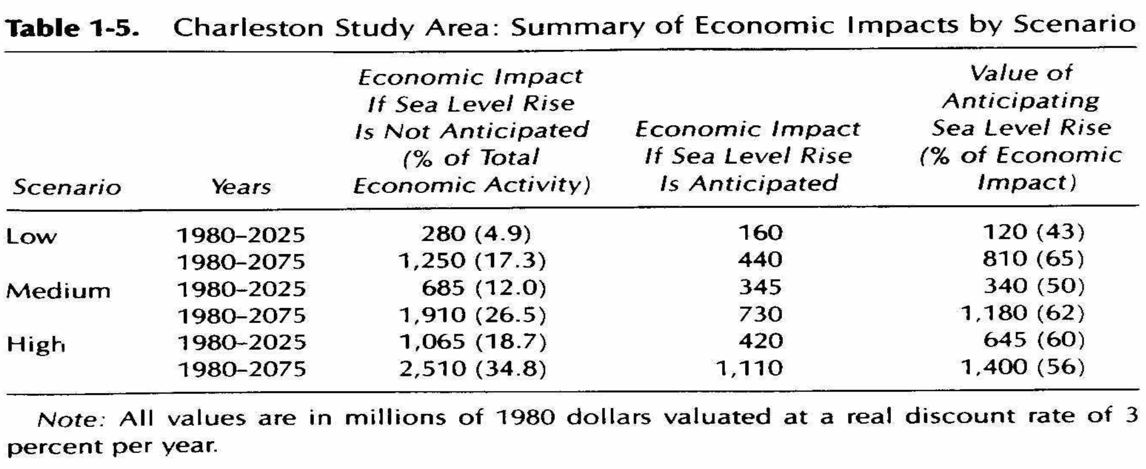

Table 1-5. Charleston Study Area: Summary of Economic Impacts by Scenario

Scenario	*Years*	*Economic Impact If Sea Level Rise Is Not Anticipated (% of Total Economic Activity)*	*Economic Impact If Sea Level Rise Is Anticipated*	*Value of Anticipating Sea Level Rise (% of Economic Impact)*
Low	1980–2025	280 (4.9)	160	120 (43)
	1980–2075	1,250 (17.3)	440	810 (65)
Medium	1980–2025	685 (12.0)	345	340 (50)
	1980–2075	1,910 (26.5)	730	1,180 (62)
High	1980–2025	1,065 (18.7)	420	645 (60)
	1980–2075	2,510 (34.8)	1,110	1,400 (56)

Note: All values are in millions of 1980 dollars valuated at a real discount rate of 3 percent per year.

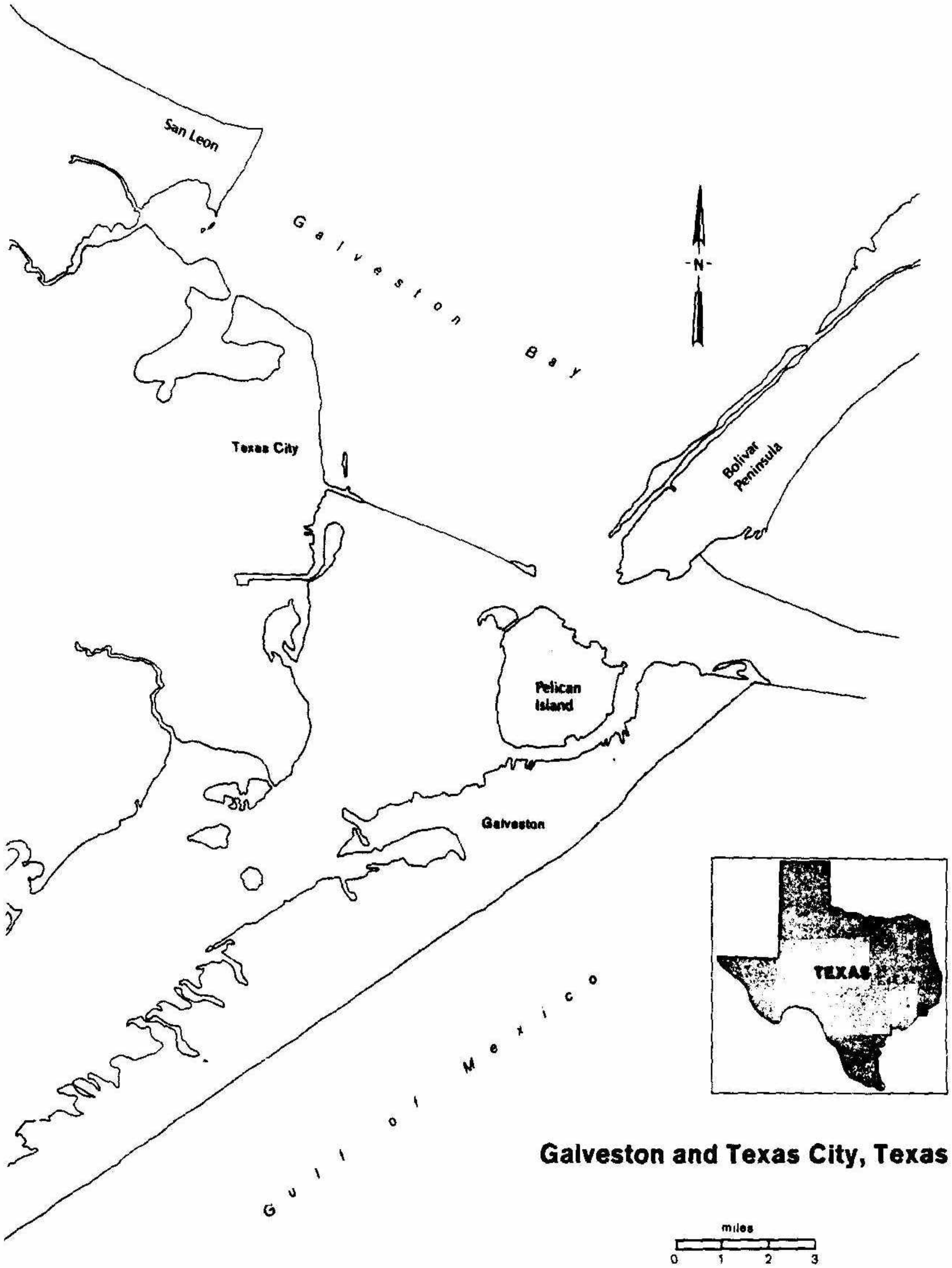

Figure 1-5. Galveston study area.

The Galveston study area has a history of shoreline retreat and storm damage. Six thousand people died in the 1900 hurricane, the worst natural disaster in U.S. history. There has been a considerable amount of land subsidence within the study area over the past century, causing a relative sea level rise of more than thirty centimeters (one foot) along the coast. Historical records show that this sea level rise has been accompanied by shoreline retreat throughout the study area. Consequently, communities in the area have built a variety of structures to reduce erosion and flooding of developed areas, including seawalls, levees, and pumping facilities.

The Galveston study area had a population of approximately 122,000 in 1980. The area is expected to grow moderately in the future with La Marque, Texas City, and San Leon growing much faster than Galveston. Major commercial development should occur in Texas City, just to the west of the study area. A lack of water supplies may, however, impede both industrial and residential development in parts of the mainland.

The city of Galveston (population 65,000) is located on the northern third of Galveston Island. This portion of the study area is mostly developed and includes residential housing, commercial districts, light industrial and port facilities, and the University of Texas medical center. A five meter seawall runs along the south side of Galveston, protecting it from storm waves and gulfside flooding. The downtown section of Galveston has sufficient elevation to avoid flooding from the bayside. However, other developed parts of the city experience flooding even during a 15-year storm.

There is little room for further development on that part of the island within the study area. Galveston's economy, based on shipping, transportation, medicine, tourism, and recreation, has limited long-term development potential, and the population of this part of the study area is likely to remain stable or increase slightly over the next fifty years. Pelican Island consists of marsh and dredge spoils, with some university and shipping facilities. The part of Bolivar Peninsula in the study area includes only a few hundred houses.

Texas City and La Marque constitute the geographic and economic center of the study area, with a population of 57,000 and taxable property valued at over two billion dollars. Three-quarters of Texas City consists of undeveloped, low-lying floodplain, some of which has been further affected by land subsidence. That portion of La Marque within the study area has undeveloped marshes to the south and southeast, and low-density residential areas and attendant commercial development in the center of the city. The densely developed portions of Texas City and La Marque are protected from storm surge by an extensive network of structures, including the Texas City Levee System. However, a 100-year storm would currently cause over $130 million in damage to the unprotected, moderately developed areas.

Texas City and La Marque's economy is based on petrochemicals, petroleum refining, shipping, and land transport. One-half of the developed land is occupied by a one billion dollar petrochemical complex, which provides the major employment and tax base for the region. The continued strength of the energy and energy-related sectors should cause these communities to grow more rapidly than Galveston and increase their population by one-third by the end of this century.

San Leon is a residential area for commuters who work in Houston, Galveston, and Texas City. There is little commercial development in this area. Its population of 2,000 is expected to double over the next twenty years. In spite of a history of shoreline retreat, San Leon has little protection against erosion or storm surge.

In the Galveston study area, the 100-year floodplain contains ten hazardous waste facilities. The carcinogens identified to be located at these sites include benzene, carbon tetrachloride, chromium VI, poly-nuclear aromatic hydrocarbons, beryllium, nickel, cadmium, and arsenic. The ecotoxins identified include the pesticides methyl parathion and lindane.

Impacts of Sea Level Rise. Because Galveston and Texas City are largely protected by seawalls and levees, the impact of sea level rise would not be as great for this study area as for Charleston. However, by 2075, a 100-year storm would overtop the Galveston seawall in the medium and high scenarios. Damage from such a storm would be approximately two billion dollars -four times greater than if sea level did not rise.

Table 1-6 shows the area lost to sea level rise for the four scenarios. Current sea level trends would erode about 2.5 percent of the study area by 2075. The low scenario would result in a loss of 1.5 and 6 percent of the study area by 2025 and 2075, respectively. Under the high scenario, 3 and 12 percent would be lost by 2025 and 2075, respectively. With the exception of Sea Leon, whose entire peninsula would erode under the high scenario, the erosion would take place in undeveloped areas, the only places not protected by seawalls.

The impact of sea level rise on floodplains would be more significant. As Table 1-6 shows, one-quarter of the study area is now in the 15-year floodplain. By 2075, this proportion would increase to one-third under the low scenario and over one-half in the high scenario.

In particular, up to 80 percent of Galveston would be vulnerable to a 15-year storm. By 2075 under the high scenario, a 15-year storm would inflict the amount of flooding that took place during hurricane Alicia in August 1983. The 10-year floodplain would increase from 60 percent of the study area currently to 95 percent by 2075, even in the low scenario. Under the medium and high scenarios, almost all the study area would be vulnerable, and storm waves would overtop all existing protective structures.

Table 1-6. Galveston Study Area: Summary of Direct Physical Impacts by Scenario (in km^2, percent of total area given in parentheses)

Scenario	*Year*	*Area Lost because of Shoreline Movement*	*Area in 15-Year Floodplain*[a]	*Area in 100-Year Floodplain*[a]
No Sea Level Rise	1980	-[b]	65.3 (23.7)	160.6 (58.4)
Trend	2025	2.6 (0.9)	71.7 (26.1)	163.2 (59.3)
Scenario	2075	6.2 (2.2)	77.4 (28.1)	165.2 (60.1)
Low	2025	4.1 (1.5)	78.2 (28.4)	165.5 (60.2)
Scenario	2075	15.6 (5.7)	91.9 (33.4)	258.7 (94.1)
Medium	2025	6.5 (2.4)	82.9 (30.1)	167.0 (60.7)
Scenario	2075	24.4 (8.9)	119.7 (43.5)	267.3 (97.2)
High	2025	8.3 (3.0)	86.5 (31.4)	206.9 (75.2)
Scenario	2075	32.4 (11.8)	142.7 (51.9)	269.1 (97.8)

Note: One square kilometer equals 0.38 square miles.

[a] Includes area lost by shoreline movement.

[b] Total area in 1980 is 275 sq km.

Twenty-two additional hazardous waste sites would be within the 100-year floodplain, for a total of thirty two under the high scenario for 2075. However, if the existing levees and seawalls were raised, these sites might not have to undertake any additional flood mitigation measures.

In their examination of the potential effects of sea level rise upon rates of salt intrusion into groundwater in the Galveston area, Leatherman et al. (1983) concluded that unconfined groundwater aquifers in the Galveston Bay area are generally polluted or salt-contaminated and that any incremental rise in sea level probably will have little effect on the two principal confined aquifers in the region.

Table 1-7 displays Gibbs's estimates of the economic impacts of sea level rise for two cases of adaptive behavior for Galveston. The actions he assumed would be taken in response to sea level rise are presented in detail in Chapter 7.

The cumulative economic impact in the Galveston study area ranges from $115 million in the low scenario through 2025 to $1.8 billion in the high scenario through 2075. These impacts range from 1.1 percent to 16 percent of the estimated total value of the economic activity that would take place in the study area over the same time periods in the absence of sea level rise. The economic value of damages would be less significant than in the Charleston area, given the smaller amounts of shoreline retreat and changes in floodplains.

Table 1-7. Galveston Study Area: Summary of Economic Impacts by Scenario

Scenario	*Years*	*Economic Impact If Sea Level Rise Is Not Anticipated (% of Total Economic Activity)*	*Economic Impact If Sea Level Rise Is Anticipated*	*Value of Anticipating Sea Level Rise (% of Economic Impact)*
Low	1980-2025	115 (1.1)	80	25 (22)
	1980-2075	555 (4.9)	310	245 (44)
Medium	1980-2025	260 (2.6)	90	150 (58)
	1980-2075	965 (8.4)	415	550 (57)
High	1980-2025	360 (3.6)	140	220 (61)
	1980-2075	1,840 (16.0)	730	1,110 (60)

Note: All values are in millions of 1980 dollars valuated at a real discount rate of 3 percent per year.

The third column of table 1-7 presents the savings from policies that anticipate sea level rise. Even in the low scenario, economic impacts can be reduced by over $245 million through 2075. Under the high scenario, impacts could be reduced by $220 million through 2025 and $1.1 billion through 2075.

Gibbs emphasizes that his methods are conservative and that the potential savings could be even greater. Chapter 7 presents estimates for both case study sites using alternate discount rates and discusses the sensitivity of the results to various assumptions about investment behavior and community responses to sea level rise.

REACTIONS AND RECOMMENDATIONS

The impacts of sea level rise on the Galveston and Charleston areas suggest that in the coming decades, sea level rise may become one of the most important issues facing coastal communities. Even today, erosion attributable to current trends is a major concern to Louisiana and many resorts. As Chapter 7 shows, many of the adverse consequencescould be avoided if timely actions are taken in anticipation of sea level rise. Although some of these actions may not be necessary until 2000 and thereafter, others may only be timely if the planning process starts soon.

In March 1983, many of this book's findings were presented to a conference of over 150 scientists, engineers, and federal, state, and local policy makers. Although those attending agreed that sea level rise, if substantiated, would justify the attention of policy makers at all levels, some doubted whether anything less than a catastrophe could motivate people to undertake the necessary actions. Chapter 10 presents the reactions of six well-known representatives of the public and private sectors to our research and its implications.

Edward Schmeltz, an assistant vice president and department manager for coastal engineering at

PRC-Harris, agrees with the conclusion of Chapter 6 that adequate technology is available to respond to sea level rise. He argues, however, that much greater confidence must be developed in the sea level rise projections before the engineering profession could convince clients to spend large sums of money to protect projects from sea level rise. Schmeltz argues that many people would view sea level rise projections as "hypothesis and conjecture." He further points out that many existing projects could withstand a one-half meter (two foot) rise in sea level but not a rise of three meters (ten feet).

Jeffrey Benoit, coastal geologist for the State of Massachusetts Coastal Zone Management Program, states that planning for sea level rise should start immediately if the projection of a four meter rise is correct. Like Schmeltz, however, he emphasizes that state agencies need a narrower range of uncertainty to address the rise properly. He also recommends that more attention be given to altered development patterns and regulation, in contrast to the "hard" coastal engineering responses described by Sorensen et al.

Sherwood Gagliano, who first popularized the relationship between relative sea level rise (subsidence) and coastal erosion in Louisiana, provides extensive comments on Chapters 4, 5, and 6. He concludes that the methods employed were very satisfactory for the sandy beaches of Galveston and Charleston but that future research should also consider the impacts on muddy beaches and changing tidal regimes.

Charles Fraser, chairman emeritus of Sea Pines Corporation (which developed Hilton Head Island, South Carolina) notes that institutions do not always respond to scientifically documented problems, even when the experts agree on the proper response. Furthermore, he questions whether coastal governments and property owners would be willing to consider the problems of the next century. He argues, however, that it could take several decades to develop societal responses and therefore that planning for sea level rise should continue.

Colonel Thomas Magness III (formerly assistant director for civil works, U.S. Army Corps of Engineers) notes that the Army Corps of Engineers has a planning horizon sufficiently long to prepare for sea level rise, and that the Corps is already starting to do so. Lee Koppleman, executive director for the Long Island Regional planning Board, indicates that on first reading, he thought that the prospect of sea level rise appeared to be sufficiently in the future that we might leave this issue for the next generation. He states, however, that as he thought about it, he decided that there is, in fact, a problem. Koppleman argues that planners can and will consider sea level rise if scientific research continues to be presented in a form they can understand. Gagliano also emphasizes the importance of presenting research in a useful form: “It was only after disclosure that a given coastal parish would last only 50 years before it eroded into the sea that the state legislature and the governor enacted a program for coastal erosion protection and shoreline restoration” (Chapter 10, page 300).

The reactions of the independent reviewers had two major messages in common: first, estimates of sea level rise must be improved; and second, even then, it will be difficult to induce an adequate response. The fact that many of the adverse consequences can be avoided does not guarantee that the necessary action will take place.

At this time, we can only speculate about the best way to overcome these difficulties. Because nothing will be done in the absence of information, increasing public awareness must be a top priority. Although this process will take time, researchers and professionals should not automatically assume that people will not plan for the future. At best, such an assumption ignores the substantial efforts that have been undertaken to respond to long-term problems such as population growth; at worst, the assumption could be self-fulfilling.

Nevertheless, it would be a mistake for research to focus only on the physical effects of sea level rise. We must also determine how to motivate society to act in a way that will lead it to be satisfied with the results of its actions, rather than regret its lack of foresight.

Based on the analysis presented in this book, the following recommendations are appropriate.

1. Federal research on the physical, environmental, and economic impacts of sea level rise should be substantially expanded. The pilot studies reported in this book provide rough estimates of some of the physical and economic impacts of sea level rise and of the value of preparing for these impacts. However, deciding which anticipatory measures should be implemented will require a better understanding of the impacts of sea level rise and possible responses.

The Army Corps of Engineers has already undertaken considerable research into the impacts of current sea level trends on beach erosion. That research should be expanded into a general model capable of predicting erosion from both storms and an accelerated rise in sea level. However, the importance of such a model requires that experts in the private sector, academia, and other government agencies also participate in its development.

Government agencies charged with protecting the environment also must assess the vulnerability of their programs to sea level rise. For example, a one meter rise could devastate much of the existing wetlands in Louisiana and perhaps elsewhere. By undertaking the necessary research now, it may be possible to identify inexpensive ways to ensure that ecosystems and economic activities adapt to sea level rise without unnecessary conflicts.

2. Federal support for scientific research on the rate of future global warming and sea level rise should be greatly expanded. The benefits of this research would clearly justify the costs. Coastal communities could save billions of dollars by implementing timely actions in anticipation of sea level rise. But better forecasts of sea level rise will be necessary for these communities to take the right actions at the right time.

The highest priority should be research into the impact of a global warming on glaciers. Experts in glaciology could substantially improve upon the estimates of ice discharges used in this book, but have not been given the support necessary to adequately collect and analyze measurements and data produced by climate models. Other areas in need of research include the sources and sinks of the minor greenhouse gases, models of ocean currents, and the impact of a global warming on the frequencies, tracks, and severities of tropical storms and northeasters.

3. State coastal programs should be strengthened. Because of federal and state budget problems, many state coastal programs are being curtailed or eliminated. These programs are absolutely necessary to ensure that communities are provided with the required technical expertise and that adjacent jurisdictions adopt compatible response strategies.

4. Federal, state, and local coastal programs should consider the impacts of accelerated sea level rise in their planning. At the state and local levels, shore protection projects and post-disaster plans have a particular need to consider sea level rise. Communities should explicitly decide the amount of resources they are willing to invest to resist erosion. State and local governments that intend to maintain current shorelines should make the public aware of the ultimate cost of doing so.

Many federal agencies should also consider these impacts. The Federal Emergency Management Agency should consider the impact of sea level rise on its programs to prevent coastal flood disasters. The National Park Service and the fish and Wildlife Service should consider whether their objective of maintaining marine ecosystems will require coastal uplands to be preserved so that future marshes can migrate landward. Finally, the Corps of Engineers should consider the impact of sea level rise on its coastal engineering programs.

5. Coastal engineers should revise standard engineering practices to consider accelerated sea level rise. Coastal structures designed today will last well into the next century and perhaps longer, while soft engineering projects such as beach nourishment are very sensitive to even slight rises in sea level. Therefore, future sea level rise is likely to have an important impact on the outcome of coastal engineering decisions made today.

6. Research into the most effective means of communicating risks and motivating effective responses should be undertaken. Such efforts could draw on the Federal Emergency Management Agency's experience with individual and community responses to flood risks.

7. A *well-respected group of coastal engineers, planners, and other decision makers should* conduct an *independent review of the necessity of planning for sea level rise.* Practitioners cannot rely solely on the conclusions of researchers, whose incentives may differ from their own. Yet the individual engineer or planner will not have the time to review completely all of the evidence. A review panel could bridge the gap between researchers and practitioners.

This book discusses only the potential physical and economic impacts of sea level rise in the United States. However, the impacts could be much more serious in other parts of the world. In 1971, the storm surge from a tropical cyclone killed three hundred thousand people in Bangladesh. Countries in the Indian subcontinent, the eastern Mediterranean and other low-lying coastal areas could be devastated by even a moderate rise in sea level. These nations are densely populated, poor, and often cannot evacuate people in the event of a storm. Planning for sea level rise would not only save economic resources but human lives as well.

NOTES

1. All measurements in this chapter are presented in the metric system. Where doing so is not redundant, English equivalents are provided in parentheses. To avoid presenting a false sense of precision, this chapter translates entire idioms in several instances. Therefore, we translate "about a meter" into "a few feet" rather than into "about 3.3 feet."
2. Prehistoric shorelines have been found in the Mesabi Range in Minnesota (Sleep, 1976).
3. This term is technically a misnomer because a greenhouse prevents convectional, rather than radiational, cooling.
4. In a related effort, EPA held a symposium on the possible relationship between increased atmospheric levels of $C0_2$ and the frequency, severity, and track of hurricanes.
5. This calculation considered the lag between global temperature and thermal expansion of the ocean, but not the lag between temperature and ice melting (from computer printouts underlying Seidel and Keyes, 1983).
6. For example, the United States is expected to be responsible for only 14 percent of all $C0_2$ emissions by 2025, less than one decade's growth in emissions.
7. The model of the National Center for Atmospheric Research has recently estimated the warming to be nearly 4EC. See Warren M. Washington and Gerald A. Meehl, "Seasonal Cycle Experiments on the Climate Sensitivity Due to a Doubling of $C0_2$ with an Atmospheric General Circulation Model Coupled to a Simple Mixed Layer Ocean Model, " NCAR/8041/82-1 [E 1, Boulder: National Center for Atmospheric Research, August 1983, paper submitted to Journal *of Geophysical Research.*
8. This equation uses specified thermal sensitivity (the NAS estimates), greenhouse gas increases generated, and surface temperatures of the ocean and was developed by the Goddard Institute for Space Studies.
9. The conservative scenario assumed a diffusion coefficient of 1.18 cm?/sec; the mid-range scenario, 1.54 cm?/sec; and the high scenario, 1.9 cm?/sec.
10. These special cases were run with coefficients of 0.2 cm?/sec and 4.0 cm?/sec.
11. The old assumptions that the case studies are based on, subsequently changed by Hoffman, are as follows: *Low:* Emissions of chlorofluorocarbons remain constant at the mid-1970s level; methane concentrations increase linearly by 2.0 percent of the 1980 level each year; and nitrous oxide concentrations increase linearly by 0.2 percent of the 1980 level each year. *High:* Concentrations of the trace gases all grow geometrically by 1.674 percent each year. These scenarios produced estimates of global sea level as follows: low- 22.4 cm in 2025 and 74.6 cm in 2075; high-57.9 cm in 2025 and 219.3 cm in 2075.
12. As is generally the case with economic analyses conducted over a long period of time, the results are sensitive to the discount rate used to compute present values. If discount rates larger than the 3 percent assumed here are used, the economic impacts and value of anticipating sea level rise would be much smaller. Chapter 7 presents estimates using alternate discount rates and discusses the sensitivity of the results to various assumptions about investment behavior and community responses to sea level rise.

REFERENCES

Albanese, A., and M. Steinburg. 1980. *Environmental Control Technology for Atmospheric Carbon Dioxide.* Islip, N.Y: Brookhaven National Laboratories.

Arrhenius, S. 1896. "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground." *Philus* 41:237.

Barnett, T. P. 1983. "Global Sea Level: Estimating and Explaining Apparent Changes." In Orville T. Magoon, ed., *Coastal Zone '83.* New York: American Society of Civil Engineers, pp. 2777-2795.

Barnett, T. P (forthcoming). *Recent Changes in Sea Level and Their Possible Causes.* La Jolla, Calif.: Climate Research Group, Scripps Institution of Oceanography

Begley, Sharon et al., 1981. "Is Antarctica Shrinking?" *Newsweek.* October 5.

Bentley, Charles. 1980. "Response of the West Antarctic Ice Sheet to $C0_2$ Induced Climatic Warming." In Environmental *and Societal Consequences of a Possible* $C0_2$*-Induced Climate Change (2)* 1. Washington, D.C: Department of *Energy.*

Bentley, C. R. 1983. "West Antarctic Ice Sheet: Diagnosis and Prognosis. " In P*roceedings: Carbon Dioxide Research Conference: Carbon Dioxide, Science and Consensus.* Conference 820970. Washington, D.C.: Department of Energy, p.p. IV.3-IV.50.

Bloom, Arthur L. 1967. "Pleistocene Shorelines: A New Test of Isostasy." *Geological Society of America Bulletin* 78:1477-1494.

Boesch, D. F., ed. 1982. *Proceedings of the Conference on Coastal Erosion and Wetland Modification in Louisiana: Causes, Consequences and Options.* FWS-OBS-82/59. Washington, D.C.: Fish and Wildlife Service, Biological Services Program.

Broecker, W. S., Tsung-Hung Peng, and R. Engh. 1980. "Modeling the Carbon System." *Radiocarbon* 22:565-598.

Bruun, P. 1962. "Sea Level Rise as a Cause of Shore Erosion." ***Journal of the*** *Waterways and Harbors Division* 88(WW1):117-130.

Bruun, R 1979. "The 'Bruun Rule,' Discussion on Boundary Conditions." In M.L. Schwartz and J. J. Msher, eds., *Proceedings of the Per Bruun* Symposium. Newport, R.I.: IGU Commission on the Coastal Environment, pp.79-83.

Chamey, J., chairman, Climate Research Board. 1979. *Carbon Dioxide and* Cl*imate: A Scientific Assessment.* Washington, D.C.: NAS Press.

Chylek, Peter, and William Kellogg. "The Sea Level Climate Connection." Unpublished paper. National Center for Atmospheric Research. Boulder, Co.

Clark, J. A., W. E. Farrell, and W. R. Peltier. 1978. "Global Changes in Post-glacial Sea Level: A Numerical Calculation." Quaternary *Research* 9(3):265-287.

Colquhoun, D. J., M. J. Brooks, J. Michie, W. B. Abbott, F. W Stapor, W H. Newman, and R. R. Pardi. 1981. "Location of Archaeological Sites with Respect to Sea Level in the Southeastern United States." *Striae* 14:144-150. Coolfont Conference. 1982. *1982 Department of Energy Research Conference.* Washington, D.C.: Department of Energy, Office of Carbon Dioxide Research. Council on Environmental Quality. 1981. *Global Energy Futures and the Carbon Dioxide Problem.* Washington, D.C.: Government Printing Office.

Development Planning and Research Associates. 1982. Report to EPA/OSW. Donn, W. L., W R. Farrand, and M. Ewing. 1962. "Pleistocene Ice Volumes and Sea-Level Lowering." *Journal of Geology* 70:206-214.

Dubois, R. N. 1979. "Hypothetical Shore Profiles in Response to Rising Water Level." In M. L. Schwartz and J. J. Msher, eds., *Proceedings of the Per Bruun* Symposium. Newport, R.I.:, IGU Commission on the Coastal Environment, pp. 13-31.

Dyson, F., 1976. *Can We Control the Amount of Carbon Dioxide in the Atmosphere?* Oak Ridge, Tenn.: Oak Ridge Associated Universities, Institute for Energy Analysis.

Edmonds,J., and J. Reilly. 1982. *Global Energy* and C02 *to the Year 2050.* Oak Ridge, Tenn.: Oak Ridge Associated Universities, Institute for Energy Analysis.

Emery, K. 0. 1980. "Relative Sea Levels fromnde-Gage Records." *Proceedings, National Academy of Sciences, USA* 12:6968-6972.

Emery, K. O., and Robert H. Mead. 197 1. "Sea Level as Affected by River Runoff, Eastern United States." *Science* 173:425-428.

Engineering-Science. 1979. *Evaluation of the Impacts of the Proposed Regulations to* Implement *the RCRA on Coal-*

Fired Electric Generating Facilities. Prepared for the Department of Energy, contract number DE-AC 01-79ET135437, pp. XV and II-2.

Etkins, R., and E. Epstein. 1982. "The Rise of Global Mean Sea Level as an Indication of Climate Changes." *Science* 215:287-298.

Fairbanks, Richard G., and R. K. Matthews. 1978. "The Marine Oxygen Isotope Record in Pleistocene Coral, Barbados, West Indies." *Quaternary Research* 10(2):181-196.

Fairbridge, R. W., and W. S. Krebs, Jr. 1962. "Sea Level and the Southern Oscillation." *Geophysical Journal* 6:532-545.

Flohn, H. 1982. "Climate Change and an Ice-Free Arctic Ocean." In W. Clark, ed., *Carbon Dioxide Review: 1982.* New York: Oxford University Press, pp. 145- 179.

Gornitz, V., S. Lebedeff, and J. Hansen. 1982. "Global Sea Level Trend in the Past Century." *Science* 215:1611-1614.

Greenberg, Don. 1982. "Sequestering," Unpublished memorandum prepared for Office of Policy Analysis, Environmental Protection Agency, Washington, D.C. Gutenberg, Beno. 1941. "Changes in Sea Level, Postglacial Uplift, and Mobility of the Earth's Interior." *Bulletin of the Geological Society of America* 52:721-772.

Hands, E. B. 1979. "Bruun's Concept Applied to the Great Lakes." In M. L. Schwartz and J. J. Asher, eds., *Proceedings of the Per Bruun Symposium.* Newport, R.I.: IGU Commission on the Coastal Environment, pp.63-66.

Hands, E. B. *1981.Predicting Adjustments in Shore and Offshore Sand Profiles on the Great Lakes,* CERC technical aid 81-4, Fort Beivoir, Va.: Coastal Engineering Research Center.

Hansen, J. 1982. *Global Climate Change Due to Increasing* $C0_2$ and *Trace Gases.* Washington, D.C.: Statement to the U.S. House of Representatives Subcommittee on Natural Resources, Agriculture Research and Environment, and the Subcommittee on Investigations and Oversight of the Science and Technology Committee.

Hansen, J., D. Johnson, A. Lacis, S. Lebedeff, D. Rind, and G. Russell. 1981. "Climate Impact of Increasing Atmospheric Carbon Dioxide." *Science* 213:957-966.

Harmon, Russel S., Lynton S. Land, Richard M. Mitterer, Peter Garrett, Henry P. Schwarcz, and Grahame J. Larson. 1981. "Bermuda Sea Level during the Last Interglacial." Nature 289:481-483.

Harmon, Russel S., Henry R Schwarcz, and Derek C. Ford. 1978. "Late Pleistocene Sea Level History of Bermuda." *Quaternary Research* 9 (2):205-218.

Haskin, H. H., and S. M. Weed. 1976. *Oyster Setting and Early Spat Survival at Critical Salinity Levels on Natural Seed Oyster Beds of Delaware Bay.* New Brunswick, N.J. Water Resources Research Institute, Rutgers University.

Hays, J. D., and W C. Pitman III. 1973. "Lithospheric Plate Motion, Sea-Level Changes, and Climatic and Ecological Consequences." Nature 246:18-22.

Hey, R. W. 1978. "Horizontal Quaternary Shorelines of the Mediterranean." *Quaternary Research* 10: 197-203.

Hicks, Steacy D. 1978. "An Average Geopotential Sea Level Series for the United States." *Journal of Geophysical Research* 83(C3):1377-1379.

Hicks, Steacy D. 1981. "Long-Period Sea Level Variations for the United States through 1978." *Shore and Beach* 26:9.

Hoffman, J., 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. 055-000-0236-3. Government Printing Office.

Hollin, John T 1983. "Climate and Sea Level in Isotope Stage 5: An East Antarctic Ice Surge at 95,000 BP?" *Nature* 283:629-633.

Hollin, John T, and R. Barry. 1979. "Empirical and Theoretical Evidence Concerning the Response of the Earth's Ice and Snow Cover to a Global Temperature Increase." *Environmental* International 2:437-444.

Hopkins, David M. 1973. "Sea Level History in Beringia during the Past 250,000 Years." *Quaternary Research* 3:520-540.

Hughes, T. 1983. "The Stability of the West Antarctic Ice Sheet: What Has Happened and What Will Happen." In *Proceedings: Carbon Dioxide Research Conference: Carbon Dioxide, Science and Consensus, 1983.* DOE Conference 820970. Washington, D.C.: Department of Energy, pp.IV.51-IV.73.

Hughes, T., J. L. Fastook, and G. H. Denton. 1979. Climatic Warming and *the Collapse of the West Antarctic Ice Sheet.* Orono, Maine: University of Maine.

Hull, C. H. J., and R. Tortoriello. 1979. "Sea-Level Trend and Salinity in the Delaware Estuary." Staff paper. West Trenton, N.J. : Delaware River Basin Commission.

Institute for Energy Analysis. 1981. *Determinants of Global Energy Supply to the Year 2050.* Oak Ridge, Tenn.: Oak Ridge Associated Universities.

Keeling, C. D., R. B. Bacastow, and T P. Whorf. 1982. "Measurements of the Concentration of Carbon Dioxide at Mauna Loa Observatory, Hawaii." In W. Clark, ed., *Carbon Dioxide Review: 1982.* New York: Oxford University Press, pp.377-384.

Keu, Richard A. 1981. "Whither the Shoreline." Science 214:428.

Keyfitz, N., E. Allen, J. Edmonds, R. Dougher, and B. Widget. 1983. *Global Population, 1975-2075, and Labor Force, 1975-2050.* Oak Ridge, Tenn.: Oak Ridge Associated Universities, Institute for Energy Analysis.

Kopec, Richard J. 1971. "Global Climate Change and the Impact of a Maximum Sea Level on Coastal Settlement." Journal *of Geography* 70:541-550.

Ku, lbh-Lung, Margaret A. Kimmel, William H. Easton, and Thomas J. O'Neil.1974. "Eustatic Sea Level 120,000 Years Ago on Oahu, Hawaii." *Science* 183:959-962.

J. G. Titus et al Kukla, G., and J. Gavin. 1981. "Summer Ice and Carbon Dioxide." *Science* 214:497-503.

LaBrecque, John L., and Peter Barker. 1981. "The Age of the Weddell Basin." *Nature* 290:489-492.

Lacis, A., J. Hanson, P Lee, T. Mitchell, and S. Lebedeff. 1981. "Greenhouse Effect Of Trace Gases, 1970-1980." *Geophysical Research Letters* 8(10):1035-1038. Lamb, H. H. 1970. "Volcanic Dust in the Atmosphere." *Philosophical Transactions of the Royal Society London,* series A, 255:425-533.

Leatherman, Stephen P., Michael S. Kearny, and Beach Clow. 1983. *Assessment of Coastal Responses to Projected Sea Level Rise: Galveston Island and Bay, Texas.* URF report TR-8301; report to ICF under contract to EPA. College Park, Md.: University of Maryland.

Lisitzin, Eugenie. 1974. *Sea-Level Changes,* Elsevier Oceanography Series 8. New York: Elsevier Scientific Publishing Co.

Lugo, Ariel. 1980. "Are Tropical Forest Ecosystems a New Sink?" In *The Role of Tropical Forests in the World Carbon Cycle.* Washington, D.C.: Department of Energy, pp. 1-18.

Manabe, S., and R. J. Stouffer. 1980. "Sensitivity of a Global Climate Model to an Increase Of C02 Concentration in the Atmosphere." *Journal of Geophysical Research* 85:5529-5554.

Marshall, J. F., and B. G. Thom. 1976. "The Sea Level in the Last Interglacial." *Nature* 263:120-121.

Massachusetts, State of. 1981. *Barrier Beaches: A Few Questions Answered.* Boston: Massachusetts Office of Coastal Zone Management.

Mercer, J. H. 1970. 'Antarctic Ice and Interglacial High Sea Levels." *Science* 168:1605-1606.

Mercer, J. H. 1972. "The Lower Boundary of the Holocene. " *Quaternary Research* 2(l):15-24.

Mercer, J. H. 1976. "Glacial History of Southernmost South America." Quater*nary Research 6:125-166.*

Mercer, J. H. 1978. "West Antarctic Ice Sheet and $C0_2$ Greenhouse Effect: A Threat of Disaster." Nature 271(5643): 321-325.

Nardin, Thomas R., Robert H. Osborne, David J. Bottjer, and Robert C. Scheidemann. 1981. "Holocene Sea Level Curves and Santa Monica Shelf, California Continental Borderland." *Science 213:331-333.*

New Jersey, Department of Environmental Protection. 1981. *New Jersey Shore Protection Master Plan* Trenton: Division of Coastal Resources.

Oerlemans, J. 1981. "Effect of Irregular Fluctuations in Antarctic Precipitation on Global Sea Level." *Nature* 290:770-772.

Palmer, A., W Moose, T. Quinn, K. Wolf. 1980. *Economic Implications for* Regulating *Chlorofluorocarbons Emissions for Non-Aerosol Applications.* R-2524-EPA. Washington, D.C.: Environmental Protection Agency.

Perry, A. M., K. J. Araj, W Fulkerson, D. J. Rose, M. M. Miller, and R. M. Rotty. 1981. *Energy Supply* and Demand *Implications of* $C0_2$. Oak Ridge, Tenn: Oak Ridge National Laboratories.

Pilkey, O., J. Howard, B. Brenninkmeyer, R. Frey, A. Hine, J. Kraft, R. Morton, D. Nummedal, and H. Wanless. 1981. *Saving the American Beach: A Position Paper by Concerned Coastal Geologists.* Results of the Skidaway Institute of Oceanography Conference on America's Eroding Shoreline. Savannah: Skidaway Institute of Oceanography.

Revelle, R., 1983. "Probable Future Changes in Sea Level Resulting from increased Atmospheric Carbon Dioxide," *in Changing* Climate. Carbon Dioxide Assessment Committee. Washington, D.C.: National Academy Press, pp.433-447.

Research Planning Institute. 1983. *Hypothetical Shoreline Changes Associated with Various Sea-Level Rise*

Scenarios for the United States: Case Study-Charleston, South Carolina. Report to ICF under contract to EPA. Columbia, *S. C.:* RPI.

Rotty, R., and G. Marland. 1980. *Constraints on Carbon Dioxide Production From Fossil Fuel Use.* ORAM-IEA-80-9(m). Oak Ridge, Tenn.: Oak Ridge Associated Universities, Institute for Energy Analysis.

Ruch, Carlton. 1982. *Ongoing Research on the Effects of Hurricanes.* College Station, Tex.: Research Center College of Architecture, Texas A&M University.

Schneider, Stephen H., and Robert S. Chen. 1980. "Carbon Dioxide Flooding: Physical Factors and Climatic Impact." *Annual Review of Energy* 5:107-140.

Schwartz, M. L. and J. J. Fisher, eds. 1979. *Proceedings of the Per Bruun* Symposium. Newport, RI.: IGU Commission on the Coastal Environments.

Seidel, S., and D. *Reyes.* 1983. *Can We Delay a Greenhouse Warming?* Washington, D.C.: Government Printing Office.

Sleep, N. H. 1976. "Platform Subsidence Mechanisms and'Eustatic'Sea-Level *Change." Techton*physics 36(1-3):45-56.

Smagorinsky, J., chairman, Climate Research Board. 1982. *Carbon Dioxide: A Second Assessment.* Washington, D.C.: NAS Press.

Sorensen, Robert M., Richard N. Weisman, and Gerard P. Lennon. 1983. *Methods for Controlling the Increases in Shore Erosion Inundation by Storm Surge and Salinity Intrusion Caused by a Postulated Sea-Level Rise.* Report to ICF under contract to EPA. Bethlehem, Pa: Lehigh University, Department of Civil Engineering.

Sullivan, Walter. 1981. "Study Finds Warming Trend That Could Raise Sea Levels." *New York Times,* August 22, p. 1, co]. 1.

Thomas, R., T *J.* 0. Sanderson, and K. E. Rose. 1979. "Effect of Climatic Warming on the West Antarctic Ice Sheet." *Nature* 277:355-362.

U.S. Department of the Interior. 1983. *Undeveloped Coastal Barriers: Final Environmental Statement.* Washington, D.C.: Coastal Barriers Task Force. U.S. Fish and Wildlife Service. 1979. *The Effect of Salinity Change on the American Oyster in Delaware Bay.* Prepared for the Army Corps of Engineers, Philadelphia District. Delaware Salinity Intrusion Study, Fish and Wildlife Service, Department of Interior, State College, Pa.

Worsley, Thomas R., and Thomas A. Davies. 1979. "Sea Level Fluctuations and Deep Sea Sedimentation Rates." *Science* 203:455-456.

APPENDIX

Summaries of Charleston, South Carolina and Galveston, Texas, Case Studies

Table1-A. Charleston Study Area: Area Lost to Sea Level Rise by Scenario (in sq. km)

	1980	*2025*				*2075*			
	Area	*Trend*	*Low*	*Medium*	*High*	*Trend*	*Low*	*Medium*	*High*
Charleston Peninsula	27.4	0.5	1.0	1.8	2.8	1.0	2.8	7.5	13.2
Mount Pleasant	29.8	0.5	1.3	2.1	3.6	0.8	3.6	6.2	10.4
Sullivans Island	2.8	-[a]	0.3	0.5	0.8	-[a]	1.0	2.1	2.3
West Ashley/ James Island	14.0	0.5	1.0	1.8	3.1	1.0	4.9	6.0	9.3
Daniel Island/ Naval Base/ Marsh	19.7	-[a]	1.3	1.6	2.6	0.8	2.8	7.0	7.8
Total	93.7	1.8	4.9	7.8	13.0	3.9	14.2	28.7	43.0

[a] Less than 0.1 sq km.

Table 1-B. Charleston Study Area: Area in 10-Year and 100-Year Floodplains by Scenario (in sq. km)

	Total Area (1980)		*2025*				*2075*			
		1980	*Trend*	*Low*	*Medium*	*High*	*Trend*	*Low*	*Medium*	*High*
					10-Year Floodplain					
Charleston Peninsula	27.4	5.4	6.0	7.0	7.8	8.5	6.7	9.8	14.8	18.9
Mount Pleasant	29.8	8.3	8.8	9.3	9.8	10.4	9.3	11.1	14.2	16.8
Sullivans Island	2.8	2.3	2.3	2.6	2.6	2.6	2.6	2.8	2.8	2.8
West Ashley/ James Island	14.0	6.5	6.7	7.2	7.5	7.8	7.0	8.5	10.9	12.7

Table 1-B. *(continued)*

	Total Area (1980)	*1980*	*2025*				*2075*			
			Trend	*Low*	*Medium*	*High*	*Trend*	*Low*	*Medium*	*High*
			10-Year Floodplain (continued)							
Daniel Island/ Naval Base/ Marsh	19.7	8.3	8.8	9.8	10.6	11.6	9.3	12.6	16	18.1
Total	93.7	30.8	32.9	35.7	38.6	41.4	34.9	45.0	58.5	69.4
			100-Year Floodplain							
Charleston Peninsula	27.4	14.7	15.3	16.3	17.3	18.1	16.0	19.4	22.3	24.0
Mount Pleasant	29.8	14.2	14.8	15.5	16.1	16.8	15.3	17.6	20.7	23.8
Sullivans Island	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
West Ashley/ James Island	14.0	11.4	11.7	12.2	12.4	12.7	11.9	12.9	13.7	14.0
Daniel Island/ Naval Base/ Marsh	19.7	16.1	16.6	17.1	17.6	17.9	16.8	18.4	19.2	19.4
Total	93.7	59.2	61.1	63.7	66.0	68.4	62.9	71.2	78.7	83.9

Table 1-C. Potential Storm Damage and Inundation Losses Under Various Sea Level Rise Scenarios For the Charleston Study Area (in millions of 1980$)

	1980	*2025*				*2075*			
Damage		*Trend*	*Low*	*Medium*	*High*	*Trend*	*Low*	*Medium*	*High*
Potential damage from the 100 year storm	316	510	555	600	640	620	800	800	720[b]
Expected annual damage across all storms[a]	13	23	25	39	45	32	62	67	64

(continued)

---

[a] Expected value equals the sum of the damage for each storm times the probability of each storm.

[b] Storm surge damage under 2075 high scenario is lower than that for low and medium scenarios because so much area would already be lost to shoreline retreat.

Table 1-C. *(continued)*

Damage	*1980*	*2025*				*2075*			
		Trend	*Low*	*Medium*	*High*	*Trend*	*Low*	*Medium*	*High*
Total value of land and structures lost by shoreline retreat for all years, 1980–2075	-	1	7	11	35	6	60	420	870

Note: All estimates are made under the assumptions that development proceeds at rates currently anticipated in the absence of sea level rise and that no additional protective structures are built.

Table 1-D. Galveston Study Area: Area Lost to Sea Level Rise by Scenario (in km, sq mi in parentheses)

City	*1980*	*2025*				*2075*			
	Area	*Trend*	*Low*	*Medium*	*High*	*Trend*	*Low*	*Medium*	*High*
San Leon	19.4	0.3	0.5	1.0	1.3	1.3	3.4	5.2	7.0
	(7.5)	(0.1)	(0.2)	(0.4)	(0.5)	(0.5)	(1.3)	(2.0)	(2.7)
Galveston Island	69.2	0.5	1.3	2.1	2.6	1.8	3.9	6.5	8.3
	(26.7)	(0.2)	(0.5)	(0.8)	(1.0)	(0.7)	(1.5)	(2.5)	(3.2)
Texas City, La Marque, other	186.5	1.8	2.3	3.4	4.4	3.1	8.3	12.7	17.1
	(72.0)	(0.7)	(0.9)	(1.3)	(1.7)	(1.2)	(3.2)	(4.9)	(6.6)
Total	275.1	2.6	4.1	6.5	8.3	6.2	15.6	24.4	32.4
	(106.2)	(1.0)	(1.6)	(2.5)	(3.2)	(2.4)	(6.0)	(9.4)	(12.5)

Table 1-E. Galveston Study Area in 15-Year and 100-Year Floodplains by Scenario (in sq km, sq mi in parentheses)

City	Total Area (1980)	1980	2025				2075			
			Trend	Low	Medium	High	Trend	Low	Medium	High
					15-Year Floodplain					
San Leon	19.4	1.0	1.6	1.8	2.1	2.1	1.8	2.3	4.4	5.4
	(7.5)	(0.4)	(0.6)	(0.7)	(0.8)	(0.8)	(0.7)	(0.9)	(1.7)	(2.1)
Galveston Island	69.2	18.9	21.2	24.2	26.4	28.5	23.8	31.1	44.5	58.8
	(26.7)	(7.3)	(8.2)	(9.3)	(10.2)	(11.0)	(9.2)	(12.0)	(17.2)	(22.7)
Texas City, La Marque, other	186.5	45.3	48.9	52.3	54.4	55.9	51.8	58.5	70.7	78.5
	(72.0)	(17.5)	(18.9)	(20.2)	(21.0)	(21.6)	(20.0)	(22.6)	(27.3)	(30.3)
Total	275.0	65.3	71.7	78.2	82.9	86.5	77.4	91.9	119.7	142.7
	(106.2)	(25.2)	(27.7)	(30.2)	(32.0)	(33.4)	(29.9)	(35.5)	(46.2)	(55.1)
					100-Year Floodplain					
San Leon	19.4	16.1	17.4	18.1	18.9	19.2	18.1	19.4	19.4	19.4
	(7.5)	(6.2)	(6.7)	(7.0)	(7.3)	(7.4)	(7.0)	(7.5)	(7.5)	(7.5)
Galveston Island	69.2	45.3	45.8	46.6	47.1	50.8	46.4	60.1	62.9	62.3
	(26.7)	(17.5)	(17.7)	(18.0)	(18.2)	(19.6)	(17.9)	(23.2)	(24.3)	(24.4)
Texas City, La Marque, other	186.5	99.2	100.0	100.7	101.0	137.3	100.7	179.2	184.9	186.5
	(72.0)	(38.3)	(38.6)	(38.9)	(39.0)	(53.0)	(38.9)	(69.2)	(71.4)	(72.0)
Total	275.0	160.6	163.2	165.5	167.0	206.9	165.2	258.7	267.3	269.1
	(106.2)	(62.0)	(63.0)	(63.9)	(64.5)	(79.9)	(63.8)	(99.9)	(103.2)	(103.9)

Table 1-F. Potential Storm Damage and Inundation Losses under Various Sea Level Rise Scenarios for the Galveston Study Area (in millions of 1980$)

	1980	*2025*				*2075*			
Damage		*Trend*	*Low*	*Medium*	*High*	*Trend*	*Low*	*Medium*	*High*
Potential damage from the 100-year storm	260	535	580	600	1,100	600	1,800	2,100	2,400
Expected annual damage across all storms[a]	6	16	22	27	38	23	57	105	170
Total value of land and structures lost by shoreline retreat for all years 1980-2075	-	2	6	12	17	17	49	87	107

Note: All estimates were made under the assumptions that development proceeds at rates currently anticipated in the absence of sea level rise and that no additional protective structures are built.

[a] Expected value equals the sum of the damage for each storm times the probability of each storm.