Effect of Climate Change on Sea Level Rise and the Implications for World Agriculture

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The global warming from the greenhouse effect could raise sea level ≈ 1 m in the next century by expanding ocean water, melting mountain glaciers, and causing ice sheets in Greenland to melt or slide into the oceans. Such a rise would inundate coastal wetlands and lowlands, erode beaches, increase the risk of flooding, and increase the salinity of estuaries, aquifers, and wetlands. This article presents an overview of the causes, effects, and responses to sea level rise, drawing on previous studies of the impacts on coastal

cities, ocean beach resorts, wetlands, and water supplies.

We also attempt to highlight implications for agriculture; but the task is made more difficult by the failure of previous studies to examine these impacts. As the director of the Environmental Protection Agency (EPA) program that initialed most of those studies, we feel obliged to explain why: 1) Until recently, our mandate was only to examine impacts on the United States; 2) considerably $<1\%$ of U.S. farmland is in the area threatened by sea level rise, whereas

all of our coastal resorts and wetlands would be threatened: 3) on a nationwide basis, other impacts of global warming on agriculture are clearly far more important; and 4) the primary objective of the case studies was to identify opportunities where private and public operations should be modified today in anticipation of future sea level rise, and we were unable to envision any studies of agriculture likely to identify such opportunities.

Recently, however, the emphasis has shifted from anticipating and adapting to sea level rise, to identifying all the important impacts-worldwide, and regardless of the need to prepare today-for the purpose of supporting worldwide deliberations on the need to curtail global warming. Many agencies are beginning to support assessments of the impacts of global warming. One can therefore anticipate that in the next few years, numerous studies will emerge that shed far more light on the implications of sea level rise for agriculture than we can offer here.

CLIMATE AND SEA LEVEL

The level of the oceans has always fluctuated with changes in global temperatures. During ice ages when global temperatures were 5C (9F) lower than today, much of the ocean's water was tied up in glaciers and sea level was often > 100 m (300 ft) lower than today (Donn et al., 1962; Kennett, 1982; Oldale, 1985). However, during the last interglacial period (100,000 years ago) when temperatures were $\approx$ 1C (2F) higher, sea level was $\approx$ 6 m (20 ft) higher than today (Mercer, 1970).

When discussing shorter periods of time, one must distinguish worldwide (eustatic) sea level rise from relative sea level rise. Although climate change alters 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 most coasts are sinking (and a few are emerging) relative sea level rise varies from > 1 m (3 ft) per century in Louisiana and parts of California and Texas to 30 cm (1 ft) per century along most of the

Fig. 1. Time series graph of sea level trends for New York, Charleston, Miami, Galveston, and Sitka.

Atlantic and Gulf Coasts, to a slight drop in much of the Pacific Northwest (Fig. 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 15 cm (4 to 6 inches) (Barnett, 1984; Fairbridge and Krebs, 1962), much of which has been attributed to the global warming of the last century (Meier, 1984; Gornitz et al., 1982).

A 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. Hughes (1983) and Bentley (1983) have estimated that it would take 200 to 500 years for a complete disintegration of west Antarctica, which would raise sea level $\approx$ 6 m (20 ft). Most recent assessments, however, have focused on the likely rise by the year 2100. Recent estimates of sea level rise, which generally fall into the range of 50 to 200 cm (2 to 7 ft), are illustrated in Fig. 2.

Although most studies have focused on the impact of global warming on global sea level, 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 < 10%; sea level could actually drop, however, at Cape Horn and along the coast of Iceland. Climate change could also have local influences on sea level by changing ocean currents, winds, and atmospheric pressure; we found no reports estimating these impacts.

EFFECTS

In this and the following section, we present the effects and responses separately. However, we caution the reader that the distinction is largely academic and is made solely for presentation purposes. In many cases, the responses to sea level rise are sufficiently well-established and the probability of no response sufficiently low that it would be misleading to discuss the potential effect

Fig. 2. Estimates of future sea level rise. Sources: Environmental Protection Agency, *Projecting Future Sea Level Rise*, 1983. National Research Council, *Responding to Changes in Sea Level: Engineering Implications*, 1987. National Research Council, *Glaciers, Ice Sheets, and Sea Level*, 1985. National Research Council, "Probable Future Changes in Sea Level Resulting from Increased Atmospheric Carbon Dioxide," *Changing Climate*, 1983. World Meteorological Organization, *International Assessment of the Role of Carbon Dioxide and Other Greenhouse Gases in Climate Variations and Associated Impacts*, 1985.

without discussing responses. For example, much of Manhattan Island is <2 m above high tide; the effect of a rise in sea level would almost certainly be an increased use of coastal engineering structures and not the inundation of downtown New York.

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 are found along the Gulf Coast and along 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.

Inundation

The dry land within 2 m of high tide includes forests, farms, low parts of some port cities, cities that sank after they were built and are now protected with levees, and the bay sides of barrier islands. Economically, the most important vulnerable areas are the recreational barrier islands and spits of the Atlantic and Gulf Coasts, where property is often worth over \$2.5 million/ha. Typically, the ocean-front block of an island ranges from 2 to 3 m (6 to 10 ft) above high tide, while the bay side is < 1 m (2 to 3 ft) above high water. The cost of protecting coastal cities could also be considerable; Boston, New York, Charleston, Miami, and New Orleans all have substantial developments built on reclaimed land just above (or in the case of New Orleans, just below) sea level. When smaller cities and moderate-density housing developments are considered, a 1-m rise in sea level threatens $\approx 2500 \text{ km}^2$ (1000 mi^2) of developed land (Park et al., 1989).

Nevertheless, most of the 17,000 km^2 (7000 mi^2) threatened by a 1-m rise is undeveloped farmland or forests that have supported agriculture in the past and may in the future (Park et al., 1989). This low land includes citrus-growing areas in Florida, rice paddies in Louisiana, and grain and vegetable farms along the eastern shores of Delaware and Chesapeake Bay, as well as the coastal plains of the Carolinas and Georgia. Due to the popularity of the coast, many of these areas are being rapidly developed and are thus unlikely to still be under cultivation by the time sea level rise threatens them with inundation.

To a large degree, the future vulnerability of coastal wetlands will depend on whether these areas remain under cultivation. Coastal

wetlands are generally found between the highest tide of the year and mean sea level. Wetlands have been able to keep pace with the past rate of sea level rise because they collect sediment and produce peat upon which they can build. Thus, 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 for wetlands to keep pace (Fig. 3), so sea level rise would cause a net loss in wetland acreage as the ecosystem shifts up the coastal plain, with the loss being greatest in Louisiana (Titus et al., 1984; Titus, 1986). Although such a loss in area would reduce the contribution of wetlands to the total biological production of a given estuary, remaining wetlands would still provide habitat for juvenile crabs, shrimp, and other commercially important species that depend more on the length of marsh shorelines than the total area. To the extent that land just above sea level remains undeveloped, the portion of the shore bordered by coastal wetlands will remain relatively unchanged.

If coastal lowlands are developed and protected with bulkheads and levees, however, wetlands will be squeezed between the estuary and the shore-protection structures (Fig. 3, lower right). Preliminary studies have estimated that if the development in coastal areas is removed to allow new wetlands to form inland, a 1-m rise would cause a loss of 25% to 65% of the U.S. coastal wetlands; if levees and bulkheads are erected to protect today's dry land, the loss could be 50% to 80% (EPA, 1989). The difference in wetland shoreline length, however, would be much greater (Fig. 3).

Although inundation does not pose a major threat to U.S. agriculture, the story would be different in countries whose nationwide production depends in large measure on cultivated river deltas. Broadhus et al. (1986), for example, found that a 2-m rise in sea level could inundate 20% of the farmland of both Bangladesh and Egypt.

Erosion

Erosion threatens valuable land along the coast that is high enough to avoid direct inundation, and is thus generally viewed as a more immediate problem than the inundation of the baysides. A rise in sea level can cause an ocean beach to retreat by considerably more than the retreat due to inundation alone (Fig. 4). 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 that comprises most of the active "surf zone." While inundation alone is determined by the slope of the land just above the water, Bruun (1962) and others have shown that the total shoreline retreat from a rise in sea level depends on the average slope of the entire beach profile.

Fig. 3. Evolution of marsh as sea rises. Coastal marshes have kept pace with the slow rate of sea level rise that has characterized the last several thousand years. Thus, the area of marsh has expanded over time as new lands were inundated. If, in the future, sea level rises faster than the capability of the marsh to keep pace, the marsh area will contract. Construction of bulkheads to protect economic development may prevent new marsh from forming and result in a total loss of marsh in some areas.

Fig. 1. The Bruun Rule. (A) Initial condition; (B) immediate inundation when sea level rises; (C) subsequent erosion due to sea level rise. A rise in sea level immediately results in shoreline retreat due to inundation, shown in the first two examples. However, a 1-m rise in sea level implies that the offshore bottom must also rise 1 m. The sand required to raise the bottom (X') can be supplied by beach nourishment. Otherwise, waves will erode the necessary sand (X) from upper part of the beach as shown in (C).

Previous studies suggest that a 1-m rise in sea level would generally cause beaches to erode 50 to 100 m from the Northeast 10 Maryland (Kyper and Sorensen, 1985; Everts, 1985); 200 m along the Carolinas (Kana et al., 1984); 100 to 1000 m along the Florida coast (Bruun, 1962); 200 to 400 m along the California coast (Wilcoxen, 1986); and perhaps several kilometers in Louisiana. Because most U.S. recreational beaches are wide at high tide, even a 0.3-m rise in sea level would require a response.

Coastal geologists have often asserted that erosion is only a problem when there is a building near the shore. Farmers along the eastern shore of Chesapeake Bay, for example, are aware that they are gradually losing area, but the losses are usually slow enough to tolerate. Few farmers are willing to forgo the purchase of critical machinery so that they can build a bulkhead that takes away less than a few tenths of a percent of their land each year, especially when it is cheaper to buy a few hectares than to build the bulkhead.

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 1-m rise in sea level would thus enable a 15-year storm 10 flood many areas that today are only flooded by a 100-year storm (Kana et al., 1984; Leatherman, 1984). 2) Beach erosion would leave particular properties more vulnerable to storm waves. 3) Higher water levels would increase flooding due 10 rain-storms by reducing coastal drainage (Titus et al., 1987). Finally, 4) 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 flood-

ing. 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 (Sorensen et al., 1984; Kyper and Sorensen, 1985; Dean et al., 1987). In areas like New Orleans that are drained artificially, the increased need for pumping could exceed current capacities.

In the United States, property damage, not agricultural losses, is usually the greatest problem with flooding. However, the saltwater contamination of crops can be as important as the direct threat to property and public safety in low-lying nations such as the Republic of Maldives and Bangladesh. A 1973 tropical cyclone in the Bay of Bengal killed > 100,000 people, but the threat that the resulting famine would kill even more people inspired an unprecedented international relief effort that included the first major effort by rock-and-roll musicians to focus their financial resources and public relations capabilities on famine, the Bangladesh concert and album produced by ex-Beatle George Harrison in 1972.

Saltwater intrusion

A rise in sea level would also increase the average salinity in rivers, bays, wetlands, and aquifers that 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 Delaware and Chesapeake Bays, and for converting cypress swamps in Louisiana to open lakes. Moreover, New York, Philadelphia, and much of California's Central Valley get their water from areas that are just upstream from areas where the water is salty during droughts. A number of aquifers are recharged by fresh surface water that could become salty if sea level rises, such as the Potomac-Raritan-Magothy aquifer in central New Jersey and Florida's Biscayne aquifer. Agriculture is a major water user in all of these regions.

RESPONSES

We divide this discussion into two parts: coastal defense and saltwater intrusion.

Coastal defense

The possible responses to inundation, erosion, and flooding 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 and others have used dikes and windmills to prevent inundation from the North Sea; these efforts have protected farmland as well as developed areas. By contrast, many cities have been rebuilt landward as shores eroded; 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 Corps of Engineers and coastal states regularly pump sand from offshore to counteract beach erosion. Venice, Italy, 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 shorelines in agricultural areas would retreat naturally (Dean et al., 1987). This conclusion has generally been based on estimates 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. In areas where levees will eventually be built, engineers should gradually incorporate accelerated sea level rise into design of public works, but there is little need for major initiatives today; levees can generally be built in a matter of decades.

Studies on the possible responses of barrier islands and moderately developed mainland communities show less agreement on the likely response, but generally suggest that environmental factors

would be as important as economics. In our view, most moderate-density barrier island communities will choose to raise their islands at first, but as sea level rises and shore-protection costs escalate, they will find retreat increasingly appealing. Heavily developed islands like Miami Beach may never retreat, while lightly developed islands such as the Outer Banks of North Carolina are already retreating (Titus, 1990a).

Given the economic importance of keeping a beach, natural shorelines along the oceans are not likely to be lost; the wetland shorelines along estuaries, however, seem more vulnerable. Bulkheads holding back the bay would be much less expensive than the projects necessary to hold back the ocean; in many cases, the shorefront property owners could afford the bulkheads themselves. Thus, while economics alone would eventually motivate a retreat along many barrier islands, the public interest of preserving wetland shorelines would be the primary reason to retreat along sheltered mainland shores.

What can we do today to facilitate the future retreat that may otherwise be thwarted by economics along wetland shores? Many states currently require new construction to be set back from the shore, but this approach will not solve the problem. Much of the coast is already developed, and prohibitions of new development in areas threatened by a 50- to 200-cm rise in sea level would substantially reduce property values of coastal farmland in developing areas and perhaps thus require compensation under "taking clause" of the Fifth Amendment; the costs of buying all the farms in coastal lowlands, however, would probably be prohibitive.

We have argued elsewhere that in many cases it would be more rational to permit areas to be developed with the stipulation that they will be abandoned as necessary to permit wetlands to migrate inland (Titus, 1986). Nevertheless, keeping coastal farms as farmland will almost certainly be a major part of any comprehensive strategy to protect coastal ecosystems.

Saltwater intrusion

The responses to saltwater intrusion fall broadly into two categories: increasing the amount of fresh water flowing into the estuary during droughts and decreasing consumptive withdrawals. Hull and Titus (1986) found that an additional reservoir could offset the salinity increases in the Delaware River. Lettenmaier et al. (1989), however, suggest decreased agricultural water consumption would probably be required to achieve the required increases in fresh water flowing into San Francisco Bay. If consumptive withdrawals of water must be reduced, agriculture will account for a major fraction.

CONCLUSION

All of the major impacts of sea level rise would have effects on agriculture. Particularly in deltaic nations, such as Bangladesh, a substantial fraction of agricultural lands could be inundated or eroded. Increased flooding could threaten crops in many areas that would be high enough to avoid direct inundation. Saltwater intrusion would threaten the availability of irrigation water in many areas.

Although these impacts could be important in particular areas, on a worldwide basis they will probably be relatively unimportant compared with the other impacts of global warming. Nevertheless, particular crops that are typically grown in low areas, such as rice, may be disproportionately affected. Given the increasing level of resources for assessing the worldwide impacts of sea level rise, it seems reasonable to conclude that someone should examine the implications of sea level rise for the world's agriculture.

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