GLOBAL SEA-RISE: AN EARLY WARNING

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INTRODUCTION

One of the most important problems facing coastal communities today is the effects of a global sea-rise on coastline habitat and infrastructure. Such a rise could inundate lowlands and wetlands, erode beaches, and exacerbate coastal flooding. Furthermore, rising sea level can influence the rate of salt-water intrusion into coastal aquifers, cause expansion of the salt-water wedge in estuaries, and increase the probability of damage from storm surges along coastlines. Predicting shoreline retreat and land loss rates is critical to planning future coastal zone management strategies and assessing biological impacts due to changes in or destruction of habitat. To date, long-term coastal planning has been done piecemeal, if at all (NRC, 1995). Consequently, facilities are being located and entire communities are being developed without consideration to the potential costs to relocate and/or protect them from the effects of sea-level rise, flooding, and/or loss of natural resources.

An average rise in global ocean levels of just a few inches could have devastating effects on coastal towns, cities, and ecosystems worldwide. More than 100 million people live within 1 meter (3.28 feet) of the mean sea level (Douglas & Kearney, 2001). The problem is exceptionally urgent and serious for the low-lying small island nations of the world. The Intergovernmental Panel on Climate Change concluded in 2006 that by 2100 the sea-level could rise as much as 0.58 meters (23 inches) (Solomon et al., 2007). Current estimates of sea-level rise by 2100 range between 0.30–0.91 meters (1–3 feet). The range reflects uncertainty about global temperature projections and how rapidly ice sheets will melt or slide into the ocean in response to the warmer temperatures.

Regardless of the future uncertainty, the current rate of sea-level rise is more than double the average sea-level rise seen over the past few centuries. Equally alarming is the fact that the rate of sea-level rise appears to have increased exponentially over the past few decades.

WHAT IS HAPPENING

It comes down to a simple principle proven thousands of years ago by the Greek scientist, Archimedes. He showed that a body immersed in a fluid is buoyed up by a force equal to the weight of the displaced fluid. In other words, since the Arctic ice pack is already floating, its melting is not likely to have very much effect on ocean levels. However, the attending planetary conditions necessary to facilitate polar melting will likely have other enormous effects on the environment. One such effect is the melting of ice sheets that currently rest upon land masses. Ice sheets that fit into this category are those covering most of Greenland, Antarctica, and various glacial mountain systems. Since these ice sheets are *not* floating, a corresponding sea-level rise will occur as they begin to melt and flow into our oceans. Another problem of a warming Earth is that water tends to

FIGURE 1. Change in annually averaged sea level at 23 geologically stable tide gauge sites with long-term records. The thick dark line is a three-year moving average of the instrumental records. This data indicates a sea level rise of approximately 18.5 cm from 1900–2000 (Douglas, 1997).

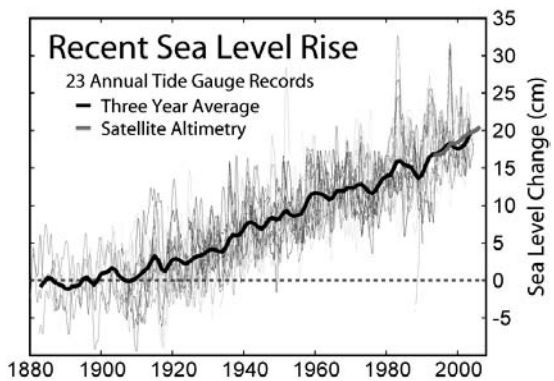

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FIGURE 2. As the ice mass shrinks over the Arctic, the land and oceans absorb more heat because less sunlight is reflected into space (NASA/Goddard Space Flight Center, 2007).

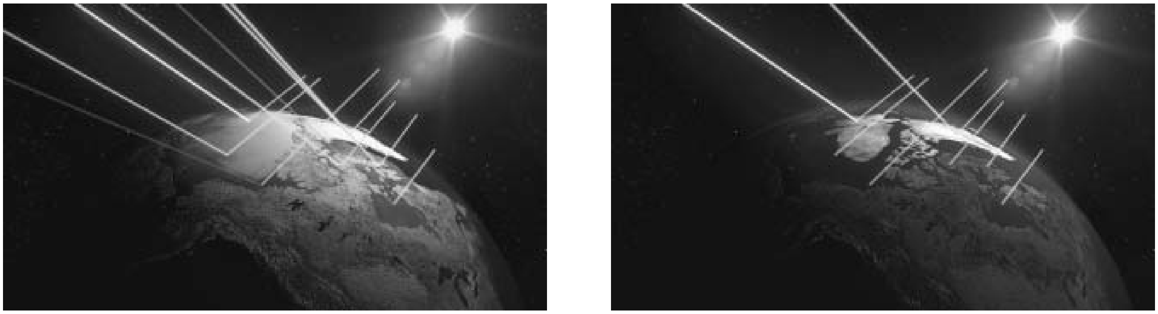
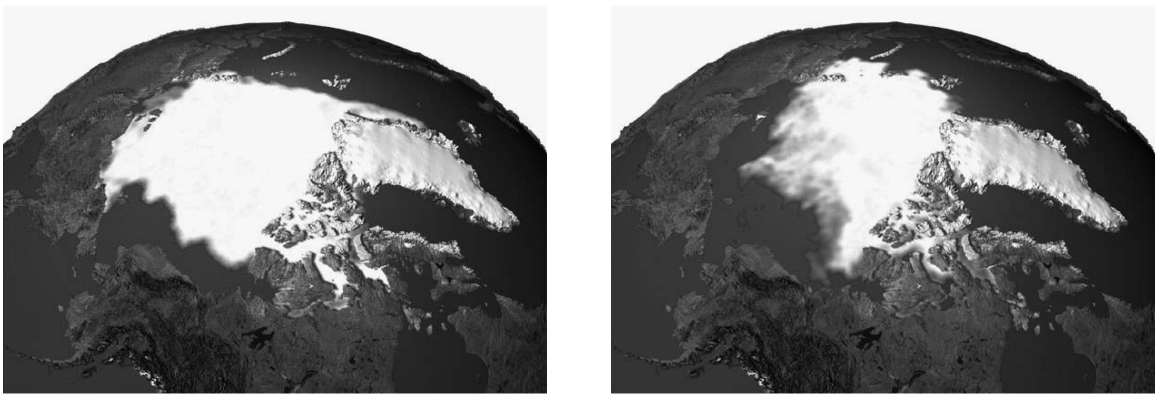


FIGURE 3. Extent of Arctic sea-ice in 1979 (left) and 2002 (right) (NASA/JPL, 2007).



expand as it grows warmer. Thus, as Earth's ocean temperatures rise in tandem with air temperatures, the thermal expansion of warmer ocean waters will further contribute to a global sea-rise. For the 1993 to 2003 decade, thermal expansion is estimated to contribute about 1.6 mm (0.063 inches) per year to sea-level rise for the upper 750 meters (2,461 feet) of the ocean alone, about 20 percent of the current average annual observed sea-level rise of 9.2 millimeters (0.36 inches) per year (Solomon et al., 2007; NASA/JPL, 2006).

The Arctic ice cover is drastically shrinking. In September 2007, the European Space Agency announced that satellite images captured by the Advanced Synthetic Aperture Radar instrument aboard its Envisat satellite showed that the Arctic ice had dwindled to its smallest size since measurement began 30 years ago. According to the report, the area covered by ice in the Arctic has shrunk by approximately 1,000,000 km^2 (386,000 $miles^2$) over the past century. The ice mass continues to dwindle. The 2007 ice mass is less than previous minimums reached in 2005 and 2006, covering just 3,000,000 km^2 (1,150,000 $miles^2$). To further illustrate, the average ice loss per year over the past decade had been about 100,000 km^2 (38,600 $miles^2$). It seems as if someone has stepped on the gas pedal in terms of global warming (Glausiusz, 2008).

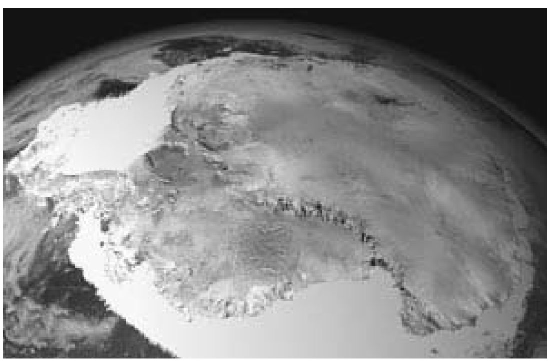
Data from NASA's GRACE satellite tells a similar story for the colossal ice sheets that sit atop Antarctica and Greenland. The GRACE data suggests that the ice sheets covering Antarctica and Greenland are both losing significant mass. The current contributing annual sea-rise from the Antarctica and Greenland ice sheets is estimated to be 1.2 millimeters (0.05 inches) and 0.56 millimeters (0.022

inches), respectively. The contribution made by the melting of Antarctica and Greenland's ice sheets can be better grasped when it is considered that the historic total average annual sea level rise for the past few hundred years has been approximately 1.8 millimeters (0.071 inches) (Munk, 2002). As sea levels continue to rise, the brunt of the blow will be dealt to the world's coastal communities.

Antarctica

NASA's GRACE program, as well as corresponding studies, has demonstrated significant loss of Antarctica's ice sheet; suggesting a loss of almost 150 kilometers^3 (36 miles^3) per year since 2002. Antarctica's ice sheet, which holds approximately 70 percent of the world's fresh water, contains approximately 27,000,000 kilometers^3 (6,500,000 miles^3) of ice (NASA, 2006). If the Antarctica ice sheet was to completely melt, it would raise global sea levels by approximately 70 meters (230 feet). The estimated annual average mass lost from Antarctica's ice sheet from 2002 through 2006 was enough to raise global sea level annually by approximately 1.2 millimeters (0.05 inches), contributing 13 percent of the overall observed sea level rise of 9.2 millimeters (0.36 inches) measured during the same period of record (NASA/JPL, 2006). This amount of ice that annually melts in Antarctica is about how much water the United States consumes in three months (a cubic kilometer is one trillion liters; approximately 264 billion gallons of water).

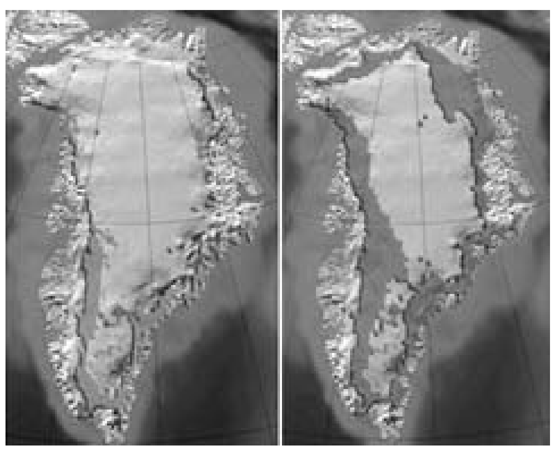
FIGURE 4. Antarctica from space in 2006 (NASA/JPL, 2007).



Greenland

Greenland lost roughly 680 kilometers^3 (164 miles^3) of ice between April 2004 and April 2006, more than the volume of water in Lake Erie (Velicogna & Wahr, 2007). Several studies have indicated that temperatures in southern Greenland have risen by approximately 2.4° Celsius (4.4° Fahrenheit) over the past two decades (Solomon et.al., 2007). Increased temperatures promote increased snowmelt. This melt-water provides increased lubrication to the bottom of the glaciers and tends to increase the velocity of the ice sheet toward the coast. Additional studies have demonstrated that Greenland's ice sheet is losing mass at an increasing speed. A 2006 study by researchers at the University of Wales, for example, showed that two glaciers in the southern portion of Greenland have doubled their speed and are dumping twice as much ice into the sea as they had been just five years ago (NASA, 2006). The increasing loss of ice mass from Greenland's ice sheet is estimated to be contributing 0.56 millimeters (0.022 inches) annually to a global increase in sea levels (Tapley & Wilson, 2006). Greenland's ice sheet holds approximately 2,500,000 kilometers^3 (600,000 miles^3) of glacial ice—enough to raise sea levels by approximately 7 meters (23 feet) worldwide if all of the ice were to melt.

FIGURE 5. The extents of seasonal ice melting in Greenland in 1992 (left) and 2002 (right) (Velicogna & Wahr, 2007).



Mountain Glaciers

A large portion of the current ice melt and associated sea rise can be attributed to mountain glaciers. Mountain glaciers are considered to be the "small glaciers"—and consist of all perennial ice masses other than the Greenland and Antarctic ice sheets. Mountain glaciers are estimated to have contributed as much as 60% of the total ice loss from glaciers and ice caps during the period of 1994–2003. The contribution of these smaller glaciers continues to accelerate. Mountain glacier wastage caused sea levels to rise at an average rate of 0.51 millimeters (0.02 inches) per year for the period 1961–2003. However, during the latter part of that time frame, the period of 1994–2003, these glaciers caused sea levels to rise as much as 0.93 millimeters (0.037 inches) per year.

Best estimates show the total area of these glaciers and ice caps to be approximately 785,000 kilometers^2 (300,000 miles^2). The total volume of this ice is estimated to be approximately 260,000 kilometers^3 (60,000 miles^3), or the equivalent of approximately 0.65 meters (2.1 feet) of global sea-level rise (Dyurgerov & Meier, 2005). The contribution to global sea rise from mountain glaciers is expected to be from 0.1 to 0.25 meters (0.32 to 0.82 feet) by 2100 (Meier et al., 2007).

In a study conducted by Dyurgerov and Meier from 1970 to 2004, 83% of surveyed mountain glaciers demonstrated signs of thinning and overall loss of mass. Some well documented examples are:

- Patagonia—Digital elevation models of the Northern and Southern Patagonia ice fields of South America were compared with earlier cartography to estimate the volume change of the largest 63 glaciers. During the period 1975–2000, these glaciers lost ice at a rate equivalent to a sea level rise of approximately 0.042 millimeters (0.0017 inches) per year. In the more recent years 1995–2000, average ice thinning rates have more than doubled to an equivalent sea level rise of approximately 0.105 millimeters (0.0042 inches) per year (Rignot, Rivera & Casassa, 2003).
- Alaskan Glaciers—The Malaspina Glacier and the equally large Bering Glacier, each with an area of approximately 5,000 kilometers^2 (1,930 miles^2) and maximum thickness of approximately 800 meters (2,625 feet) are now known to be major sources of runoff to the ocean causing sea-level rise. These and nearby glaciers in southern Alaska and adjacent Canada are now supplying about as much glacial runoff as all the other glaciers in the world, exclusive of the two major ice sheets. Many previous analyses underestimated this contribution because of the lack of quality meteorological and glaciological data from the area (Douglas & Kearney, 2001).
- Himalayan region—The Himalayan glaciers regulate the water supply to the Ganges, Indus, Brahmaputra, Mekong, Thanlwin, Yangtze, and

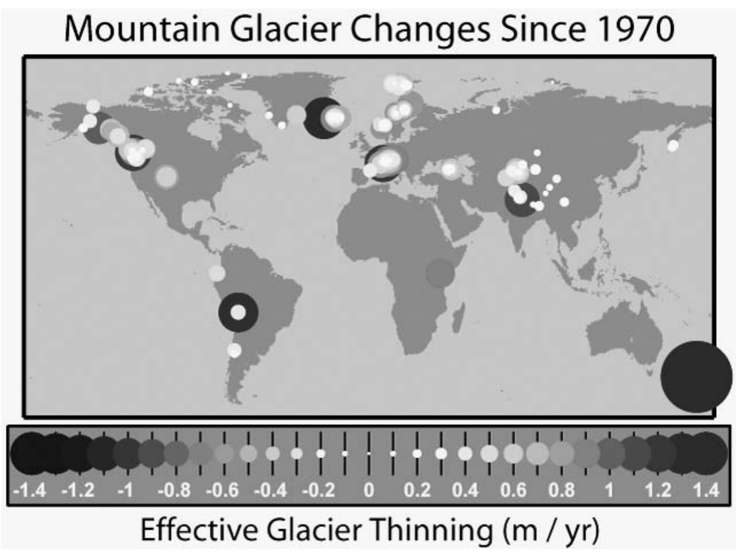
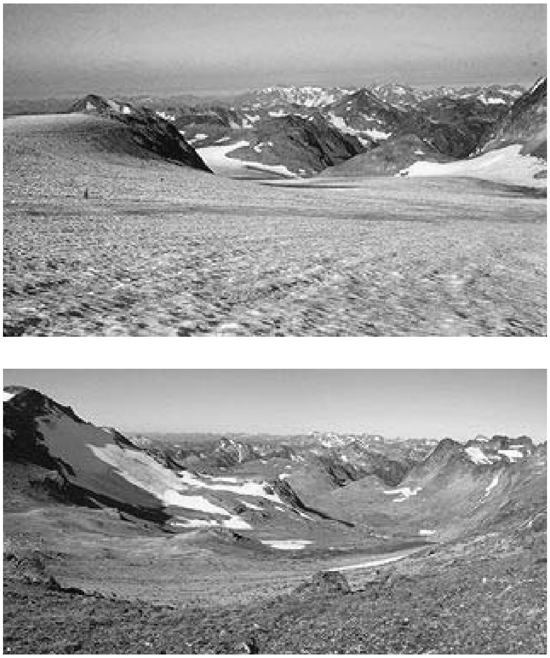


FIGURE 6. Average annual rate of thinning since 1970 for the 173 glaciers that have been measured at least 5 times between 1970 and 2004. Larger changes are plotted as larger circles and towards the back (Dyurgerov & Meier, 2005).

FIGURE 7. The view down the Whitechuck Glacier in North Cascades National Park in 1973 (top) and 2006 (bottom). The glacier has retreated more than 1.9 km (1.2 miles).



Yellow Rivers and ensure a year-round water supply for 2 billion people. These rivers comprise the primary source of fresh water for western China, Nepal, and northern India. The glaciers are the largest store of water outside of the polar ice caps. The glaciers are estimated to be retreating at a rate of about 10–15 meters (33–49 feet) each year. In the Ganga, the loss of glacier meltwater would reduce July-September flows by two thirds, causing water shortages for 500 million people and 37% of India's irrigated land (Combes et al., 2007).

IMPACTS

With global sea rise expected to be from 0.30–0.91 meters (1–3 feet) over the next century, hundreds of thousands of square kilometers of coastal wetlands and other lowlands could be inundated. Beaches could retreat as much as a few hundred meters and protective structures may be breached. Flooding would threaten lives, agriculture, buildings, and infrastructure. Saltwater could advance landward into aquifers and up estuaries, threatening water supplies, ecosystems, and agriculture in some areas.

Some variables affecting coastal vulnerability are geomorphology, regional coastal slope, rate of relative sea-level rise, shoreline erosion and accretion rates, and tide range and mean wave height (Thieler & Hammar-Klose, 1999). Some nations are particularly vulnerable. Eight to ten million people live within one meter of high tide in each of the unprotected river deltas of Bangladesh, Egypt, and Vietnam. Approximately 500,000 people live in archipelagos and coral atoll nations that lie almost entirely within three meters of sea level, such as the Maldives, the Marshall Islands, Tuvalu, Kiribati, and Tokelau. Other archipelagos and island nations in the Pacific, Indian Ocean, and Caribbean could lose much of their beaches and arable lands, which would cause severe economic and social disruption (Harrabin, 2006).

Even in nations that are not, on the whole, particularly vulnerable to sea level rise, some areas could be seriously threatened. Examples include Sydney, Shanghai, coastal Louisiana, and Florida, as well as areas economically dependent on fisheries or sensitive to changes in estuarine habitats (Kanah, 2000).

North America—Southeast Region

In the United States, approximately 13,000 kilometers^2 (5,000 miles^2) of dry land are within 0.61 meters (2 feet) of high tide. Although the majority of this land is currently undeveloped, many coastal counties are growing rapidly. Land within a few feet above the tides could be inundated by rising sea level, unless additional dikes and bulkheads are constructed (USEPA, 2008). In the last century, sea level rose 12.7 to 15.2 centimeters (5 to 6 inches), more than the global average along the Mid-Atlantic and Gulf Coasts, because coastal lands there are subsiding (USEPA, 2008). The Southeast region of the United States would bear the brunt of the sea rise. With a sea rise of 1 meter (3.28 feet), approximately 90% of the land loss would occur in the southeastern region of the United States (Titus, 1989). A sea rise of 1 meter (3.28 feet) would drown approximately 25 to 80% of the U.S. coastal wetlands and inundate up to 25,900 kilometers^2 (10,000 miles^2)

FIGURE 8. Low-lying coastal areas and areas near river deltas are especially susceptible to a rise in global sea levels (Rohde, 2007).

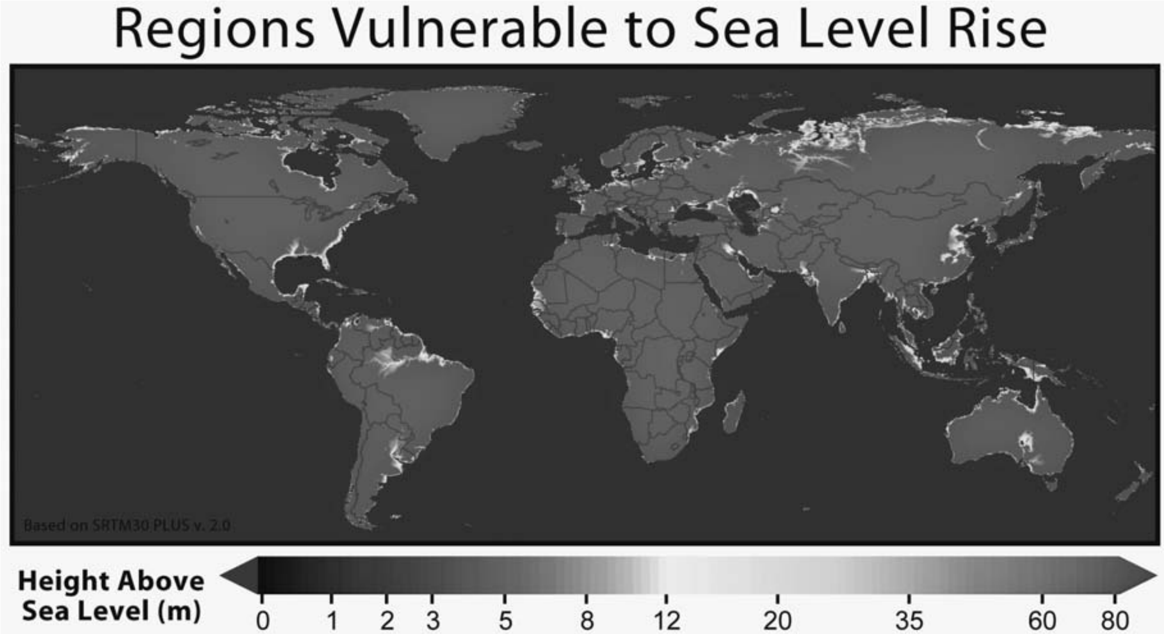
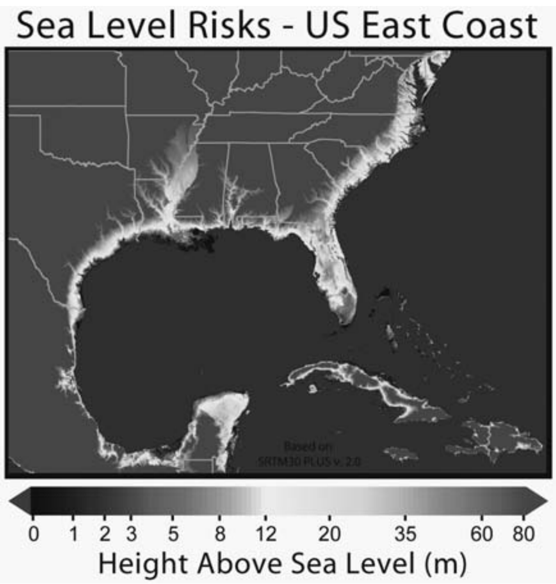


FIGURE 9. The Southeast coast of the United States is quite sensitive to sea-rise. Large portions of Louisiana and Florida are located within 1 meter of mean sea level (Rohde, 2007).



of dry land if shores were not protected. Protecting developed areas against such inundation and erosion caused by a 1 meter (3.28 feet) sea rise by building bulkheads and levees, pumping sand, and raising barrier islands could cost $140 to $213 billion (cumulative capital costs in 2007 dollars) (Titus, 1989).

Most assessments in the United States have concluded that low-lying coastal cities would be protected with bulkheads, levees, and pumping systems, and that sparsely developed areas would adapt to a naturally retreating shoreline (e.g., Munk, 2002; Solomen, 2007; Titus, 1989). This conclusion has generally been based on estimates that the cost of structural protection would be far less than the value of the urban areas being protected but would be greater than the value of undeveloped land.

Rising sea levels increase the salinity of both surface and ground water through salt water intrusion. California's Central Valley, New York City, and Philadelphia all obtain some of their water from portions of rivers that are slightly upstream from the point where water becomes brackish during droughts. If sea level rise pushes saline water further upstream, then the existing water intakes might draw on this salty water during dry periods. Salinity increases in estuaries can also harm aquatic plants and animals that do not tolerate high salinity.

Shallow coastal aquifers are also at risk (Solomon et al., 2007). The freshwater Everglades currently recharge Florida's Biscayne aquifer, the primary water supply to a large portion of South Florida. As rising water levels submerge low-lying portions of the Everglades, portions of the aquifer would become saline. Aquifers in New Jersey, east of Philadelphia, are recharged by fresh portions of the Delaware River that may become saline in the future. Underground brackish water can extend 10 percent to 50 percent further inland than the saltwater on the surface. These coastal communities could lose a large proportion of their fresh water supplies (Ibaraki, 2007).

In all of these cases, water management authorities currently prevent excessive salinity by releasing fresh water from reservoirs during droughts. One possible response to sea level rise would be to store more water during wet seasons so that more water can be released during droughts. For example, the Delaware River Basin Commission protects Philadelphia's freshwater intake on the river and New Jersey aquifers recharged by the river by storing water in reservoirs during the wet season and releasing it during droughts, thereby forcing the saltwater back toward the sea. However, other water management goals (e.g., flood prevention) may make it difficult to save extra water for the occasional drought. The impacts of climate change on local hydrology may offset or increase salinity increases due to sea level rise (USEPA, 2008).

Europe—The Netherlands

Due to its low-lying coasts, the Netherlands will be seriously affected by rising sea levels. Presently, about one half of the Netherlands' total territory lies below sea level. Without dikes, this part of the country would be permanently flooded.

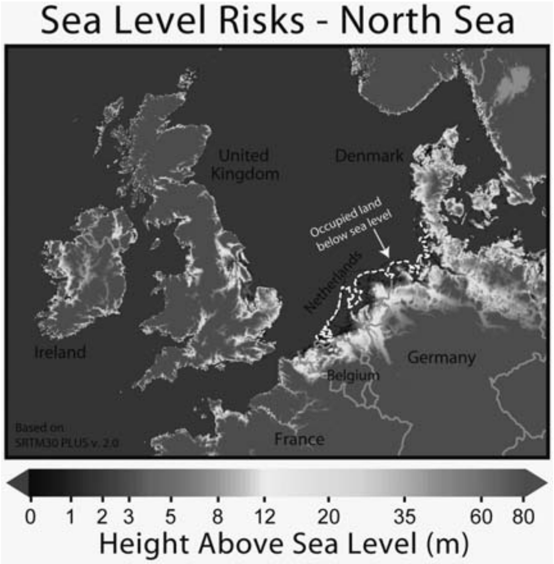
The sea level in the Netherlands has risen by approximately 20 centimeters (7.9 inches) over the past century. As in the case in the southeastern United States, some of this sea rise can be attributed to the subsiding of the land. However, as the sea continues its upward rise the threats of floods and salt water intrusion into groundwater supplies in this area will be largely increased. Though the presently existing infrastructure provides a high level of protection, further countermeasures will have to be taken to combat the rise of the North Sea.

Southeast Asia—Bangladesh

Wide regions of Bangladesh, one of the heaviest populated regions on earth, are situated just above sea level and in the estuary of three large rivers—the Brahmaputra, Ganges, and Meghna. As in the case of the Netherlands, floods from the sea as well as from rivers bursting their banks threaten the country. Additionally, the situation in Bangladesh is intensified by tropical cyclones and monsoon rainfalls. Unlike the Netherlands, there exists hardly any protection such as modern dikes.

A rise in sea level is a threat to the existence of millions of people in Bangladesh. Compared to the Netherlands, the relative sea level rises with double to quadruple speed. Due to tectonic movements the ground level has been slightly falling down, thus an average relative rise in sea levels by 4–8 millimeters (0.16–0.31 inches) per year has taken place. This equals a rise by 8–16 centimeters (3.15–6.30 inches) within 20 years (Kanah, 2000).

FIGURE 10. Europe's Netherlands is particularly sensitive to sea level rise. Large portions of the country are already located below mean sea level (Rohde, 2007).



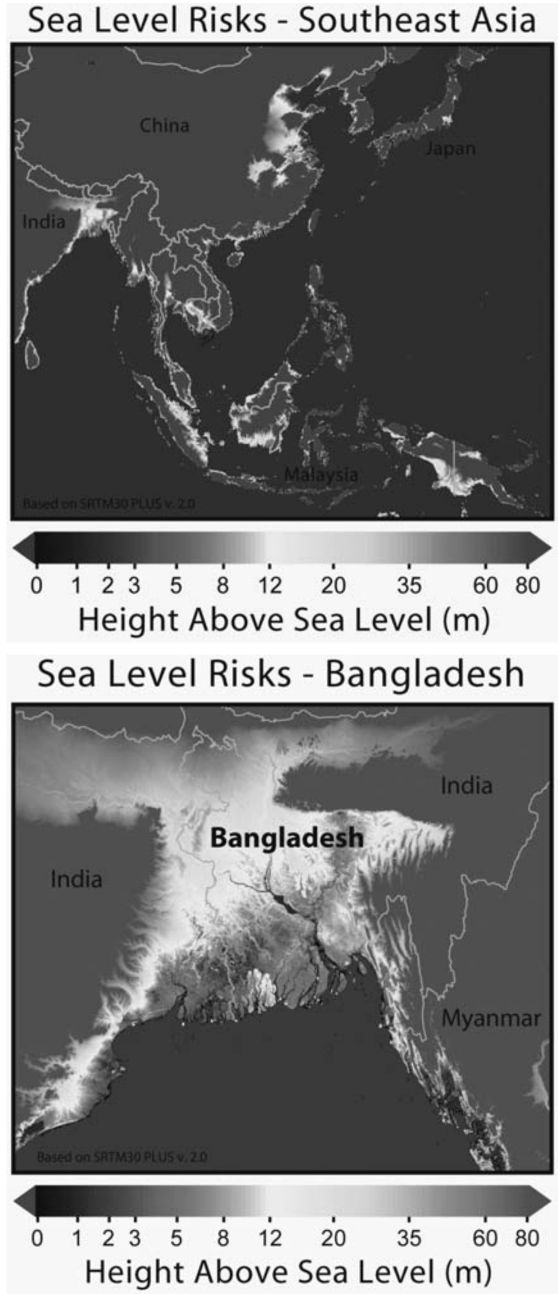
If the sea level rises by 45 centimeters (17.71 inches), scientists expect a permanent loss of up to 15,600 kilometers^2 (6,000 miles^2) of land. If sea levels rise by one meter and no dike enforcement measures are taken, 14,000 to 30,000 kilometers^2 (5,400 to 11,600 miles^2) will be permanently flooded, which means more than one fifth of Bangladesh will be under water (Nicholls, 1993)—as many as 30 million Bangladeshis could become climate refugees (Harrabin, 2006).

SOLUTIONS

The possible responses to inundation, erosion, and flooding fall broadly into three categories: protect (erecting walls to hold back the sea), accommodate (raising the land), and retreat (allowing the sea to advance and adapting to the advance) (Neumann, Yohe, and Nicholls, 2000). Both 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 three responses.

- ***Protect,*** which aims to protect the land from the sea, so that existing land uses can continue, by constructing hard structures (e.g., seawalls) as well as using soft measures (e.g., beach nourishment).

FIGURE 11. With a population of approximately 150 million, Bangladesh is the 7th most populous country on Earth and has the highest population density of any country larger than 2,000 km^2 in area. As large portions of Bangladesh are near sea level, sea level rise here has the potential to displace tens of millions of people (Rohde, 2007).



Hard structures are perhaps most sensibly applied in developed and urban areas.

Hard structures do not have to be constructed until they are needed. Ideally, hard structures would be built just in advance of the threat of inundation. Because the pace of sea level rise is unknown, some anticipation and monitoring is required to implement appropriate pre-emptive responses.

For new development, hard structures can be integrated into the planned infrastructure. If a dike system is to be used for protection, planners can integrate infrastructure needs to meet future conditions. Rather than raising surrounding land surfaces incrementally in response to future flooding hazards, the dike system can be incorporated onto a road parallel to shore, seaward of development and construction. Such a road could be the location of the eventual dike system, which may include a drainage canal and road for dike construction and maintenance. Without this integrated approach, the public authority would otherwise have to purchase shorefront lands for the dike, and perhaps demolish waterfront homes, and displace homeowners.

Since hard protection in response to an erosion problem does not solve the fundamental problem of a diminishing sediment resource, an alternative approach is artificial addition of sediment and/or improved sediment management, or soft protection, to increase the size of the beach or wetland (Neumann, Yohe, and Nicholls, 2000).

Beach nourishment (i.e., the placement of sand usually dredged from off shore) is a popular and cost effective option in highly developed areas with popular beaches and valuable beachfront real estate, especially during the early onset of erosion (American Society of Coastal Engineers, 1992).

• ***Accommodate,*** which implies that people continue to occupy the land but make some adjustments. Examples of accommodation include: floodproofing, elevating structures, and growing flood or salt tolerant crops. Accommodation of rising sea levels can be seen as a sustainable solution.

• ***Retreat,*** which involves no attempt to protect the land from the sea; in an extreme case, the coastal area is abandoned.

The primary tools for accommodation and planned retreat are land use and development planning. Setback measures, a zoning mechanism for planned retreat employed by states, require that new structures be set back from the shore, usually by some multiple of the average annual rate of erosion (e.g., 20 to 60 times). These types of measures can be controversial and legally contentious, but once implemented they are an effective means of communicating and enforcing a planned retreat strategy.

Examples of forward-looking land use governmental policies:

- *Aruba and Antigua:* Setback established at 50 meters (164 feet) inland from current high-water mark.
- *Australia:* Several states have coastal setback and minimum elevation policies, including those to accommodate potential sea-level rise and storm surge. In South Australia, setbacks take into account the 100-year erosional trend plus the effect of a 0.3 meter (1 foot) sea-level rise.
- *Barbados:* A national statute establishes a minimum building setback along sandy coasts of 30 meters (98.4 feet) from mean high-water mark; along coastal cliffs the setback is 10 meters (32.8 feet) from the undercut portion of the cliff.
- *Canada:* New Brunswick completed remapping of the entire coast of the province to delineate the landward limit of coastal features. Setback for new development is defined from this limit. Some other provinces have adopted a variety of setback policies, based on estimates of future coastal retreat.
- *Sri Lanka:* Setback areas and no-build zones identified in Coastal Zone Management Plan. Minimum setbacks of 60 meters from line of mean sea level are regarded as good planning practice.
- *United Kingdom:* In 1998 the House of Commons endorsed the concept of managed realignment as the preferred long-term strategy for coastal defense.
- *United States:* The states of Maine, Massachusetts, Rhode Island, and South Carolina have implemented various forms of rolling easement policies to ensure that wetlands and beaches can migrate inland as sea levels continue to rise.

CONCLUSION

Though future sea level rise predictions vary widely, it is almost certain that the world's seas will continue to rise and that a solution for this rise in sea levels will need to be found for millions of people. The cause of this rise in sea levels may be the subject of debate—however, the sea-rise itself should not be. Governments, business entities, and private citizens of the world should begin to consider and plan for this eminent sea rise of 0.30–0.91 meters (1–3 feet) to occur within the next century. The sea rise will almost certainly not come with catastrophic quickness. However, short- and long-term planning should already be implemented to deal with loss of lands, increasing storm surges, and loss of coastal water supplies.

Continuing and future research is needed to better predict future sea-rise as well as its causes and effects. Research is also needed to determine a best means to deal with the effects of a global sea-rise. Some emerging technological solutions include: desalinization, clean energies, and coastal protective structures. Community planners and developers should also heed the warning and take preemptive measures to stave off future losses and damages, almost certain to occur, associated with a continuing rise in the sea levels around the world.

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