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Ge For
Jol

Paul Bernstein

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This table shows, without any other changes in Dr. Yellen's assumptions, how important her optimism about costless improvement in energy efficiency and international emissions trading is. Her estimates under an ideal emissions trading regime involving just Annex 1 countries would be a direct cost of \$31 billion and a cost for emission permits of \$76 per ton. I have used full Annex B trading in this calculation rather than the "Double Bubble" or "Double Umbrella" in which European countries are excluded from access to low-cost Russian emissions permits, because that scenario is so disadvantageous to Europe that I cannot believe they would agree to it.

Incomplete measurement of costs

The definition of "costs" used in Dr. Yellen's testimony and in the "Second Generation Model" on which it relies is incomplete. She provides estimates of what she calls "direct cost" – measured as the cost in energy markets of switching fuels and investing in energy conservation plus the cost of purchasing permits from other countries. However, this measure ignores the ripple effects of higher energy costs in other sectors of the economy, as well as the dynamic effects of higher costs, reduced competitiveness, reduced profits, and reduced incomes on investment.

At CRA, we have had considerable experience over the years in comparing so-called "direct costs" to the full impact of regulatory programs on the economy. In work by Kopp and Hazilla at Resources for the Future, studies of the costs of air quality regulations by Jorgenson and Wilcoxon, and studies of energy taxes by Goulder, Jorgenson, and Wilcoxon in addition to our own work, there emerges a consistent pattern. In all these studies, the full impact on GDP exceeds the direct cost of a regulatory program or tax by a factor of 2 to 4.

Table 2: Comparison of CRA and SGM: No Trading, 1990 Emissions Limit in 2010

	SGM	CRA BASE	CRA ADJUSTED*
CARBON TAX (\$/METRIC TON)	108	213	109
EMISSIONS REDUCTION (MILLIONS OF METRIC TONS)	400	370	370
DIRECT COST (\$BILLION)	20	39	20
GDP LOSS (\$BILLION)	NA	-120	-55

Source: CRA Multi-Region Trade Model and "Return to 1990: The Cost of Mitigating United States Carbon Emissions in the Post-2000 Period", J.A. Edmonds, et al., October 1997.

*"CRA Adjusted" refers to running CRA's MRT model under Dr. Yellen's assumptions.

Table 2 compares our estimates of direct cost and full GDP loss to estimates from the SGM for a comparable scenario. Note that this is not the Kyoto Protocol, but comes from an earlier study of the cost of limiting emissions to 1990 levels. The important point is that when we change one parameter in our model so that we are estimating the same carbon price as SGM, we calculate the same direct costs but a total GDP loss almost three



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05/28/98 10:25:48 AM

Record Type: Record

To: Zachary M. Candelario/CEA/EOP

cc:

Subject: References

Hi,

Sorry for the delay in getting these to you.

1) Jorgenson and Wilcoxon. 1992, "Impact of Environmental Legislation on W.S. Economic Growth Investment and Capital Costs." In US Environmental Policy and Economic Growth: How do we Fare?
Washington, DC: American Council on Capital Formation.

2) Jorgenson and Wilcoxon. 1993. "Reducing US carbon emissions: An econometric general equilibrium assessment" Resource and Energy Economics (15) 7-25.

3) Hazilla, M. and R, Kopp. 1990. "Social Cost of Environmental Quality Regulations: A General Equilibrium Analysis", Journal of Political Economy, 98(4), pp. 853-73.

Cheers,
Paul Bernstein

Author: Schuh, G. Edward
Institution: University of Minnesota
Title: Agricultural Policies for Climate Changes Induced by Greenhouse Gases.
Appendix: Volume C - Agriculture

Authors: Sheer, Daniel P., and Dean Randall
Institution: Water Resources Management Inc.
Title: Methods for Evaluating the Potential Impacts of Global Climate Change: Case Studies of the State of California and Atlanta, Georgia.
Appendix: Volume A - Water Resources

Authors: Stem, Edgar, Gregory A. Mertz, J. Dirck Strycker, and Monica Huppi
Institution: Tufts University
Title: Changing Animal Disease Patterns Induced by the Greenhouse Effect.
Appendix: Volume C - Agriculture

Authors: Stinner, Benjamin R., Robin A.J. Taylor, Ronald B. Hammond, Foster F. Purrington, David A. McCartney, Nick Rodenhouse, and Gary Barrett
Institution: Ohio Agricultural Research and Development Center and Ohio State University
Title: Potential Effects of Climate Change on Plant-Pest Interactions.
Appendix: Volume C - Agriculture

Authors: Titus, James G., and Michael S. Greene
Institution: U.S. Environmental Protection Agency
Title: An Overview of the Nationwide Impacts of Sea Level Rise.
Appendix: Volume B - Sea Level Rise

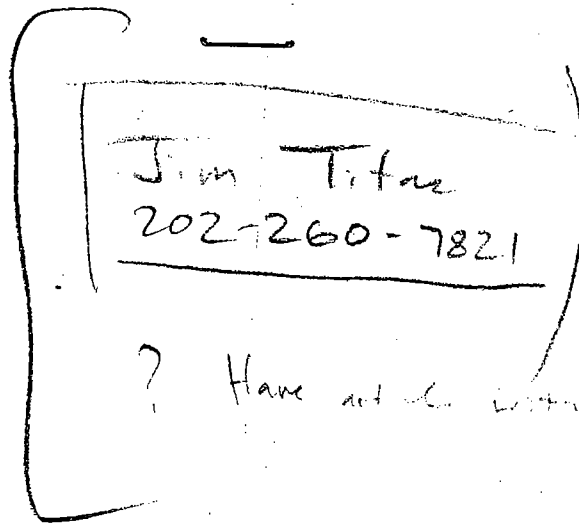
Authors: Urban, Dean L., and Herman H. Sheer
Institution: University of Virginia
Title: Forest Response to Climate Change: A Simulation Study for Southeastern Forests.
Appendix: Volume D - Forests

Authors: Walker, Christopher J., Ted R. Miller, G. Thomas Kingsley, and William A. Hyman
Institution: The Urban Institute
Title: Impact of Global Climate Change on Urban Infrastructure.
Appendix: Volume H - Infrastructure

Authors: Weggel, J. Richard, Scott Brown, Juan Carlos Escajadillo, Patrick Breen, and Edward L. Doheny
Institution: Drexel University
Title: The Cost of Defending Developed Shorelines Along Sheltered Waters of the United States from a Two Meter Rise in Mean Sea Level.
Appendix: Volume B - Sea Level Rise

Author: Williams, Philip B.
Institution: Philip Williams & Associates
Title: The Impacts of Climate Change on the Salinity of San Francisco Bay.
Appendix: Volume A - Water Resources

Titus, James G. 2/28/98



EPA

www.epa.gov/globalwarming

Reports

Slides

→ Notes

↑ sea level

Coastal wetland

Dryland above this

Assume No

Coastal Protection:

(Absurd)

Carried = 20 yr

Signal Miles

Protect Current
Developed Areas

Assume 50cm Rise ⇒
protect existing development

Developed
Area 1170
in

	Dryland Loss		Wetland Loss		
	TP	No Protect	Total Protect	Current	No Protect
NE	71	139	88	55	27
MA	705	904	485	201	120
SA	886	1094	2295	1438	1313
StW Florida	717	768	623	92	63
L	1249	1364	2450	2368	2354
Rest of	809	905	530	396	360
West Pac Coast	444	511	37	+286	

sea level
rise 1

Appendix B
7/1989

sample
Point
Count

THE COST OF HOLDING BACK THE SEA

EPA study estimates that a one meter rise inundates 7000 sq mi of dry land, 50-80% of U.S. wetlands, and costs over \$100 billion in the United States alone.

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REFERENCES

[Link to A List of other Reports that Deal With the Implications of Rising Sea Level and What We Can Do About It](#)

[Article in the Washington Post on Rising Seas and the Loss of Bay Beaches](#)

The standard way of citing this article is: Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene, P.W. Mausel, S. Brown, C. Gaunt, M. Trehan, and G. Yohe. 1991. Greenhouse Effect and Sea Level Rise: The Cost of Holding Back the Sea." Coastal Management 19:171-210. This web page provides the final text as submitted to the journal in response to the peer review. Only minor editing changes were made in the published version. Any text in red signifies changes that we would make if the article were submitted in 1997 (e.g., downward revisions on how rapidly sea level will rise).

GREENHOUSE EFFECT AND SEA LEVEL RISE

The Cost of Holding Back the Sea

By

James G. Titus, Richard A. Park, Stephen P. Leatherman,

J. Richard Weggel, Michael S. Greene, Paul W. Mausel,

Scott Brown, Cary Gaunt, Manjit Trehan, and Gary Yohe

ABSTRACT

Previous studies suggest that the expected global warming from the greenhouse effect could raise sea level 50 to 200 centimeters (2 to 7 feet) in the next century or two. This article presents the first nationwide assessment of the primary impacts of such a rise on the United States: (1) the cost of protecting ocean resort communities by pumping sand onto beaches and gradually raising barrier islands in place; (2) the cost of protecting developed areas along sheltered waters through the use of levees (dikes) and bulkheads; and (3) the loss of coastal wetlands and undeveloped lowlands. The total cost for a one meter rise would be \$270-475 billion, ignoring future development.

We estimate that if no measures are taken to hold back the sea, a one meter rise in sea level would inundate 14,000 square miles, with wet and dry land each accounting for about half the loss. The 1500 square kilometers (600-700 square miles) of densely developed coastal lowlands could be protected for approximately one to two thousand dollars per year for a typical coastal lot. Given high coastal property values, holding back the sea would probably be cost-effective.

The environmental consequences of doing so, however, may not be acceptable. Although the most common engineering solution for protecting the ocean coast--pumping sand--would allow us to keep our beaches, levees and bulkheads along sheltered waters would gradually eliminate most of the nation's wetland shorelines. To ensure the long-term survival of coastal wetlands, federal and state environmental agencies should begin to lay the groundwork for a gradual abandonment of coastal lowlands as sea level rises.

INTRODUCTION

At the turn of the century, scientific opinion regarding the practical implications of the greenhouse effect was sharply divided. Since the 1860s, people had known that by absorbing outgoing infrared radiation, atmospheric CO₂ keeps the earth warmer than it would otherwise be (Tyndall, 1863). Svante Arrhenius (1896), who coined the term "greenhouse effect," pointed out that the combustion of fossil fuels might increase the level of CO₂ in the atmosphere, and thereby warm the earth several degrees.

Because the 19th century had experienced a cooling trend, however, others speculated that the oceans and plant life might gradually reduce CO₂ levels and cause an ice age (Barrel et al., 1919).

Throughout the first half of the 20th century, scientists generally recognized the significance of the greenhouse effect, but most thought that humanity was unlikely to substantially alter its impact on climate. The oceans contain 50 times as much CO₂ as the atmosphere, and physical laws governing the relationship between the concentrations of CO₂ in the oceans and in the atmosphere seemed to suggest that this ratio would remain fixed, implying that only 2 percent of the CO₂ released by human activities would remain in the atmosphere. This complacency, however, was shattered in 1957 when Revelle and Seuss (1957) demonstrated that the oceans could not absorb CO₂ as rapidly as humanity was releasing it: "Human beings are now carrying out a

large-scale geophysical experiment." Only then were monitoring stations set up to measure worldwide trends in atmospheric concentrations. By the mid 1960s, it was clear that Revelle and Seuss had been correct (President's Science Advisory Committee, 1965).

In the last decade, climatologists have reached a consensus that a doubling of CO₂ would warm the earth 1.5-4.5°C (3-8°F), which could leave our planet warmer than it has ever been during the last two million years (National Academy of Sciences, 1979). Moreover, humanity is increasing the concentrations of other gases whose combined greenhouse effect could be as great as that due to CO₂ alone, including methane, chlorofluorocarbons, nitrous oxide, and sulfur dioxide (Ramanathan et al., 1985). Even with the recent agreement to curtail the use of CFCs, global temperatures could rise as much as 5°C (9°F) in the next century (Smith and Tirpak, 1988). Global warming would alter precipitation patterns, change the frequency of droughts and severe storms, and raise the level of the oceans.

This article presents the first attempt to quantify the nationwide impacts of an accelerated rise in sea level. The study was undertaken in response to a request from the U.S. Congress to the Environmental Protection Agency, and had to be completed in twelve months with a budget of \$300,000. With these constraints, we were only able to focus on the loss of dry and wet land and the cost of holding back the sea.

Because our focus was on aspects that can be most readily estimated on a nationwide basis, we have disregarded impacts whose importance is limited to a few areas--in particular the threat to coastal water supplies from saltwater intrusion and the unique situation in Louisiana. We hope that this study will motivate others to improve on the methods presented here and to start quantifying other impacts of global warming.

CAUSES AND EFFECTS OF SEA LEVEL RISE

Climate and Sea Level

The level of the oceans has always fluctuated with changes in global temperatures. During ice ages when global temperatures were 5°C (9°F) lower than today, much of the ocean's water was tied up in glaciers and sea level was often over one hundred meters (three hundred feet) lower than today (Donn et al., 1962; Kennett, 1982; Oldale, 1985). On the other hand, during the last interglacial period (100,000 years ago) when temperatures were about 1°C (2°F) warmer, sea level was approximately 6 meters (20 feet) higher than today (Mercer, 1970).

When discussing shorter periods of time, one must distinguish worldwide (eustatic) sea level rise from relative sea level rise, which includes land subsidence. Although climate affects worldwide sea level, the rate of sea level rise relative to a particular coast has more practical importance and is all that current monitoring stations can measure. Because some coastal areas are sinking while others are rising, relative sea level rise in the United States varies from more than one meter (three feet) per century in Louisiana and parts of California and Texas, to thirty centimeters (one foot) per century along most of the Atlantic and Gulf Coasts, to a slight drop in much of the Pacific Northwest as shown in Figure 1.

Global sea level trends have generally been estimated by combining the trends at tidal stations around the world. These records suggest that during the last century, worldwide sea level has risen 10 to 25 cm (4 to 10 in) (Barnett, 1984; Peltier and Tushingham, 1989), much of which has been attributed to the global warming of the last century (Gornitz et al., 1982; Meier, 1984).

The projected global warming could raise worldwide sea level by expanding ocean water, melting mountain glaciers, and causing the ice sheets of Greenland and Antarctica to melt or slide into the oceans. A report by the Department of Energy estimated that over a period of two to five hundred years, the West Antarctic Ice

Sheet could disintegrate, raising sea level 6 meters (20 feet) (Bentley, 1983; Hughes, 1983). Studies after 1983, however, have focused on the next century. Figure 2 illustrates recent estimates of sea level rise, which generally fall into the range of 50 to 200 cm (2 to 7 feet) by 2100; Studies since 1990, however, generally suggest that the 50-200 cm rise is more likely to take 150-200 years. This assessment uses rises of 50, 100, and 200 cm. A. (For a discussion on the downward revision of sea level rise scenarios, see Chapter 8 of The Probability of Sea Level Rise The greenhouse effect would not necessarily raise sea level by the same amount everywhere. Removal of water from the world's ice sheets would move the earth's center of gravity away from Greenland and Antarctica; the oceans' water would thus be redistributed toward the new center of gravity. Along the coast of the United States, this effect would generally increase sea level rise by less than 10 percent; sea level could actually drop, however, at Cape Horn and along the coast of Iceland (Clark and Lingle, 1977). Climate change could also influence local sea level by changing winds, atmospheric pressure, and ocean currents, but no one has estimated these impacts.

Effects of Sea Level Rise

A rise in sea level would inundate wetlands and lowlands, accelerate coastal erosion, exacerbate coastal flooding, threaten coastal structures, raise water tables, and increase the salinity of rivers, bays, and aquifers (Barth and Titus, 1984). Most of the wetlands and lowlands of the United States are found along the Gulf Coast and the Atlantic coast south of the central part of New Jersey, although there is also a large low area around San Francisco Bay. Similarly, the areas vulnerable to erosion and flooding are also predominantly in the southeast, while potential salinity problems are spread more evenly throughout the coast. We briefly describe the impacts that would result if nothing was done to address sea level rise, and then discuss the responses that have been investigated in the last several years.

Shoreline Retreat. Coastal marshes and swamps are generally found between the highest tide of the year and mean sea level ¹. Because they collect sediment and produce peat upon which they can build, most wetlands have been able to keep pace with the past rate of sea level rise (e.g. Kaye and Barghoom). Thus, as Figure 3a-3c illustrate, the area of wetlands today is generally far greater than the area that would be available for new wetlands if sea level rose too rapidly (Titus, 1986; Titus, 1988) ². The potential loss would be the greatest in Louisiana (U.S. Environmental Protection Agency and Louisiana Geological Survey, 1987). Moreover, in many areas people have built bulkheads just above the marsh; if sea level rose, the wetlands would be squeezed between the estuary and the bulkhead (Figure 3d). Such a loss would reduce available habitat for birds and juvenile fish, and would reduce the production of organic materials on which estuarine fish rely.

The dry land within two meters (seven feet) of high tide include forests, farms, low parts of some port cities, communities that sank after they were built and are now protected with levees, and the bay sides of barrier islands. The low forests and farms are generally in the mid-Atlantic and southeast, and would provide potential areas for new wetland formation. Major port cities with low areas include Boston, New York, Charleston, Miami, and New Orleans; the latter averages about two meters below sea level, and parts of Texas City, San Jose, and Long Beach California are about one meter below sea level.

Some of the most important vulnerable areas are the recreational barrier islands and spits of the Atlantic and Gulf Coasts. Coastal barriers are generally long narrow islands and spits (peninsulas) with the ocean on one side and a bay on the other. Typically, the ocean-front block of an island ranges from two to four meters above high tide, while the bay side is less than a meter above high water. Thus, even a one meter rise in sea level would threaten much of this valuable land with inundation.

Erosion, moreover, threatens the high parts of these islands, and is generally viewed as a more immediate problem than the inundation of their bay sides. As Figure 4 shows, a rise in sea level can cause an ocean beach to retreat by considerably more than the retreat due to inundation alone. The shape of a beach profile is determined

by the pattern of waves striking the shore; generally, the visible part of the beach is much steeper than the underwater portion which comprises most of the active "surf zone." While inundation alone is determined by the slope of the land just above the water, Bruun (1962) showed that the total shoreline retreat from a rise in sea level depends on the average slope of the entire beach profile.

Previous studies suggest that a one meter rise in sea level would generally cause beaches to erode 50-100 meters from the Northeast to Maryland; 200 meters along the Carolinas; 100-1000 meters along the Florida coast; and 200-400 meters along the California coast (Everts, 1985; Kyper and Sorensen, 1985; Kana et al, 1984; Bruun, 1962; Wilcoxon, 1986). Because most U.S. recreational beaches are less than 30 meters (100 feet) wide at high tide, even a thirty centimeter (one foot) rise in sea level would require a response.

Flooding. Coastal areas would become more vulnerable to flooding for four reasons: (1) A higher sea level provides a higher base for storm surges to build upon; a one meter rise in sea level would thus enable a 15-year storm³ to flood many areas that today are only flooded by a 100-year storm (Kana et al., 1984). (2) Beach erosion would leave particular properties more vulnerable to storm waves. (3) Higher water levels would increase flooding due to rainstorms by reducing coastal drainage (Titus et al., 1987). (4) Finally, a rise in sea level would raise water tables.

Many coastal areas are protected with levees and seawalls, and would thus not necessarily experience inundation, erosion, or flooding. However, these structures have been designed for current sea level. Higher water levels would threaten the integrity of these coastal structures because (1) higher flood levels might overtop them, and (2) erosion could undermine them from below (National Research Council, 1987). In areas like New Orleans that are drained artificially, the increased need for pumping could exceed current capacities (Titus et al., 1987).

Saltwater Intrusion. Finally, a rise in sea level would enable saltwater to penetrate farther inland and upstream in rivers, bays, wetlands, and aquifers, which would be harmful to some aquatic plants and animals, and would threaten human uses of water. Increased salinity has already been cited as a contributing factor to reduced oyster harvests in the Delaware (Gunter, 1974) and Chesapeake Bays, and for converting cypress swamps in Louisiana to open lakes (U.S. Environmental Protection Agency and Louisiana Geological Society, 1987). Moreover, New York, Philadelphia, and much of California's Central Valley get their water from areas that are just upstream from where the water is salty during droughts. Farmers in central New Jersey as well as the city of Camden rely on the Potomac-Raritan-Magothy aquifer, which could become salty if sea level rises (Hull and Titus, 1986). The South Florida Water Management District already spends millions of dollars per year to prevent Miami's Biscayne aquifer from becoming salty (Miller et al., 1989).

Responses

Inundation, Erosion, and Flooding. Possible responses fall broadly into three categories: erecting walls to hold back the sea; allowing the sea to advance and adapting to it; and raising the land. The slow rise in sea level over the last thousand years and the areas where land has been sinking more rapidly offer numerous historical examples of all these responses. For over five centuries, the Dutch have used dikes and windmills to prevent inundation from the North Sea. By contrast, many cities have been rebuilt landward as structures and land were lost to erosion; the town of Dunwich, England has had to rebuild its church seven times in the last seven centuries. More recently, rapidly subsiding communities such as Galveston, Texas, have used fill to raise land elevations; The U.S. Army Corps of Engineers and coastal states regularly pump sand from offshore to counteract beach erosion. Venice is a hybrid of all three responses, allowing the sea to advance into the canals, while raising some low lands and erecting storm protection barriers.

Most assessments in the United States have concluded that low-lying coastal cities would be protected with bulkheads, levees, and pumping systems, while in sparsely developed areas shorelines would retreat naturally (National Research Council, 1987). This conclusion has generally been based on the commonly accepted assumption that the cost of these structures would be far less than the value of urban areas being

protected but greater than the value of undeveloped land.

Studies on the possible responses of barrier islands (Titus, 1985; Howard et al., 1985) and moderately-developed mainland communities (Kana et al., 1986; Titus, 1988) suggest that environmental and aesthetic factors would be as important as economics. Figure 5 illustrates four possible responses by which barrier islands could respond to sea level rise: no protection, engineering a landward retreat, raising the island in place, and building a levee. A case study of Long Beach Island, New Jersey, concluded that all three protection options are far less costly than the value of the land that would be threatened. Although levees and retreat are somewhat less expensive than raising islands, the latter option would probably be preferred because (1) constructing levees and seawalls would result in the loss of beaches and waterfront views; and (2) retreat would not be feasible for islands with high-rises and would only be marginally less expensive for moderately developed islands, while requiring major changes in how people view ownership of coastal property (Titus, 1990).

Responses to erosion are more likely to have adverse environmental impacts along sheltered water than on the open coast. Because the beach generally is a barrier island's most important asset, economics would encourage ocean beach communities to preserve their natural shorelines; and preventing the island from breaking up would also protect the adjacent wetlands. But along most mainland shorelines, economic self-interest would encourage property owners to erect bulkheads, which would prevent new wetland formation from offsetting the loss of wetlands that were inundated. Figure 6 illustrates possible policy responses for ensuring that development does not block the inland migration of coastal wetlands.

Saltwater Intrusion. Most of the measures for counteracting saltwater intrusion due to sea level rise have also been employed to address current problems. The Delaware River Basin Commission, for example, protects Philadelphia's freshwater intake on the river--as well as New Jersey aquifers recharged by the river--from excessive salinity by storing water in reservoirs during the wet season and releasing it during droughts, forcing the saltwater back toward the sea (Hull and Titus, 1986). Other communities have protected coastal aquifers by erecting underground barriers and by maintaining freshwater pressure through the use of impoundments and injection wells (Sorensen et al., 1984).

PROJECTING THE NATIONWIDE IMPACTS: OBJECTIVES AND STRATEGY

Ideally, we would like to know the economic and environmental impacts of all the possible scenarios of sea level rise for all possible policy responses for every coastal community in the nation. Every community would then have sufficient information to rationally consider how it should respond. Moreover, we could estimate the nationwide impact by picking the best policy response for each community and adding all the costs. However, because such a comprehensive analysis is not yet possible, our study had the more limited objective of developing nationwide estimates that considered as many factors as possible.

Our first step was to choose which of the impacts to study. We chose shoreline retreat (i.e., erosion and inundation) for several reasons: First, we excluded saltwater intrusion because only two case studies had examined the physical impacts and none had examined the economic impact of rising sea level; the processes are too complicated to meaningfully represent without detailed models; and the unavoidable⁴ economic and environmental impact of increased salinity appeared to be an order of magnitude less than shoreline retreat--and much more sensitive to possible changes in the frequency of droughts than to sea level rise (Hull and Titus, 1986). We would have liked to include flooding, which is closely related to shoreline retreat, but the cost of applying flood models to a large number of sites was prohibitive, and models of the resulting property damage are inaccurate without detailed surveys of the elevations and types of structures.

By contrast, estimating the impacts of (1) natural shoreline retreat and (2) holding

back the sea seemed feasible. In the former case, estimating inundation of dry land simply requires one to determine its elevation; wetland loss requires the elevation and an assumption regarding how rapidly the wetlands might accrete; beach erosion can be approximated using topographic maps and the Bruun (1962) rule; and the value of lost land can be estimated using tax maps. The costs of holding back the sea are also fairly straightforward: Wetland loss is estimated the same way as under the natural retreat scenario, except that one must specify which areas are likely to be protected from the sea (and hence, unavailable for creation of new wetlands); the cost of nourishing beaches can be derived using data collected by the Corps of Engineers; and the cost of elevating land, houses, and of erecting shore-protection structures can be estimated by engineers based on experience.

Moreover, the procedures for assessing shoreline retreat tend to implicitly account for flooding caused by storm surges (at least after the first foot of sea level rise). Where development is protected from sea level rise, levees and pumping systems used for preventing inundation would also prevent sea level rise from increasing flood damages; and raising barrier islands and the structures on them by the amount of sea level rise would leave flood risks constant.⁵ Where development is unprotected, the estimates of lost land and structures would probably account for the costs of increased flooding; although flood plains would move inland, the value of structures standing in the new flood plain would be approximately balanced by the inundated structures that are lost. Nevertheless, for the first foot of sea level rise, examining shoreline retreat probably does not account for flooding: if development is protected, major measures would probably not be taken to counteract the first foot, so the frequency of flooding would increase. If development is not protected, the first foot would increase flooding but not threaten many structures with inundation.

At the outset, it was clear that it would not be possible to estimate both the cost of holding back the sea and the cost of not holding it back with the resources we were allotted. We chose to focus on the former because it currently seems more likely. We would learn little, for example, from estimating the value of buildings on Manhattan Island that would be lost if the sea was not held back; because of its value, we know Manhattan will be protected, and that assuming otherwise in a nationwide study would substantially skew the results. By contrast, assuming that shores would be protected in a lightly-developed area more likely to be abandoned would introduce a more modest error. Accordingly, we divided the assessment into three tasks:

1. Estimating the areas of dryland and wetlands that would be lost for various scenarios.
2. Estimating the cost of protecting developed areas along sheltered coasts.
3. Estimating the cost of protecting developed areas along the open coast.

Each task used four scenarios of sea level rise: the historic trend of 12 cm per century, and accelerated rises of 50, 100, and 200 cm by the year 2100. In all cases, local subsidence was added to the projections of global sea level rise.

LOSS OF COASTAL WETLANDS AND DRY LAND

Methods

This part of the study was based on a sample of 46 coastal sites selected at regular intervals along the coast, accounting for 10 percent of the contiguous U.S. coastal zone. Because of funding constraints, we had to exclude Alaska, Hawaii, and the U.S. territories.

This task required us to (1) characterize existing elevations and (2) model the impact of sea level rise. We estimated elevations of dry land by interpolating between contours on U.S. Geological Survey topographic maps. For wetlands, however, the procedure was more complicated: First we determined the dominant wetland types (e.g. high marsh, low marsh, mangrove) for 57- by 79-meter "pixels", based on LANDSAT

imagery (DeSарthy, 1974). (Because of computer limitations, these pixels had to be aggregated to 500-meter squares.) We then calculated the distribution of wetland elevations based on known tidal ranges,⁶ the relationship between tides and wetland types (Lefor et al., 1987), and the assumption that elevations for particular wetland types are distributed uniformly between their upper and lower bounds.

Given our estimates of current elevations, we estimated loss of wet and dry land for three scenarios of shoreline protection: no protection, (standard) protection of currently developed areas, and (total) protection of all shores. Although estimating the loss of dry land depends solely on current elevations, determining the loss of coastal wetlands requires an assumption regarding vertical accretion. Because no one had assessed the possible impact of global warming and sea level rise on accretion, we assumed that current accretion rates would continue.

An evaluation of the implications of coastal land loss is outside the scope of this report. Nevertheless, the reader interested in understanding the entire economic impact of sea level rise requires at least a rough conversion of the wetland loss estimates into monetary terms. We use high and low assumptions of \$6,000 and \$30,000 per acre. The first assumption is based on the low end of previous studies that valued each of the various services from wetlands that can be quantified, such as fisheries, flood control, and water purification (e.g. Gosselink et al. 1974; Farber and Costanza 1987). This assumption is almost certainly too low because it does not consider the various aesthetic benefits of better environmental quality. Our high assumption is based both on the upper end of previous studies and on the observation⁷ that wetland mitigation programs generally cost about \$30,000 per acre; this assumption is also an understatement, since the artificially created wetlands generally have a lower quality than the natural wetlands that are lost.

We also made a rough estimate of the undeveloped land that would be lost if only currently developed areas are protected. These estimates were based on the subjective assessments of real estate agents regarding the value of undeveloped land, as reported in Yohe (1990).

Limitations

The most frequently criticized aspect of our approach is that we have assumed constant wetland accretion rates. Because sea level itself can limit the rate of vertical accretion of wetlands, one might hope that accelerated sea level rise would enable wetland vertical accretion to accelerate as well.⁸ Although our results for the 50-cm scenario are sensitive to this assumption, they are not particularly sensitive for the one- and two-meter scenarios: No one has suggested that wetlands could generally keep pace with sea level rising 1 to 4 cm/yr, which these scenarios imply for the second half of the 21st century.

(This is not to say that most areas would lose all their wetlands. Even in areas that are rapidly losing wetlands due to sea level rise, such as Louisiana, one can find parcels of wetlands that have kept pace with sea level. In areas with substantial sediment supplies, accelerated sea level rise simply implies that a fixed supply can sustain a proportionately smaller are of wetlands. Even in areas with relatively little sediment supply, the loss of wetlands due to erosion, inundation, or saltwater intrusion frees up sediment that had been previously bound up with the wetlands that are lost; this extra sediment may help to accelerate the vertical accretion of the remaining wetlands. Finally, some types of low-salinity marshes and mangroves appear to be able to sustain much larger rates of sea level rise than are prevalent today (Stevenson et al. 1990).

Although remote sensing provides greater vertical resolution than topographic maps, it requires interpretation which can cause errors. In California, for example, redwoods have a spectral signature very similar to some marsh grasses. Although we checked our interpretation against other sources such as U.S. Fish and Wildlife Service Wetland Inventory maps, detailed survey information was only available for a few sites. Nevertheless, as Table 1 shows, our estimate of current nationwide wetland acreage is fairly close to the estimate developed by the National Oceanic and Atmospheric Administration.

Our failure to consider the potential implications of alternative ways of managing river flow is a particularly serious limitation for application to Louisiana, where a wide variety of measures have been proposed for increasing the amount of water and sediment delivered to the wetlands.

We made no attempt to predict which undeveloped areas might be developed in the next century. Currently, only about one-seventh of the coastal lowlands are developed; even a low growth rate would imply substantially greater protection costs and higher land values for the currently undeveloped land. Finally, our conversion of the area of lost wetlands into dollar values is completely dependent on a few case studies that have never considered the implications of the large nationwide loss that could result from a rise in sea level. The law of diminishing returns implies that the cost to society of 50 percent of the coastal wetlands would be much greater than, for example, fifty times the cost of losing 1 percent.

Results

In presenting results, we group the sites into seven coastal regions, as shown in Figure 7. New England, Mid-Atlantic, South Atlantic, South Florida/Gulf Coast Peninsula, Louisiana, Other Gulf (Texas, Mississippi, Alabama, Florida Panhandle), and Pacific Coast.

Figure 8 illustrates our point estimates of nationwide wetland loss for the three policy scenarios -- total, standard, and no protection. If all shorelines were protected, a one meter rise would result in a loss of 50-82 percent of U.S. coastal wetlands, while a two meter rise would result in a loss of 66-90 percent. If only currently developed areas are protected, the losses would be 29-69 percent and 61-80 percent for the one and two meter scenarios. Table 2 provides regional detail for the one-meter scenario; Table 3 provides nationwide results for all three scenarios. The greatest losses of wetlands would be in the southeast, which currently has 85 percent of U.S. coastal wetlands; for a one meter rise 90-95 percent of the loss would take place in this region, 40-50 percent in Louisiana alone. By contrast, neither the northeast nor the west² would lose more than 10 percent of their wetlands if only currently developed areas are protected. Except for the northeast, no protection results in only slightly lower wetland loss than protecting only densely developed areas.

Figure 9 illustrates our projections of the inundation of dry land for the seven coastal regions. If shorelines retreat naturally, a one meter rise would inundate 20,000 square kilometers (7,700 square miles) of dry land, an area the size of Massachusetts; rises of 50 and 200 cm would result in losses of 13,000 and 31,000 square kilometers (5,000 and 12,000 square miles), respectively. Seventy percent of the losses would occur in the southeast, particularly Florida, Louisiana, and North Carolina; the eastern shores of Chesapeake and Delaware Bays would also lose considerable acreage. Table 4 provides estimates of the value of wet and dry land that might be lost if currently developed areas are protected.

COST OF PROTECTING CURRENTLY DEVELOPED SHORES ALONG SHELTERED WATERS

Methods

Our approach here was to develop cost estimates¹⁰ for protecting six index sites and extrapolate those estimates to the other sites in the sample based on the total amount of developed shoreline to be protected and the portion of the protected area threatened with inundation.

The six index sites were metropolitan New York; Long Beach Island, New Jersey; Dividing Creek, New Jersey; metropolitan Miami; Corpus Christi, Texas; and parts of San Francisco Bay. Because our resources were not sufficient estimate the costs of

shore-protection strategies for several sea level scenarios, we did so only for the 2-meter scenario, (and interpolated for the other scenarios, as we describe below).

Our assessments of the index sites assumed that developed areas below the 10-ft (NGVD) contour would require protection. Because contours are only available in 5-ft increments, this assumption was a computational necessity. Nevertheless, it is fairly reasonable: with a 2-meter rise, the contour would only be about 60 cm above mean sea level and hence very close to spring high tide.¹¹ Levees were assumed to cost \$1.6 million per kilometer (\$500 per linear foot) (Sorensen et al., 1984). As an alternative, we considered protection with bulkheads, whose cost is only \$0.42 million per kilometer (\$130 per foot) (Sorensen et al., 1984). In the case of areas that already have bulkheads, we netted out the costs that would be incurred without sea level rise due to routine replacement, using the standard engineering assumption that that bulkhead costs increase with bulkhead height raised to the 1.5 power. In cases where the area requiring protection is isolated and connected to higher ground by low-lying roads, we estimated the cost of raising the elevation of the roadway. In areas that are too lightly developed to warrant protection, we estimated the cost of moving buildings assuming a cost of \$10,000 per structure.

Developing the nationwide estimates involved two steps: extrapolating the index sites to the entire sample, which gave us an estimate for the 2-meter scenario, and interpolating the results for each site for the 50- and 100-cm scenarios. The first step required us to estimate the total length of shorelines that would require bulkheads or levees, the total length of roads that would have to be rebuilt, and the number of structures that would be moved. We used the digitized maps described above to estimate shoreline length, assuming that the ratio actual shoreline to digitized shoreline would be the same for the rest of the sample as it had been for the 6 index sites.¹² We calculated the amount of roads that had to be rebuilt and structures to be moved by fitting regression equations that expressed those variables as functions of the amount of low-lying land that is developed and the slope of the land, both of which were available from the digitized maps.

We then interpolated for the 50 and 100 cm scenarios. The cost estimates assumed that the fraction of shoreline protected by levees would correspond to the fraction of lowland in the particular site that was inundated, and that the remainder of protected shorelines would be bulkheaded. We interpolated unit protection costs on the assumption that costs rise with the 1.5 power of the height of the structures. Finally, we use Yohe's (1990) data for the average value of vulnerable land in developed areas (\$91,000 to 266,000 per acre) to estimate the value of the land that would be required to build the necessary dikes, assuming that the dikes and related infrastructure average 9 meters (30 feet) wide.

Limitations

This task is almost certainly the least accurate part of our assessment. Only one of the index-site studies involved a visit to the site. Unit-cost estimates were based on the literature, not site-specific designs that take into consideration wave data for bulkheads and potential savings from tolerating substandard roads. Although digitized topographic and development data were considered for all 46 sites, the results depend largely on a very small sample of only six sites.

Results

Table 4 illustrates our estimates of the value of the necessary land, while Table 5 provides estimates of the cost of the dikes themselves. Unlike wetland loss, the cost of protecting developed areas from the sea would be concentrated more in the northeast than the southeast, because a much greater portion of the coast is developed in the northeast. (The southeast still accounts for a large percentage of the total costs due to its majority share of U.S. sheltered shorelines.)

COST OF PROTECTING THE OPEN COAST

Methods

Because resources were limited, we could only consider a single technology for the entire coast. We chose the island raising approach, based on the Long Beach Island study discussed in the background section. We assumed that all developed barrier islands would be protected in this fashion, as well as a few undeveloped recreational and Louisiana's barrier islands, where shore protection is a state policy.

This task consisted of estimating (1) the cost of placing sand on the beach profile and low parts of barrier islands and (2) the cost of elevating houses and infrastructure.

Sand Quantities. This part of the analysis required us to estimate the amount of sand each state would require and the average unit cost of sand in that state. For the former task, we employed the "raise the profile" method, which is consistent with the Bruun (1962) rule but does not require as many assumptions (Titus and Greene, 1989). This method simply states that the amount of sand required is equal to the area being raised times the rise in sea level. For small amounts of sea level rise, only the active beach profile must be raised (to curtail erosion); for larger rises, dry land must also be raised (to prevent inundation).

The only difficulty in applying this method is deciding the extent of the beach profile being raised. Hallermeier (1981) recommended that analysts calculating the amount of sand necessary for beach nourishment use the critical closure depths for significant offshore transport, which he estimated as generally about 5-7 meters on the Atlantic Coast, 4-5 meters on the Gulf Coast, and 5-10 meters along the Pacific Coast. He also estimated the closure depths for significant transport of any type, but he recommended these depths only for use in erosion calculations. Thus, in the peer review draft, we used bathymetric charts to estimate the distance out to sea of the closure depths for offshore transport, and topographic maps to estimate the inland distance of the dune crest, added the two distances, and multiplied by the shoreline length to arrive at an estimate of the area of the beach profile that needed to be raised.

In a previous publication (Titus and Greene 1989), we had noted that this procedure probably provided estimates that were too low. The closure depth and distance recommended by Hallermeier approximate the profile adjustment in a single year; should a major hurricane come along, material will be carried much further out to sea. Indeed, most cost studies of beach nourishment may be acknowledging this implicitly by also including an allowance for periodic "renourishment" projects. However, it would be inappropriate to use the normal renourishment formulas, because they generally lump the additional sand necessitated by long-term profile adjustment in with other factors that are outside the scope of this analysis (such as alongshore transport) or already included (such as post-project sea level rise).

Nevertheless, about half the reviewers of the original version of this paper suggested that its most serious flaw was that the sand quantity estimates were too low. Accordingly, we decided to call the original estimates our low scenario and develop a high scenario adapted from the Titus and Greene paper: Low: $Sand_t = A * SLR_t$

High: $Sand_t = A * SLR_t - B * SLR_{t-1} + c * Sand_{t-1}$,

where the asterisk "*" denotes multiplication, $B = A * (1 - (1-c) * (d_i/d_1)^{1.5})$

and A is the ratio of the horizontal and vertical extents of the beach profile, $1/(1-c)$ is the "e-folding" time for long-term profile adjustment in years, and $(d_i/d_1)^{1.5}$ is an estimate of the ratio of the profile lengths from the two closure depths suggested estimated by Hallermeier, using the assumption that profiles follow the shape $y=x^{2/3}$. We then assumed that $c=.96$ for the Gulf coast and $.98$ for the Atlantic and Pacific Coasts.

Simply put, the high scenario assumes that in the first year after a rise in sea level, the sand required to stabilize the shore is the same as the sand projected by the low scenario; but in equilibrium, the required sand will be 6.0, 3.5, and 15.7

times as great for the Atlantic, Gulf, and Pacific Coasts, based on the alternative estimates of the profile length. The values of c imply that 90 percent of the adjustment will occur in 57 years for the Gulf and 114 years elsewhere.

Sand would also be required for elevating dry land. We assumed that after the first foot of sea level rise, portions of coastal barrier islands below 152 cm (5 ft NGVD) would be raised with the sea, and that other parts of coastal barriers would be raised after the third foot.

We employed this procedure for every developed recreational beach from Delaware Bay to the mouth of the Rio Grande, as well as the state of California. For the rest of the coast, we picked one representative site for each state; we then extrapolated the individual sites to the rest of the state based on the length of the developed shoreline.

Sand Costs. For both of the sand quantity formulas, we developed high and low cost estimates for each state, based on inventory surveys by the Corps of Engineers and state agencies contemplating beach nourishment projects.¹³ The low estimates were based on the assumption that unit sand costs remain constant, while the high estimates assume that unit costs increase as the least expensive nearshore deposits are exhausted and it becomes necessary to go farther out to sea or mine lower-quality deposits.

For the most part, existing inventories identify sufficient sand for the projects that officials are currently contemplating, but not the far greater quantities that would be necessary to address a substantial rise in sea level. Therefore, we were unable to specify separate reliable sand cost functions for each state in developing our high scenario. However, sufficient sand has been identified for such a cost function for Florida's Atlantic coast, illustrated in Table 6. Therefore, we calculated sand costs for each state by assuming that costs would escalate by the same pattern (scaling for the length of the state's shore); i.e. we considered current differences in sand costs for various states but assumed that those differences would not change as sea level rises.

Cost of Raising Land and Structures. Estimating the cost of elevating roads and structures required us to obtain estimates of (1) the area of developed land that would be elevated, (2) the density of structures, and (3) unit cost factors. Because the only case study to address this issue was the study of Long Beach Island (Weggel et al., 1989), this part of our analysis consisted primarily of extrapolating that case study to other barrier islands based on our estimates of bay and ocean-side areas and Census data on building density (Bureau of the Census, 1980).

Because Census data for barrier islands is limited, this part of the analysis had to be conducted at a greater level of aggregation than the portion on sand costs; we divided the coast into Northeast/Mid Atlantic, South Atlantic, and Gulf, ignoring the west coast where there are no barrier islands. For each group, we randomly sampled coastal towns for which Census data is available, and calculated the density of structures.

As Table 7 shows, our extrapolation equations assumed that the cost for elevating structures could be described as

$$\text{Cost}_{\text{slr}} = \text{aslr} * \text{Shoreline_length} + \text{bslr} * \text{buildings},$$

where the number of buildings is area multiplied by housing density. Our rationale was that the Long Beach Island study had found that most of the costs were associated with roads and utilities. We derived parameters for this equation by assuming that the length of primary roads is equal to the length of the island and that secondary road mileage is proportional to the number of buildings, with constants of proportionality and the cost of responding to 50, 100, and 200 cm rises in sea level based on Long Beach Island. For the 50 cm scenario, we assumed that only the low bay sides would be raised; for the 200 cm scenario, we assumed that entire islands would be raised. However, for the 100 cm scenario, we developed two equations to acknowledge that we are not certain whether communities would elect to raise land currently above the 5 ft NGVD contour. On one hand, much of this land is about 3

meters (10 ft) above NGVD, and hence would still be above sea level; on the other hand, with a typical spring tide range of 200 cm, historic sea level rise, and future subsidence, land at the 10 ft NGVD contour would only be about 60 cm above spring high tide, which would leave the island vulnerable during severe storms.

Limitations

Because state-specific inventories and sand-cost assessments have been conducted, our estimates of future dredging costs are probably much more accurate than our estimates of the cost of elevating structures. Nevertheless, both sets of estimates faced important data and model limitations.

Sand Quantities. Because of its geometric simplicity, the "raising the profile" method of estimating the necessary sand is conceptually appealing. But one must decide whether to use a short or long-term profile. Communities could delay much of the costs by placing most of the sand on the upper part of the beach (Titus, 1984). By using the annual storm to determine the profile, the low scenario fails to account for the fact that the success of the project is only temporary; eventually the entire profile must be raised. The high scenario may be more realistic, but because there is no research available to estimate the likely adjustment times, we had to simply take a guess. Moreover, Hallermeier's estimates do not explicitly consider hurricanes and other rare but severe storms, which might extend the effective profile even farther out to sea. This limitation is particularly important given the possibility that hurricanes may become more severe as global temperatures rise.

Unit Costs. Both our low and high estimates assumed that the sand placed on the beach has sufficient grain size to remain within the beach system; we lacked the data to estimate the quantity that would wash away. Moreover, both estimates assume that developments in technology do not change the costs. Although improvements in technology and economies of scale have the potential to lower the cost, future increases in energy prices may offset these economies. Finally, we assumed that the same sources would be employed for raising the active beach profile as for raising dry land; low-cost material unsuitable for the beach may prove acceptable for raising building lots.

Our procedure for extrapolating the cost escalation in Florida to the rest of the nation is even more suspect. In many areas, sand costs are currently higher because they already have to go farther out to sea, suggesting a greater scarcity, which might result in the escalation being greater; in other areas, there may be ample sand close to the shore. We assumed that tidal deltas would not be mined for sand.¹⁴

Costs of elevating structures. The Bureau of the Census does not provide data on the number of structures for various barrier islands; one must infer the density based on (1) data for jurisdictions that are entirely on coastal barriers, and (2) by assuming that communities that include both mainland and barrier islands have a uniform density. Moreover, our analysis treated all structures the same, even though hotels or apartments would be far more costly to elevate than the single family homes that dominate on Long Beach Island. Finally, the extrapolation of a single community to the entire nation implies that our estimates are valid only if that community's costs are "typical", a condition that can only be verified by examining other communities.

Results

Table 7 shows our estimates by state of the dredging costs that would accompany the various scenarios of future sea level rise. A total of 3,100 kilometers (1,920 miles) of shoreline would be nourished. An area of 7,233 square kilometers (2753 square miles) would potentially have to be raised, one quarter of this after the first foot of sea level rise.¹⁵ One-half to two-thirds of the nationwide cost would be borne by four southeastern states: Texas, Louisiana, Florida, and South Carolina. However, much of the costs for Texas result from the width of its barrier islands; if urban centers such as Galveston are protected with levees, dredging costs for that state could be less than half as great as shown here.

Table 8 illustrates our estimates of the cost of elevating roads and structures. For

a 50-cm rise, Gulf Coast barrier islands account for over 50 percent of the \$32 billion cost, largely due to their lower elevations. By contrast, for a 2-meter rise, the Mid-Atlantic and Northeast would account for over 50 percent of the \$286 billion cost because they are on average the most densely developed.

SUMMARY AND CONCLUSIONS

We estimate that shoreline retreat from a one meter rise in sea level would cost the United States 270 to 475 billion dollars. Like all cost estimates involving unprecedented activities, our estimates ignore the impacts we could not readily quantify and those we can not foresee, and hence, are almost certainly too low. But policymakers are accustomed to "soft" estimates, and we see no reason to believe that our underestimates are any worse than the norm.

Table 9 summarizes our calculations. Thirty six thousand square kilometers (fourteen thousand square miles) of land could be lost from a one meter rise, with wet and dry land each accounting for about half the loss. For a few hundred billion dollars, fifteen hundred square kilometers (six to seven hundred square miles) of currently developed land could be protected, but the loss of coastal wetlands would be that much greater.

At the national level, protecting developed coastal areas appears to be cost-effective. The cumulative figure would be spread over one hundred years; even at the end of the century, the annual cost of protection on barrier islands would be about \$2,000 for a quarter-acre lot--hardly a welcome prospect for coastal property owners but nevertheless one well worth bearing in order to maintain the property. The cost of protecting developed mainland areas would be only about one-tenth as great.

The fact that it may be cost effective to protect property does not necessarily imply that it would be in the interest of society to do so. We must also consider the loss of natural shorelines and coastal wetlands that would result. Our results suggest that up to a point, the objectives of protecting wetlands and coastal property may be compatible. Abandoning developed areas would increase the area of surviving wetlands by only 5 to 10 percent--but at great cost. By contrast, limiting coastal protection to areas that are already densely developed (and allowing currently-undeveloped areas to flood) would increase the area of surviving coastal wetlands by 40 to 100 percent, depending on how much the sea rises.

However, estimates in areal losses understate the differences in environmental impacts for the various policy options. Although a substantial loss would occur even if developed areas were abandoned, most of today's wetland shorelines would still have wetlands; the strip would simply be narrower. By contrast, protecting all mainland shorelines could result in wetlands being confined to a small number of isolated reserves, a situation that humanity has already imposed on many terrestrial species.

Our results are consistent with the hypothesis of a 1987 study by the National Academy of Engineering that shore protection will be cost-effective for most developed areas (Dean et al., 1987). From the perspective of civil engineers, that study concluded that little action is necessary today because shore protection structures can be erected rapidly compared with the rate of sea level rise. However, the speed with which communities could build these structures is small comfort to the birds and fish whose habitat would be destroyed by doing so.

Sea level rise is an urgent issue for coastal environmental planners for the very reason that it lacks urgency for directors of public works. If environmentalists do not lay the necessary groundwork today to institutionalize a gradual abandonment of the coastal plain as sea level rises, the public will almost certainly call upon engineers to protect their homes in the years to come.

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FOOTNOTES

1. Mean sea level refers to the average water level over the course of a year.

2. A critical question requiring research is: How rapidly is "too rapidly"? If salinity is low, mangroves may be able to keep up with almost any rate of sea level rise. In deltas and other areas with large sediment supplies, at least some of the marshes can keep up with a 1-2 cm/yr rise. In this case, a net loss will still occur, since there is a fixed sediment supply (e.g. a threefold increase in the rate of relative sea level rise would eventually cut the area of the delta by a factor of three).

3. A 15-year storm is a storm whose flood levels have a probability of 1/15 of being exceeded in any given year.

4. In many estuaries, the direct environmental impact of saltwater intrusion would probably be greater than shoreline retreat, especially in the short run. However, the upstream penetration of the salt front due to sea level rise can generally be offset by relatively modest releases of freshwater from dams or river diversion structures, at a modest cost compared with abandoning developed areas, erecting dikes, and other options investigated by this report.

5. Assuming that storm frequency does not change, which is appropriate for an analysis designed only for sea level rise. Note, however, that hurricanes require a water temperature of 79°F to form; thus, as global temperatures warm, hurricanes may become more frequent (Emmanuel, 1987).

6. For example, if the tidal range is 4 feet, mean high water is 2 feet above sea level. If an area appears to be low marsh, we would assume that elevations are uniformly distributed between 0 and 2 ft. MSL (which would generally be 0.5 to 2.5 ft

NGVD, since sea level has risen 6 inches since NGVD was established).

7. Dennis King, University of Maryland.

8. Edward T. LaRoe, U.S. Fish and Wildlife Service, Washington, D.C., Personal communication.

9. The anomalous west coast results were caused by a small sample size. However, given the west coast's relatively small share of the nation's wetlands, the impact on the nationwide results are small.

10. All costs are in constant 1988 dollars.

11. In most locations, sea level has risen 15-20 cm since NGVD was established in 1929, and an additional 20-25 cm of subsidence could be expected through the year 2100.

12. For the index sites, we estimated shoreline length using a planimeter and on a USGS quadrangle.

13. The last national assessment of shore erosion and the planning implications was undertaken by the U.S. Army Corps of Engineers in 1971. Their national survey, based on District Corps office reports, indicated the prevalence of shore erosion. In addition, there are numerous site specific reports and information available for various locales (we referenced well over one hundred). These data were assembled and analyzed to extract information pertinent to the study. Corps district personnel and State Coastal Zone Management (CZM) officials were also queried for any up-to-date information and insights. The CERC Inner-Continental Shelf Studies (ICON) data sets provided the information on offshore sand resources.

14. Although resorting to these sources would create erosion, the savings resulting from their proximity may be greater than the additional costs resulting from the increased erosion.

15. For the reader concerned by the apparent contradiction that the area of barrier island that must be raised would be greater than the total amount of dryland requiring protection from inundation: Most of the land being raised would be above high water even if sea level rises, but would have to be raised for flood-control purposes. Similarly, the dikes that protect the dry mainland areas threatened by inundation would also provide incidental flood protection to adjacent areas with higher elevations, but we do not explicitly estimate the area.

For the sake of some search engines, Table 7 has state-specific estimates for Maine, Massachusetts, Rhode Island, New Hampshire, Connecticut, New York, New Jersey, Delaware, Maryland, Virginia, North Carolina, South Carolina, Georgia, Florida, Mississippi, Alabama, California, Texas, Washington, Oregon, and Hawaii. I would not take the Louisiana estimate too seriously--loss of the delta itself is the issue. There are also region-specific area loss estimates. This report is about global warming and climate change.

A. The following paragraph also appeared in the published article; but whether or not it was a reasonable thing to say then, it was clearly obsolete after 1992 as emissions scenarios came down. For a discussion on the downward revision of sea level rise scenarios, see Chapter 8 of *The Probability of Sea Level Rise*

"Although the most recent reports have been at the lower end of the range, recent press accounts have exaggerated the extent to which those reports should be viewed as downward revisions. Meier's (1990) recent paper (entitled *Reduced Rise in Sea Level*), led major newspapers to report that sea level projections are being lowered. However, as Figure 2 shows, the main reason the projections were lower was that Meier changed his target year from 2100 to 2050. The Intergovernmental Panel on Climate Change (1990) released projections that were lower than most previous studies, based on the assumption that Antarctica will accumulate more ice in response to global warming, an assumption that has not met universal acceptance from glaciologists. Clearly, the models are unable to adequately estimate how much sea level will rise; and the

experts disagree. Under these circumstances, revisions of sea level projections are just as likely to result from changes in who chairs the panel that forecasts sea level rise as from any new information."

Table 1. Comparison of This Study's Baseline Data for Vegetated Wetlands (1985) with NOAA Wetlands Inventory

Region (Sites)	BASELINE DATA		NOAA ^a	
	Percent of Coast in Sample	Wetland Area (sq. mi.)	Sampling Error (sq. mi.)	Wetland Area (sq. mi.)
Northeast (4)	3.4	600	389	382
Mid-Atlantic (7)	8.6	746	245	2,080
South Atlantic (8)	10.1	3,813	848	3,697 ^b
Louisiana ^a (7)	13.7	4,835	876	4,491
Gulf except LA (14)	12.2	3,087	1,169	3,608
SW/W Florida ^a (6)	10.7	1,869	957	NA
Other Gulf (8)	13.1	1,218	673	NA
West (6)	4.9	64	45	195
United States (46)	9.7	13,145	2,105 ^b	14,723

Notes:

NA Not applicable.

a Alexander et al. (1986) also estimate the area of tidal flats for several states; we present only the sum of their estimates for vegetated wetlands.

b We have modified the data from Alexander et al. to account for differences in the definition of coastal wetlands for North Carolina. Alexander et al. include all wetlands in coastal counties regardless of elevation, while Park et al. excluded wetlands above 12 ft NGVD. Because of extensive swamps above 12 ft NGVD in North Carolina's coastal counties, Alexander et al. found the area of coastal swamps to be 8.4 times the area of marsh, while the boundaries of the sample of Park et al. found only 1.6 times as much.

c Standard deviation of the estimate of the sum (i.e., sample times the square root of the sample size).

NOAA Source:

Alexander, C.E., M.A. Broutman, and D.W. Field. 1986. An Inventory of Coastal Wetlands of the USA. Rockville, MD: National Oceanic and Atmospheric Administration.

Table 2. Regional and National Wetland Losses for the Trend and 1.0 Meter Sea Level Rise Scenarios (percent loss of current area)

Region	Current Wetland Area (sq mi)	Trend		1.0 Meter	
		Standard ^b	Total ^b	Standard ^b	Nonec

Northeast	600	7	16	10	1 ^a
Mid-Atlantic	746	-5	70	46	38
South Atlantic	3,814	-2	64	44	40
South/Gulf					
Coast of Florid ^a	1,869	-8	44	8 ^a	7 ^a
Louisiana ^d	4,835	52	85	85	85
FL panhandle,					
AL, MS, & TX	1,218	22	85	77	75
West ^b	64	-111	56	-688	-809
United States	13,145	17	66	49	50
Confidence Intervals:					
95% Low	--	9	50	29	26
95% High	--	25	82	69	66

Notes:

- a Results are not statistically significant; sampling error exceeds estimate of wetlands lost.
- b This anomalous result is from small sample size. The impact on the nationwide results is negligible.
- c Total protection refers to all shores being diked or bulkheaded; standard protection refers to only currently developed areas being protected.
- d An evaluation of the management options currently contemplated for Louisiana (e.g., restoring natural deltaic processes) was outside the scope of this study.

Table 3. National Wetland Losses By the Year 2100
(percent of current area)

	Baseline	50 cm	100 cm	200 cm
No Protection:				
Best Estimate	NC	30	50	52
95% Low CI	NC	17	26	29
95% High CI	NC	43	66	76
Standard Protection:				
Best Estimate	17	32	49	56
95% Low CI	9	20	29	33
95% High CI	25	45	69	80
Total Protection:				
Best Estimate	NC	50	66	78
95% Low CI	NC	38	50	66
95% High CI	NC	61	82	90

Notes: NC Not calculated.

Table 4
Value of Lost Dry and Wetland By the Year 2100
(billions of dollars)

Baseline	50 cm	100 cm	200 cm
----------	-------	--------	--------

Wetlands				
Best Estimate	15.0	31.2	47.5	53.0
Low	5.2	11.5	17.5	19.5
High	43.1	82.4	128.5	143.7
Undeveloped Dry Land				
Best Estimate	12.7	23.5	45.9	74.6
Low	5.8	12.8	20.6	28.6
High	18.5	34.3	71.2	120.6
Developed Dry Land Used for Building Dikes				
Best Estimate	0.0	17.7	25.6	39.3
Low	0.0	9.5	13.7	21.6
Estimate	0.0	33.0	47.8	73.5

NOTE: Calculations are based on the current level of development and on the assumption that currently developed areas will be protected.

Table 5. Cost of Protecting Developed Sheltered Shores Through 2100 (billions of dollars)

Region	Baseline	50 cm	100 cm	200 cm
Northeast	0.41	2.66	6.22	22.64
Mid-Atlantic	0.31	2.03	5.12	13.97
Southeast	0.91	3.43	8.91	24.59
West	0.04	0.88	1.82	4.10
United States	2.00	9.00	22.07	65.30
Confidence Intervals:				
95% Low	1.20	4.98	10.82	29.60
95% High	2.80	13.02	33.32	100.99

TABLE 6. COST FUNCTION FOR FLORIDA'S ATLANTIC COAST

Distance Offshore (miles)	Available Sand (millions yards ³)	Unit Cost (\$/yard ³)
0-1	66	4
1-2	87	5
2-3	122	6
3-4	48	7
4-5	0	8
5+	Plenty	10

Source: Sand quantities are based on surveys by the Corps of Engineers. Unit sand cost estimates up to five miles assume that dredges pump the sand onto the shore and use the generally accepted rule-of-thumb that each additional mile offshore adds \$1/yard³ for the additional booster pumps. For all distances greater than five miles, barges and dump trucks would be employed at a cost of \$10/yard³.

Table 8. Cost of Elevating Roads and Structures

Data	Gulf	South Atlantic	Mid-Atlantic & Northeast	USAA
Shoreline Length (mi)	565	522	511	1,598
Bayside Area (mi ²)	543	72	90	705
Oceanside Area (mi ²)	975	501	612	2088
Building Density (units/mi ²)				
Mean	377	586	1,726	NC
Standard Deviation	282	469	1,177	NC
Standard Deviation of Mean	85	130	294	NC

Cost (billions of dollars)

50 cm	17.4	4.2	10.8	32.4 + 3.5
100 cm	32.7	7.8	21.6	62.1 + 6.6
100 cm (Alternative cost)	51.6	34.2	84.3	170.1 + 17.6
200 cm	81.6	54.3	150.3	286.2 + 29.6

Cost Equations^b

$$\text{Cost (50 cm)} = 6,580,400 * \text{Length} * \text{Bayside_Area/Area} + 65,947 * \text{Bayside_Area} * \text{Density}$$

$$\text{Cost (100 cm)} = 12,327,000 * \text{Length} * \text{Bayside_Area/Area} + 123,542 * \text{Bayside_Area} * \text{Density}$$

Alternative

$$\text{Cost (100 cm)} = 6,903,000 * \text{Length} + 69,518 * \text{Area} * \text{Density}$$

$$\text{Cost (200 cm)} = 10,952,000 * \text{Length} + 110,287 * \text{Area} * \text{Density}$$

Notes:

NC Not calculated

a Results are for the Atlantic and Gulf coasts only; the Development of Pacific Coast barriers is negligible.

b Mean Cost is based on plugging in mean density into the equations. Confidence intervals based on sampling error can be derived by plugging in the standard deviation of the mean.

Table 7a Cumulative Cost of Sand to Protect the United States' Open Coast
(Low Scenario for Required Sand)

		FIXED UNIT COST FOR SAND				INCREASING UNIT COST FOR SAND		
		Trend	50 cm	100 cm	200 cm	50 cm	100 cm	200 cm
Northeast:	ME ^a	23	119	217	412	155	384	874
	NH ^a	8	39	73	142	55	135	305
	MA ^a	168	490	842	1,546	540	990	2,230
	RI ^a	16	92	161	298	100	197	464
	CT ^a	102	516	944	1,800	710	1,562	3,283
Mid-Atlantic:	NY ^a	144	770	1,374	2,581	876	1,824	3,960
	NJ ^a	158	902	1,733	3,493	1,038	2,438	5,538
	DE	5	34	71	162	34	83	230
	MD	6	35	83	213	41	123	375
	VA	30	201	387	798	272	587	1,314

Southeast:	NC	137	656	1,271	3,240	744	1,645	5,305
	SC	184	1,158	2,148	4,348	2,232	4,548	9,681
	GA	26	154	263	640	301	661	1,520
	FL(Atlantic)	120	787	1,938	8,565	850	1,934	8,556
	FL(Gulf)	149	904	1,688	4,092	1,180	2,962	8,986
	AL	11	59	105	260	68	130	472
	MS	13	72	128	370	90	198	959
	LA	1,956	2,623	3,493	5,232	5,355	7,251	11,084
	TX	350	4,188	8,490	17,608	5,773	12,857	27,853
West:	CA	36	174	324	626	203	437	1,170
	OR ^a	22	61	153	336	70	241	701
	WA ^a	52	143	360	794	182	662	1,752
	HA ^a	74	338	647	1,268	435	1,101	2,464
United States		3,790	14,515	26,893	58,824	21,304	42,950	99,075

Notes: a Indicates states where estimate was based on extrapolating a representative site to the entire state. All other states have 100% coverage.

Table 7b. Cumulative Cost of Sand to Protect the United States' Open Coast
(High Scenario for Required Sand)

		FIXED UNIT COST FOR SAND			INCREASING UNIT COST FOR SAND		
		50 cm	100 cm	200 cm	50 cm	100 cm	200 cm
Northeast:	ME ^a	427	751	1397	914	1722	3339
	NH ^a	139	253	480	304	588	1,155
	MA ^a	1786	2954	5291	2650	4709	8827
	RI ^a	332	560	1015	531	986	1897
	CT ^a	1851	3266	6097	3383	6214	11876
Mid-Atlantic:	NY ^a	2776	4775	8772	4300	7826	14879
	NJ ^a	2576	4304	7851	3923	6970	13228
	DE	110	195	381	143	292	616
	MD	125	230	471	206	415	897
	VA	739	1220	2220	1209	2049	3801
Southeast:	NC	2348	4292	8933	3648	7259	15877
	SC	4236	7018	12794	9421	15910	29388
	GA	558	956	1803	1316	2310	4428
	FL(Atlantic)	2306	4130	9118	4306	8864	21334
	FL(Gulf)	2297	4090	8508	4492	8973	20019
	AL	161	282	585	224	526	1283
	MS	197	344	766	412	880	2224
	LA	6768	8792	12840	14466	18919	27826
	TX	8483	15143	28983	12838	23818	46637
West:	CA	1546	2770	5217	3477	6536	12654
	OR ^a	422	1081	2399	916	2563	5858
	WA ^a	998	2556	5672	2256	6151	13941
	HA ^a	2869	5303	10171	5994	11348	22058
United States		44,059	75,267	141,771	81,334	145,834	284,049

Notes: a Indicates states where estimate was based on extrapolating a representative site to the entire state. All other states have 100% coverage.

Table 9. Summary of Nationwide Results
(billions of dollars unless otherwise stated)

	Baseline	50 cm	100 cm	200 cm
If No Shores Are Protected				
Dryland Lost (sq mi)	N.C.	3,315-7,311	5,123-10,330	8,191-15,394
Wetlands Lost (%)	N.C.	17-43	26-66	29-76
If Developed Areas Are Protected				
Dryland Lost (sq mi)	1470-4686	2,200-6,100	4,100-9,200	6,400-13,500
Wetlands Lost (%)	9-25	20-45	29-69	33-80
Value of Lost Land		52-130	86-212	112-297
Wetlands	5-43	11-82	17-128	19-144
Undeveloped Land	6-19	13-34	21-71	29-121
Land for Dikes	16-47	9-33	14-48	22-74
Cost of Coastal Defense		55-123	143-305	402-645
Open Coast:				
Sand	4	15-81	27-146	59-284
Elevate Structures	0	29-36	62-170	257-316
Sheltered Shores				
Dike Construction	0	5-13	11-33	30-101
Total Cost of Inundation and Erosion	20-51	128-232	270-475	576-880
If All Shores Are Protected				
Wetlands Lost (%)	N.C.	38-61	50-82	66-90
N.C. = Not Calculated				

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To: Zachary M. Candelario/CEA/EOP

cc:

Subject: Vostok temperature record

Dear Zachary,

The attached ASCII file contains the Vostok isotope temperature record for the past 240 kyr. The temperature variations are relative to the mean annual surface temperature at Vostok (i.e., -55.5 degrees C).

Sincerely,

Tom Boden

Thomas A. Boden
Carbon Dioxide Information Analysis Center
World Data Center-A for Atmospheric Trace Gases
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, Tennessee USA 37831-6335

Telephone: 423 241 4842

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e-mail: tab@ornl.gov

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"Data worth collecting are worth saving"



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Historical carbon dioxide record from the Vostok ice core

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J.M. Barnola, D. Raynaud, C. Lorius

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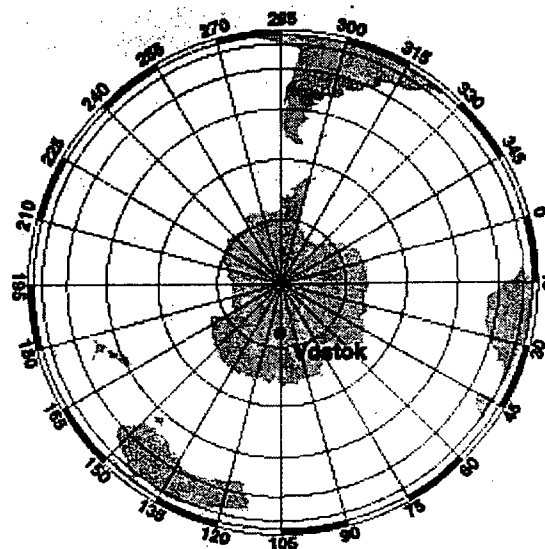
Period of Record

160,000-1,700 years BP

Methods

The 2083-m-long ice core recovered by the Soviet Antarctic Expeditions at Vostok has been used to extend the ice record of atmospheric CO₂ to 160,000 years ago through analysis of the air bubbles trapped in the core. Because air bubbles do not close at the surface of the ice sheet but only near the firm-ice transition (that is, at ~90 m below the surface at Vostok), the air extracted from the ice is younger than the surrounding ice (Barnola et al. 1991). Using semiempirical models of densification applied to past Vostok climate conditions, Barnola et al. (1991) reported that the age difference between air and ice may be ~6000 years during the coldest periods instead of ~4000 years, as previously assumed. Ice samples were cut with a bandsaw in a cold room (at about -15°C) as close as possible to the center of the core in order to avoid surface contamination (Barnola et al. 1983). Gas extraction and measurements were performed with the "Grenoble analytical setup," which involved crushing the ice sample (~40 g) under vacuum in a stainless steel container without melting it, expanding the gas released during the crushing in a pre-evacuated sampling loop, and analyzing the CO₂ concentrations by gas chromatography (Barnola et al. 1983). The analytical system, except for the stainless steel container in which the ice was crushed, was calibrated for each ice sample measurement with a standard mixture of CO₂ in nitrogen and oxygen. For further details on the experimental procedures and the dating of the successive ice layers at Vostok, see Barnola et al. (1987, 1991) and Lorius et al. (1985).

*Rel. to the present
Deg. Surface temperature*



*Vostok, Antarctica
78°28' S, 106°48' E
3488 m above MSL*

Trends

An atmospheric CO₂ record for the past 160,000 years was obtained from the 2083-m-long ice core recovered by the Soviet Antarctica Expeditions at Vostok (East Antarctica). This CO₂ record is probably the purest available, covering the last climatic cycle (Barnola et al. 1987). When the Vostok ice core data were compared with other ice core data (Delmas et al. 1980; Neftel et al. 1982) for the past 30,000 - 40,000 years, good agreement was found between the records: all show low CO₂ values [~200 parts per million by volume (ppmv)] during the Last Glacial Maximum and increased atmospheric CO₂ concentrations associated with the glacial-Holocene transition. Barnola et al. (1987) found that over the 160,000-year time scale a high correlation existed between CO₂ concentrations and Antarctic climate, with significant oscillatory behavior of CO₂ between high levels during interglacial periods and low levels during glacial periods. According to Barnola et al. (1991) these measurements and the results obtained from other ice cores indicate that, at the beginning of the deglaciations, the CO₂ increase either was in phase or lagged by less than ~1000 years with respect to the Antarctic temperature, whereas it clearly lagged behind the temperature at the onset of the last glaciation. Barnola et al. (1987) reported that long-term CO₂ changes were dominated by marked glacial-interglacial oscillations between ~190 - 200 and 260 - 280 ppmv and that a period of ~20,000 years similar to the orbital precession period appeared in the decreasing CO₂ trend during most of the last glaciation and is supported by spectral analysis.

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Date revised 7/1/97

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*** Historical CO2 Record from the Vostok Ice Core (September 1994) ***
***
*** Source: J.M. Barnola ***
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***           38402 Saint Martin d'Heres Cedex, France ***
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***           Arctic and Antarctic Research Institute ***
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***           St. Petersburg 199226, Russia ***
*****

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	Mean		
Depth	Age of	age of	CO2
(m)	the ice	the air	concentration
	(yr BP)	(yr BP)	(ppmv)
126.4	4050	1700	274.5
173.1	5970	3530	270.0
250.3	9320	6800	252.0
266.0	10040	7500	257.0
302.6	11870	9140	259.0
375.6	16350	12930	245.0
426.4	20330	16250	193.0
474.2	24280	20090	194.5
525.1	28530	24390	200.0
576.0	32680	29720	198.0
602.3	34770	30910	223.0
625.6	36600	32800	207.0
651.6	38600	34870	210.0
700.3	42320	38660	207.0
748.3	45970	42310	178.5
775.2	48000	44350	200.0
800.0	49850	46220	207.7
852.5	53770	50150	201.0
874.3	55450	51770	201.0
902.2	57660	53860	219.5
926.8	59670	55780	214.5
951.9	61790	57800	206.5
975.7	63880	59770	201.0
1002.5	66230	62080	192.0
1023.5	68040	63960	193.0
1052.4	70470	66540	205.5
1074.8	72330	68490	226.5
1101.4	74500	70770	243.0
1124.2	76330	72690	235.0
1148.7	78270	74720	230.5

1175.0	80320	76860	219.5
1225.7	84220	80900	222.5
1251.5	86220	82920	234.0
1274.2	87980	84700	218.8
1299.3	89940	86680	210.0
1322.5	91760	88520	221.5
1349.0	93860	90630	226.0
1374.8	95910	92700	234.0
1402.5	98130	94940	226.5
1425.5	100000	96810	236.0
1451.5	102210	98950	225.0
1476.1	104410	101040	229.0
1499.6	106610	103130	238.5
1526.3	109240	105620	234.5
1547.0	111250	107650	244.0
1575.2	113850	110510	233.5
1598.0	115850	112700	240.0
1626.5	118220	115290	276.0
1651.0	120170	117410	271.5
1676.4	122100	119500	280.0
1700.9	123900	121430	271.0
1726.8	125730	123380	265.3
1747.3	127150	124880	267.0
1774.1	129020	126770	275.0
1802.4	131030	128780	266.5
1825.7	132700	130460	275.0
1850.5	134510	132280	266.0
1875.9	136450	134170	296.5
1902.0	138660	136170	266.0
1928.0	141170	138410	246.5
1948.7	143440	140430	231.0
1975.3	146860	143370	217.0
1998.0	150330	146340	191.0
2025.7	154980	150700	200.5
2050.3	159100	154970	191.3
2077.5	163670	159690	195.5

The record presented here was published in Barnola et al. (1987). Please refer to Barnola et al. (1991), which presents new CO₂ measurements and age of air determinations. According to Barnola et al. (1991), the agreement between the two sets is good although the new results are slightly lower than the previous ones between 10 and 50 kyr BP.

The reported CO₂ concentration for each depth level takes into account the correction of +3 ppmv for the effect of water vapor where unambiguous water-vapor peaks occurred.

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CLIMATE CHANGE

State of Knowledge



Historical carbon dioxide record from the Siple Station ice core



A. Neftel, H. Friedli, E. Moor, H. Lötscher, H. Oeschger, U. Siegenthaler, B. Stauffer

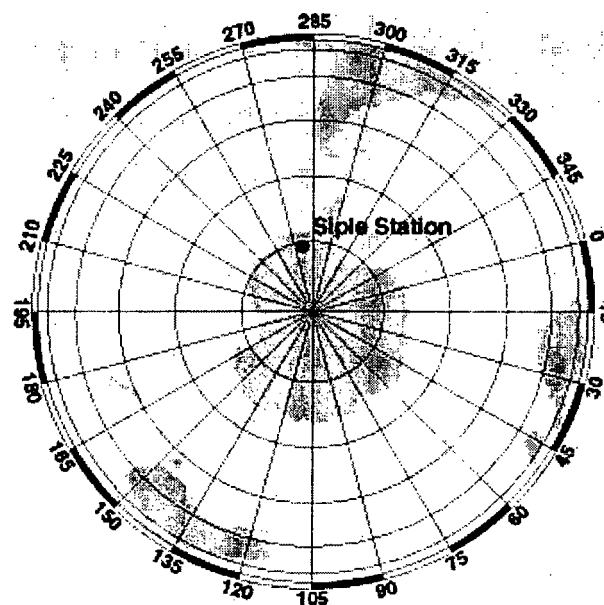
Physics Institute, University of Bern, CH-3012 Bern, Switzerland

Period of Record

1734-1983

Methods

Determinations of ancient atmospheric CO₂ concentrations for Siple Station, located in West Antarctica, were derived from measurements of air occluded in a 200-m core drilled at Siple Station in the Antarctic summer of 1983-84. The core was drilled by the Polar Ice Coring Office in Nebraska and the Physics Institute at the University of Bern. The ice could be dated with an accuracy of approximately ± 2 years to a depth of 144 m (which corresponds to the year 1834) by counting seasonal variations in electrical conductivity. Below that depth, the core was dated by extrapolation (Friedli et al. 1986). The gases from ice samples were extracted by a dry-extraction system, in which bubbles were crushed mechanically to release the trapped gases, and then analyzed for CO₂ by infrared laser absorption spectroscopy or by gas chromatography (Neftel et al. 1985). After the ice samples were crushed, the gas expanded over a cold trap, condensing the water vapor at -80°C in the absorption cell. The analytical system was calibrated for each ice sample measurement with a standard mixture of CO₂ in nitrogen and oxygen. For further details on the experimental and dating procedures, see Neftel et al. (1985), Friedli et al. (1986), and Schwander and Stauffer (1984).



Siple Station, Antarctica
75°55' S, 83°55' W

Trends

An atmospheric CO₂ record for the past 200 years was obtained from the Siple Station ice core. At shallow depths, atmospheric air still circulates through the open pores (Friedli et al. 1986). The enclosed air was younger than the surrounding ice because the enclosure of air in bubbles occurred only between depths of 64 and 76 m. On the basis of porosity measurements, investigators determined that the time lag between the mean age of the gas and the age of the ice was 95 years and that the duration of the close-off process was 22 years (Schwander and Stauffer 1984). Neftel et al. (1985) concluded that the atmospheric CO₂ concentration ca. 1750 was 280±5 parts per million by volume (ppmv) and that it increased by 22.5% to 345 ppmv in 1984 essentially because of human factors. Graphs in Friedli et al. (1986) also reported that the preindustrial (pre-1800) CO₂ concentration was ~280 ppmv.

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*** Historical CO2 Record from the Siple Station Ice Core ***
***
*** September 1994 ***
***
*** Source: A. Neftel ***
***           H. Friedli ***
***           E. Moor ***
***           H. Lotscher ***
***           H. Oeschger ***
***           U. Siegenthaler ***
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***           CH-3012 Bern, Switzerland ***
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Depth (m)	Samples measured	Date of ice (yr AD)	Date air enclosed (yr AD)	CO2 concentration in extracted air (ppmv)
187.0-187.3	10	1663	1734-1756	279
177.0-177.3	10	1683	1754-1776	279
162.0-162.3	9	1723	1794-1819	280
147.0-147.2	10	1743	1814-1836	284
128.0-129.0	47	1782	1842-1864	288
111.0-112.0	26	1812	1883-1905	297
102.0-103.0	26	1832	1903-1925	300
92.0-93.0	25	1850	1921-1943	306
82.0-83.0	28	1867	1938-1960	311
76.2-76.6	11	1876	1947-1969	312
72.4-72.7	11	1883	1954-1976	318
68.2-68.6	8	1891	1962-1983	328

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Average      CO2
depth  Gas  concentration
(m)    (yr AD) (ppmv)
187.70 1744 276.8
177.50 1764 276.7
168.30 1791 279.7
154.89 1816 283.8
142.75 1839 283.1
140.75 1843 287.4
138.20 1847 286.8
134.47 1854 288.2
126.80 1869 289.3
123.80 1874 289.5
121.80 1878 290.3
116.82 1887 292.3

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110.20	1899	295.8
108.80	1903	294.8
107.20	1905	296.9
105.25	1909	299.2
101.80	1915	300.5
98.80	1921	301.6
95.17	1927	305.5
90.77	1935	306.6
86.80	1943	307.9
81.22	1953	312.7

Data in the first table were published in Neftel et al. (1985); data in the second table were published by Friedli et al. (1986).

CO2 concentrations are expressed in parts per million by volume.

Draft 10, Do Not Cite, 6/17/98

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