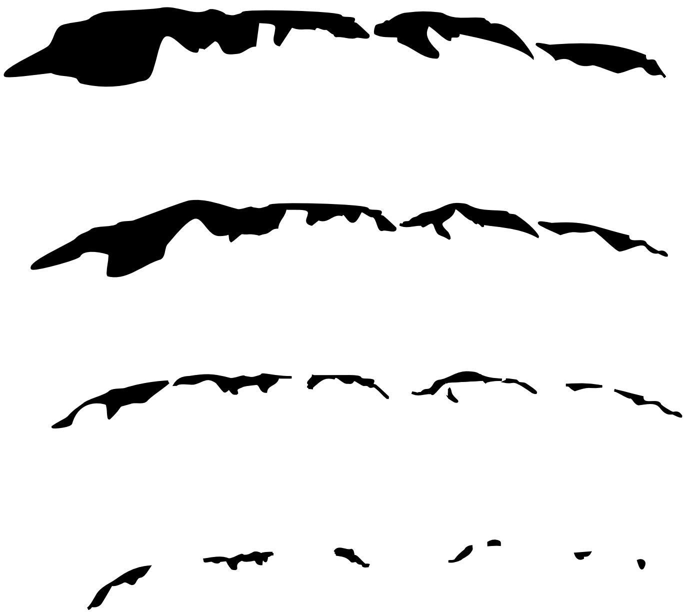
HIGH WATER BLUES



Outlines of a vanishing barrier island

Impacts of Sea Level Rise on Selected Coasts and Islands

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Cover Image

The image depicts a time series of aerial views of a vanishing barrier island over a century as sea level rises. It is adapted from maps showing shrinkage of Iles Dernieres, a sandy barrier island, off the Mississippi sub-delta.

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Executive Summary

The accumulation of anthropogenic greenhouse gases in the atmosphere, principally carbon dioxide but also methane and nitrous oxide, is expected to cause substantial warming of the Earth. Atmospheric concentration of carbon dioxide has increased 30% over its pre-industrial level. Without policy intervention, it will continue to increase to much higher levels over the next century due to increasing energy demand related to development and population growth. Climate models project that, as a result, the Earth's surface could warm anywhere between 2 and 6 degrees Fahrenheit (1 to 3.5 degrees Celsius). Many ecological consequences will ensue, among the most direct of which will be the melting of small glaciers and ice caps on land and the expansion of seawater as it warms. Both these effect will cause global sea level to rise. This report discusses the impacts of that rise on selected coastlines and islands.

Many case studies estimating land loss and other impacts of global sea level rise have been conducted around the world and reported in the scientific assessment reports of the Intergovernmental Panel on Climate Change (IPCC). By convention most of these studies have reported impacts associated with benchmark sea level rises of 1 or 0.5 meters. Obviously, these impacts will not occur as isolated "events" in the future, but rather as a continuing and accelerating process of impacts, and large land losses will take place with sea level increases below 1 meter and also below 0.5 meters.

For this report we surveyed the literature of impacts and, using downward proportioning when necessary, we illustrate a range of possible impacts below 1 meter sea level rise both for selected sites worldwide and for the United States. We also superimpose these impacts onto the IPCC projections for future global sea level rise. In addition we present general trends of crustal movement around the world that will alter (accelerate, decelerate, or complicate) how different coastlines experience submergence due to global sea level rise.

Introduction

Sitting on a beach that in their childhood extended farther seaward several hundred feet would be a jarring experience for most people. And it would be intensified by the thought that such a change is just the beginning of human intervention with the global climate system.[1] Equally unsettling is the converse scene, visible to people living nowhere near the sea: beautiful mountain glaciers around the world are shrinking to fractions of their original size in single lifetimes, their meltwater contributing to sea-level rise.[2] Such reactions pale perhaps when compared with that reported for small island populations far off in the Pacific. For countless generations these people and their cultures saw the oceans as a deified friend. Now, because of looming sea level rise, it has become a deadly enemy to be fought because it will soon engulf their entire landscape[3] and considerable anxiety about the numerous other impacts of climate change also exists.

The threat of sea level rise spans an enormous range of possible impacts from the relatively small and manageable to the catastrophic.[4] And all the possible repercussions are assuredly negative.

One must include in any calculation of the effects of sea level rise a rapidly growing human population that relies heavily on coastal lands for food,[5] recreation and natural resources. The majority of the world's people live near sea level in large coastal cities or on coastal plains. Although more work needs to be done to quantify the number, a commonly cited estimate is that 50 to 70 percent of humanity lives within the coastal zone. More relevant and rigorous though is the estimate that 46 million people, mostly in developing countries, presently live in the flood zone and are exposed to a storm surge in an average year and that this number would double if sea level rises 50 centimeters (cm).[6]

As with current population distribution, population *growth* over the next few decades will also be concentrated near the sea. However, like picnickers on the beach ignoring the coming high tide, we show little inclination to retreat from the edge. For this reason, some have referred to the trends of sea level rise and coastal population growth as a "collision course."[7]

Responding to sea level rise by retreat, accommodation, or protection will impose a complex set of hard choices on society that will vary widely around the globe. The choices made will be dictated by many issues, including geography, technology, human resources, politics, cultural acceptance, and economic considerations.

1. Estimates of Current and Past Century Sea Level Rise

The seas have risen over the past century. Based on global tide gauge data, the rate of rise has averaged between 1 and 2.5 millimeters (mm) per year over the past 100 years, with a best estimate of 1.8 mm / yr.[8] Therefore over the past century the oceans have risen between 10 and 25 cm, with a best estimate of 18 cm (= 7 inches).

The past century of sea level rise is roughly consistent with that expected from models of oceanic thermal expansion and analysis of the retreat of the world's mountain glaciers: seawater expansion and glacial meltwater seem to have contributed roughly equal amounts.[9] However, the uncertainties involved in this consistency check are still large and is an area needing further study.

There is compelling geologic and archaeological data that the rate of sea level rise during the past 100 years represents a significant acceleration of that over the previous 2,000 years. Such studies constrain the rate of rise over the previous two millennia at 0.4 mm / yr.[10] There is no strong evidence that sea level rise has accelerated during the past few decades, but this conclusion depends critically on a small number of long tide gauge records.[11] Measurements made with satellite radar altimeters will improve significantly the observational database on sea level rise in the future.

2. Projecting Future Sea Level Rise

The Intergovernmental Panel on Climate Change (IPCC) has published forecasts of future sea level rise using a variety of assumptions about future global warming and the physical processes leading to sea level increases.[12] The most recent projections are shown in figure 1. These projections are referred to in the IPCC reports as the "extreme" range of possible sea level increases due to the various uncertainties, as explained below.

The projections were made using "business-as-usual" (i.e., no-further-climate-policy) emissions scenarios published by IPCC in 1992 and referred to as the "IS92 a-e" series. These scenarios, in turn, were based on a range of assumptions about future population growth, economic development, resource availability, and technological changes. The IS92e scenario is the "high" emissions projection, while the IS92c scenario is the "low" projection. The IS92a scenario is a widely used "best" estimate.

The emissions scenarios drive models of sea level rise that take into account both the thermal expansion of seawater as it warms and the thinning of mountain glaciers on land. Critical model estimates include the extent to which both the climate will warm in response to a given increase in atmospheric greenhouse gases and the glaciers will melt as a result of this warming.

Despite the large range in the emissions scenarios (6-35 billion tonnes of carbon in the year 2100), this uncertainty results in only a small spread in the projections for sea level. By far, most of the range shown in figure 1 is due to the climate sensitivity and ice melt parameter assumptions. The forecasts suggest that over the next century thermal expansion will contribute about 60 percent to sea level rise, while the remaining 40 percent will result from glacial, ice cap, and Greenland ice-sheet melting.[13]

Also shown in figure 1, for comparison, is the sea level projection that results from a scenario of greenhouse gas emissions that stabilizes atmospheric carbon dioxide at 450 parts per million (ppm) in the future. Although greenhouse gases are stabilized in this projection, global warming continues because of lags in the climate system and the sea level rises accordingly. Environmentalists and ecologists favor 450 ppm as the stabilization target to facilitate adaptive responses by ecosystems. However, even this low-end target results in considerable sea level rise that continues for centuries past 2100.[14]

An important point to bear in mind when reviewing Figure 1 is that the IS92a estimate represents a future rate of sea level rise that is two to five times that experienced over the past century (1-2 mm/yr). Thus the rate of land loss and increase in storm surges experienced in the past will not be an adequate guide to the losses that will be suffered and the adjustments that will be required in the future.

Titus and Naryanan[15] have developed an innovative probabilistic model of sea level rise based on oceanic warming and ice cap melting but treating model uncertainties as a probability distribution as gauged by 20 climate experts. Among the more notable conclusions is that they report there is a 1% chance that global warming will raise sea level by 1 meter in the next 100 years and 4 meters in the next 200 years.

3. Correcting Skeptics’ Claims About Sea Level Rise

Following is a sampler of skeptics’ claims (selected from recent Internet postings) contrasted with the information published by the IPCC in *Climate Change 1995*. Compared with other aspects of climate change, skeptics do not address sea level rise extensively, perhaps because of its ubiquitous negative nature.

[E]vaporation from the ocean with subsequent deposition on the ice caps, principally in the Antarctic, is more important in determining sea-level changes than the melting of glaciers and thermal expansion of ocean water.
F. Singer [16]

The IPCC estimates that this increased accumulation of ice is expected to occur only in Antarctica and that there the offsetting effect is minimal and equivalent to only a 1-cm decrease in sea level rise by 2100.[17] Thus instead of a 50-cm increase forecast by the IS92a scenario, a 49-cm rise is projected using the Antarctic correction factor. Also the Antarctic contribution may turn strongly positive over the long term.

[R]ising sea levels are natural between ice ages. Contrary to the predictions of global-warming theorists, the current rate of increase is slower than the average rate over the 18,000-year period.
H. S. Burnett [18]

As noted earlier, there is compelling geologic evidence that the sea level rise that has occurred over the past 100 years is larger than that of the preceding 2,000 years and thus is a recent phenomenon. This evidence is based on analyses of hundreds of geologic and coastal archeological sites that collectively bound the rate of global sea level rise for the past 2,000 years at 0.2 to 0.4 mm / yr[19] (compared with about 1.8 mm / yr over the past 100 years).

[T]he net rise in sea level from global warming, in the year 2100, will be only 8.2 inches, assuming a warming that is most consistent with the observed temperature record and greenhouse changes. How many beachcombers do you think will notice that yearly tenth-of-an-inch rise in the water level?
P. Michaels [20]

As already stated, the best estimate of the most recent IPCC report on sea level rise is 49 cm or 19.3 inches by the year 2100.

There is no credible evidence that sea level is rising worldwide as a result of human activities. However, changes do occur frequently from decade to decade, or by region. For example, waters around the Mississippi Delta have been slowly rising, but parts of Scandinavia have experienced a decline—not a rise—in sea level... Uncertainty and incorrect information about sea level rise exists even in the Clinton Administration. In fact, in his June 26 speech to the U.N. Earth Summit+5, President Clinton himself stated that sea level will rise "two feet or more" by 2100.

American Petroleum Institute [21]

Citing peer-reviewed scientific literature the IPCC clearly and "credibly" states that "global sea level has risen between 10 and 25 cm over the past 100 years and much of this rise may be related to the increase in global mean temperature ..."[22] This estimate is based on extensive tide-gauge data, as described in the report. Thus warming has likely caused sea level rise. To what degree the warming is induced by human greenhouse gas emissions is still not fully understood however the IPCC did conclude that: "...the balance of evidence suggests there is a discernible human influence on climate."[23]

Regarding Mississippi and Scandinavia, there is no question that different regions of the world will experience different rates of sea level rise (and some will even experience sea level retreat) in the future due to the complicating effects of local land movements. The fact remains, however, that globally there will be accelerated submergence especially in low-lying coastal areas. The additional subsidence in Mississippi simply means it will be even harder hit because the local submergence will accelerate the effects of a global rise.

Similarly, President Clinton’s reference to a 2-foot rise in sea level by 2100 takes into account the fact that much of the United States’ seaboard is subsiding, so that local sea level around the US will rise faster than the IPCC middle projection. As President he would naturally be most interested in the accelerated impact the US will experience and for this reason quotes the corrected impact in the year 2100.

4. Global and Relative Sea Level Rise

The statement by the American Petroleum Institute above makes clear the need to distinguish between two types of sea level rise: global and relative. Global sea level rise corresponds to the intuitive notion of the volume of water in a bathtub. Adding more water increases the volume, and the water level goes up.

The oceans are not a bathtub with rigid porcelain walls, however. The "walls" are not vertical but, for the most part, nearly horizontal as a result of the sedimentary processes that determine land gradients near the sea. In addition, the “floor” is not immobile. The crust of the Earth can undergo rapid vertical movements (even on human timescales as for example with earthquakes) that can cause water to suddenly engulf or retreat from the coast. Finally the oceans are not surrounded by rigid bedrock, but by mobile and dynamic sediments both of a physical nature (sands and muds) and of a biological origin (marshes, mangroves, and coral reefs). The dynamics of these sediments are critical to the response of the shoreline to sea level rise.

Because of these complicating local effects, it is necessary to define a second type of sea level change: relative sea level rise. This refers to changes in sea level observed at a particular coastline due to changes in the land surface (including sedimentary changes) underlying that coastline. Both global and relative sea level changes will alter the configuration of the coastline. To predict such new coastline positions one must know both the global and relative contributions and, ideally, many other pieces of information such as relief, rock types, sediment characteristics, wave energies and so on.

5. Human Activities Are Enhancing Vulnerability to Rising Sea Level

Although the human influence on sea level is most often spoken of in terms of global warming, we also affect relative sea levels in profound ways apart from the greenhouse effect. Indeed, it seems that human activities are systematically biased to *raise* sea level and not to lower it. Two general categories can be defined: (1) human- induced land subsidence and (2) human-induced sedimentation impacts.[24]

Human-induced land subsidence Humans create land subsidence most notably by withdrawing oil, gas and water and by draining of wetlands associated with land reclamation activities.

Subsidence above oil and gas fields is caused by the compaction of sediments after a drop in pore pressure from a deep reservoir. The amount of subsidence can vary widely, from fractions of a meter (e.g. in the Netherlands)[25] to many meters (e.g., in Long Beach, California).[26]

Subsidence due to groundwater extraction occurs because the water extraction decreases the groundwater pressure and because coastal basins consist of large volumes of unconsolidated sediment that can then compress. Pumping of groundwater also leads to saltwater intrusion into acquifers, deterioration of drainage systems and flooding by tidewater.[27]

Drainage has also lowered the groundwater level in wetlands reclaimed for agricultural, urban, or industrial use. Since reclaimed areas are protected against natural flooding, the subsidence will not be compensated for by natural coastal deposition.[28]

Human-induced sedimentation impacts When human activities affect river systems, catchment areas, and deltas the sediment supply processes are disturbed. Embankments along river channels keeps sediment out of the adjacent land. The construction of dams and reservoirs in upper river areas for flood protection, power supply, and irrigation can stop or strongly decrease the downstream supply of sediment. For example, as a result of such activities, relative sea level is rising in the Mississippi river delta by as much as 1 meter per 100 years.[29]

Sand and coral-reef mining, as well as removing natural sea level rise buffers, can lead to interruptions in alongshore sediment transport and cause additional erosion. Clear-cutting of mangroves and their replacement by brackish water aquaculture systems, and wetland rice patties can have similar effects.

6. General Impacts of Global Sea Level Rise

In assessing the general impacts of a rising sea, it should be noted that the world's coastlines (like the world's climate) have enjoyed relative stability for thousands of years following the end of the last ice-age cycle which terminated 10,000 years ago. Thus most coastal landforms have had time to achieve relatively stationary configurations,[30] although changes are continually taking place due to such short-lived disturbances as earthquakes and storm events.

It is easily appreciated that a global sea level rise will lead to increased marine submergence of low-lying coastal areas, generally referred to as inundation. High and low tides will advance landward accordingly.[31] The new high and low tides will lead to increased erosion as nearshore waves break farther inland.

Erosion is an important effect amplifying inundation, thus leading to even greater land loss. The magnitude of the erosion accompanying a sea level rise is generally determined by an equation called the "Bruun Rule."[32] A simple explanation is given by Titus and coworkers[33] which we repeat here. The visible part of a beach is generally much steeper than the underwater portion, which comprises the active "surf zone." While the extent of inundation is determined by the slope of land just above water, the total shoreline retreat is determined by the average slope of the entire beach profile. The slope of the whole beach profile is generally shallower than that of the above-water portion, leading to greater land losses.

As an example, for the United States, a 1 meter rise in sea level would cause beaches to retreat (erode plus inundate) 50 to 100 meters from New England to Maryland, 200 meters along the Carolina coast, 100 to 1000 meters along the Florida coast, and 200 to 400 meters along the California coast.[34]

8. Effects of Sea Level Rise on Small Island Nations

Small island nations, many of which are only a few meters above sea level, may be facing annihilation due to the inevitability of significant sea level rise as shown in Figure 1. Thus they deserve special attention in any report on sea level rise impacts. Among the most vulnerable of these islands are the Marshall Islands, Kiribati, Tuvalu, Tonga, the Line Islands, Federated States of Micronesia, Cook Islands (in the Pacific ocean); Antigua and Nevis (in the Caribbean Sea); the Maldives (in the Indian ocean).

Pernetta offers an excellent authoritative summary of the climatic horizon for small island nations, taking into account geology, demography, economics, oceanography, social traditions, and marine and island biology among other subjects.[35] Here are some salient points to offer a brief synopsis.

The total land area of most small island nations is extremely small whereas their exclusive economic zones are considerable.

In the Pacific island countries, land area may be only 0.001 % of the exclusive economic zone. Not surprisingly, marine resources compose most of their commercial and subsistence activities. Island relief is variable, but in many cases is only a few meters. Island types consist of volcanics, mixed volcanics and sediments, raised corals, and atolls (coral reefs growing on volcanic cores).

Population level and densities are very high. The population growth rates are also high with some cities approaching 7 percent per year, for instance Male. Improvements in health care and social services have greatly reduced mortality rates but at the same time leading to extremely rapid population growth. The high survival rate of children has resulted in pressures on social services such as education which have been unable to cope. Out-migration is an important source of income through remittances; in some cases, high birth rates are related to the perceived need to have children who can eventually emigrate and send money home for subsistence.

Cultural and, especially, linguistic diversity is enormous; for example, more than one third of the world’s languages are spoken in four island countries in Melanesia. Accelerated emigration (due to climatic or environmental degradation) would weaken the elements of the traditional cultures.

Among the impacts that small islands will face due to sea level rise and climatic warming are (1) increased coastal erosion; (2) changes in aquifer volumes with increased saline intrusion; (3) greater demand for air conditioning and hence energy consumption and fossil fuel importation; (4) coral reef deterioration resulting from sea level rise accompanied by thermal stress; (5) social instability related to inter-island migration; (6) loss of income through negative impacts on tourist resort location; and (7) increased vulnerability of human settlements because of increasing size.

Policies and practices that will exacerbate these problems include (1) coral reef mining; (2) land reclamation; (3) construction of harbors, jetties, and breakwaters; (4) overutilization of acquifer resources; (5) lack of in-country data covering physical and biological resources; (6) shortage of manpower; and (7) inadequate disposal of sewage and toxic chemicals. The failure to adequately address current environmental problems will leave the islands more vulnerable to future climatic and sea level changes.

Climate change will affect rainfall, wind and monsoon patterns. Upwelling zones in the ocean may shift, affecting fisheries. Storms and droughts may increase. Evapo-transpiration rates may change. The general weather related changes may lead to impacts on agricultural crops, natural vegetation and the growing season.

Finally it is interesting to note that since marine resources provide the bulk of small island income, if they could continue to occupy the island through protection, they may remain economically viable. However protection measures will have to be carefully analyzed. Dikes, for example, are infeasible because of coral atoll porosity. Thus the islands would most likely have to elevate.[36]

The complexity of the details of the impacts on small islands of a sea level rise is a useful prelude to keep in mind when considering the abbreviated land loss impacts shown in Figure 1.

8. Impacts of Sea Level Rise Superimposed on IPCC Projections

Abbreviated summaries of the consequences of sea level rise on selected coastlines and islands are presented in Figures 1 and 2. Figure 1 focuses on global impacts while Figure 2 is restricted to the United States.

The figures superimpose captions for land loss impacts at various locations on top of the IPCC sea level rise projections. The impacts are keyed to "global/relative" sea level rises in 10-cm increments starting at 20-cm and increasing to 100-cm.

Many more country case studies are available in the scientific literature than could effectively be placed on these figures. The particular counties shown were selected because they are often cited for being especially vulnerable to sea level rise and are subject to large land-loss risks.

The numbers quoted for land loss are derived from published case studies for the different locations. Many, but not all, of the numbers are from impacts studies that assume 1 meter of relative sea level rise in that location. Although 1 meter is a widely adopted benchmark level, in reality sea level rise will be a continuous process, with serious impacts occurring at elevations well below 1 meter. Therefore the effects are presented as a sequence of 10-cm increments. Thus it was often, but not always, necessary to linearly interpolate the impact at a different, generally higher, benchmark level (0.5 meter, 1 meter) down to a lower level.

Linear interpolation will introduce errors that both overestimate and underestimate the impact. The details of these errors are not easily determined. However, the potential error involved is obviously greatest at the lowest levels of 20 and 30 cm and less so at the 80 or 90 cm mark. Moreover, some studies suggest that linear interpolation is a justified approximation.[37] Although it would be most desirable to use impact studies devoted to the specific levels shown in the figures, the paucity of studies dealing with sea level rises other than those of benchmark values makes the linear-interpolation approximation a necessary one.

The term "global/relative sea level rise" is meant to convey the additional fact that most of the impact studies are based on a local rise without distinguishing whether the rise was due to global sea level increases or local land subsidence or both. In other words, the studies answer the question: Tell me what will happen at your location if sea level goes up 1 meter there? As noted earlier, at many locations (Mississippi, Shanghai, Bangladesh), rapid land subsidence is already taking place and will greatly accelerate global sea level rise. In other places (areas adjacent to former large glaciers), uplift is occurring and will diminish the impact of global sea level rise. Nevertheless, some of the studies do take local land movements into account when quantifying the 1 meter rise impact. Finally in some areas (Alexandria, Egypt), local land movement is considered minimal so the projections of global sea level rise may be good approximations to the relative sea level rise there.[38]

Because of these complicating factors relating to global versus relative sea level rise, caution must be exercised in trying to correlate the quoted impact with a particular year, as given in the IPCC projections. In other words one should avoid trying to determine from Figure 1 "when" 50 cm of sea level rise will be experienced in Bangladesh and result in "10 percent land loss" there.

In order to help sort out the general trends of coastal land movements that are taking place and that will distort the IPCC global sea level projections, Figure 3 presents a map of subsiding, uplifting, and tectonically active coastal areas around the world. As noted, subsiding regions will experience accelerated sea level rises, uplifting regions will experience decelerated rises, and tectonically active regions will experience much more complicated "noisy" trends in sea level.[39]

The loss of land and the extent of vulnerability shown in Figures 1 and 2 generally refer to losses that will be suffered without any attempts at protection, mitigation, or adaptation. Obviously, such human responses will be considerable, and the ability of various countries to deal with sea level rise will differ greatly. However projections of human mitigation strategies are obviously uncertain and in some cases protection measures may not lower the land-loss estimates but merely be measures to protect economically valuable structures.

Finally, even though the impacts cited are generally confined to “land-loss” estimates, as illustrated with the discussion of the small islands, a much more complex array of threats will be involved, including infrastructure losses, storm surges, salt water intrusion into both the freshwater supply and agriculture, altered tidal and wave action.

9. Response Strategies

Response strategies to sea level rise can be grouped into three categories: retreat, accommodate and protect.[40]

As described in the IPCC reports, retreat strategies measures emphasize the abandonment of land and structures and the resettlement of inhabitants. This policy would further entail preventing development in coastal areas and withdrawing of government subsidies for coastal protection. In Maine and South Carolina, for example, state legislation exists to explicitly limit how land can be developed that is vulnerable to sea level rise.

Accommodation stresses the conservation of ecosystems with continued occupancy and adaptive management. This strategy would employ advanced planning, modification of land-use and building codes, protection of ecosystems, and hazard insurance.

Protection relies on the defense of vulnerable areas, populations, and economic activities. Hard structural options include dikes, levees, seawalls, breakwaters, floodgates, and saltwater intrusion barriers. Soft options include periodic beach nourishment, dune restoration, wetland creation, drift replenishment and afforestation.[41] In the Netherlands, for example, dikes are built with extra elevation in order to allow for sea level rise. Similarly in San Francisco reclaimed land has to be of a certain elevation in order to allow for sea level rise.

Not all of these options are feasible for all regions. For example, heavily populated areas, island nations like Japan and seaside tourist centers probably have little choice but to protect. In many countries, the scarcity of technology and a dearth of personnel will limit the choice of accommodation options. Retreat and resettlement options will involve questions of international refugees and related disputes as well as issues of cultural traditions: To what extent will various communities be willing to resettle? How will changed or lost access to traditional fishing and hunting sites be tolerated?

Most of all though, economic considerations (resources and costs) will probably determine the feasibility of various options. In many countries, just the maintenance of existing shoreline could require substantial funding compared with the nation's GNP.[42]

The literature on costs usually divides them into three categories: (1) capital costs of protective measures, (2) annual costs of forgone land services and (3) the costs associated with increased flood and storm frequencies.[43]

The literature estimating the costs of protection is summarized in IPCC[44] and will not be reviewed here. However we do note that in the United States further thinking about beach protection policy is needed given the prospect of accelerated sea level rise. In 1996 the US administration attempted to limit beach nourishment projects because of the extensive US coastline (88,000 miles) and the costs now and in the projected future.[45] Clearly US governmental policy will have to more carefully consider the need for beach nourishment programs because the impacts will only be worse in the future.

10. Conclusion

Of all the forces of nature, the oceans may inspire the deepest respect and awe in many people. To see this powerful force humbled by human activity through global warming, such that its basic characteristics of sea level, coastal configuration, and (possibly) wave and storm activity are fundamentally altered must also strike a deep chord in many people. The comparative ‘irreversibility’ of sea level rise -- it will continue for many centuries even if global warming were stopped -- is far longer than most other impacts from climatic change. Through greenhouse gas emissions we risk jeopardizing our complex socio-economic relationship with the sea. The rational response must be to prevent, to as great an extent as possible, dangerously high levels of greenhouse gas accumulation in the atmosphere.

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[1] W. Greene, “Falling Off the Edge,” *New York Times Magazine*, 7 September 1997, p. 68.

[2] Vice President Al Gore visited Glacier National Park in Montana in September 1997 to witness firsthand the shrinking mountain glaciers. Hiking up 1,600 feet, he saw Grinnell Glacier, which has lost 80 percent of its mass since its discovery. Other glaciers in the park and around the world are also showing a dramatic retreat, including mountain glaciers in Austria, France, Norway, Sweden, and Switzerland. Also see Commentary by Bruce Babbit, “Where Have All the Glaciers Gone?,” *Los Angeles Times*, 24 October, 1997.

[3] “In Pacific, Growing Fear of Paradise Engulfed,” *New York Times*, 2 March 1977, p.1.

[4] M. Oppenheimer, “Global Warming and the West Antarctic Ice Sheet,” submitted manuscript, 1997.

[5] For example, the marshes in Louisiana support 40 percent of all seafood caught in the United States. J.Titus, “A Tale of Land Loss in Louisiana,” in *Impacts of Sea Level Rise on Cities and Regions*, proceedings of the first international meeting “Cities on Water,” edited by R. Frassetto, pp. 109–116 (Venice: Marsilio Editori, 11-13 December 1989).

[6] Intergovernmental Panel on Climate Change, *Climate Change1995: Impact, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses* (New York: Cambridge University Press, 1996), p.294. [Cited hereafter as IPCC 1995, WG2]

[7] S. P. Leatherman, presentation at Cheasapeake Bay Sea Level Rise Meeting, Chestertown, Maryland, October 18, 1996.

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[8] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science Of Climate Change* (New York: Cambridge University Press, 1996), p.366. [Cited hereafter as IPCC 1995, WG1]

[9] Ibid., p. 380.

[10] B.C. Douglas, "Global Sea Level Change: Determination and Interpretation," *Reviews of Geophysics* 33 supp. (1995). [available at http://earth.agu.org/revgeophys/dougla01/dougla01.html]; N.C. Fleming and C.O. Webb, "Tectonic and Eustatic Coastal Changes During the Last 10,000 Years Derived from Archaeological data," *Z. Geomorph. N.F.* 62 supp. (1986); I. Shennan and P.L. Woodworth, " A Comparison of Late Holocene and Twentieth- Century Sea Level Trends from the UK and North Sea Region," *Geophys J. Int*. 109 (1992): 96–105; J. C. E. Thomas Varekamp and O. Van de Plassche, " Relative Sea Level Rise and Climate Change over the Last 1500 Years," *Terra Nova* 4 (1992): 293–304; M.S. Kearney and J.C. Stevenson, " Island Land Loss and Marsh Vertical Accretion Rate Evidence for Historical Sea-Level Changes in Chesapeake Bay," *Journal of Coastal Research* 7 (1991): 403–415.

[11] IPCC 1995 WG1, p. 366.

[12] Ibid., pp. 382–389.

[13] Ibid.

[14] Ibid.

[15] J. G. Titus and V. K. Narayanan, *The Probability of Sea Level Rise,* (Washington, D.C., Environmental Protection Agency, 1995).

[16] F. Singer, "Global Warming Will Not Raise Sea Level" (Abstract for presentation at the meeting of the American Geophysical Union, 1997)

[Website: posted on "Science and Environment Project" Website at www.his.com / ~sepp / scirsrch / slr-agu.html].

[17] IPCC 1995 WG1, p.381.

[18] H. Sterling Burnett, " The Mythology of Global Warming," *Washington Times,* 13 June 1997 [Website: posted on "Cooler Heads Coalition" Website at www.globalwarming.org / archiveF.html].

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[20] P. Michaels, "Sea Level Rise: An Erosion of Truth" [Website: posted on " World Climate Change Report" Website at http: / / www.nhes.com / FT / features.html#Erosion].

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[30] E. C. F. Bird, *Submerging Coasts: The Effects of a Rising Sea Level on Coastal Environments* (New York: Wiley, 1993).

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[35] J. C. Pernetta, “Cities on Oceanic Islands: A Case Study of Male, Capital of the Republic of the Maldives,” in *Impacts of Sea Level Rise on Cities and Regions,* proceedings of the first international meeting “Cities on Water,” edited by R. Frassetto, pp. 169–182 (Venice: Marsilio Editori, 11-13 December 1989).

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[36] J. Titus (personal communication).

[37] Titus et al., " Greenhouse Effect and Sea Level Rise"; G. S. Giese and D. G. Aubrey, "Loss of Coastal Upland to Relative Sea-Level Rise," Woods Hole Oceanographic Institution, Electronic Coastal Brief 1994-02 [Website: www.whoi.edu / coastal-briefs / Coastal-Brief-94-02.html]. In Giese and Aubrey's study of Massachusetts, the impacts of sea level rise below 50cm scale linearly downward, with the sea-level rise number used.

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[39] An informative graph illustrating the various possible trends is in IPCC 1995 WG2, p. 297.

[40] Ibid., pp. 313–317.

[41] Ibid.

[42] Ibid.

[43] Ibid.

[44] Intergovernmental Panel on Climate Change, *Climate Change 1995: Economic and Social Dimensions of Climate Change* (New York: Cambridge University Press, 1996), pp. 191–192.

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Impacts of Global/Relative Sea Level Rise on Selected Coasts and Islands Worldwide

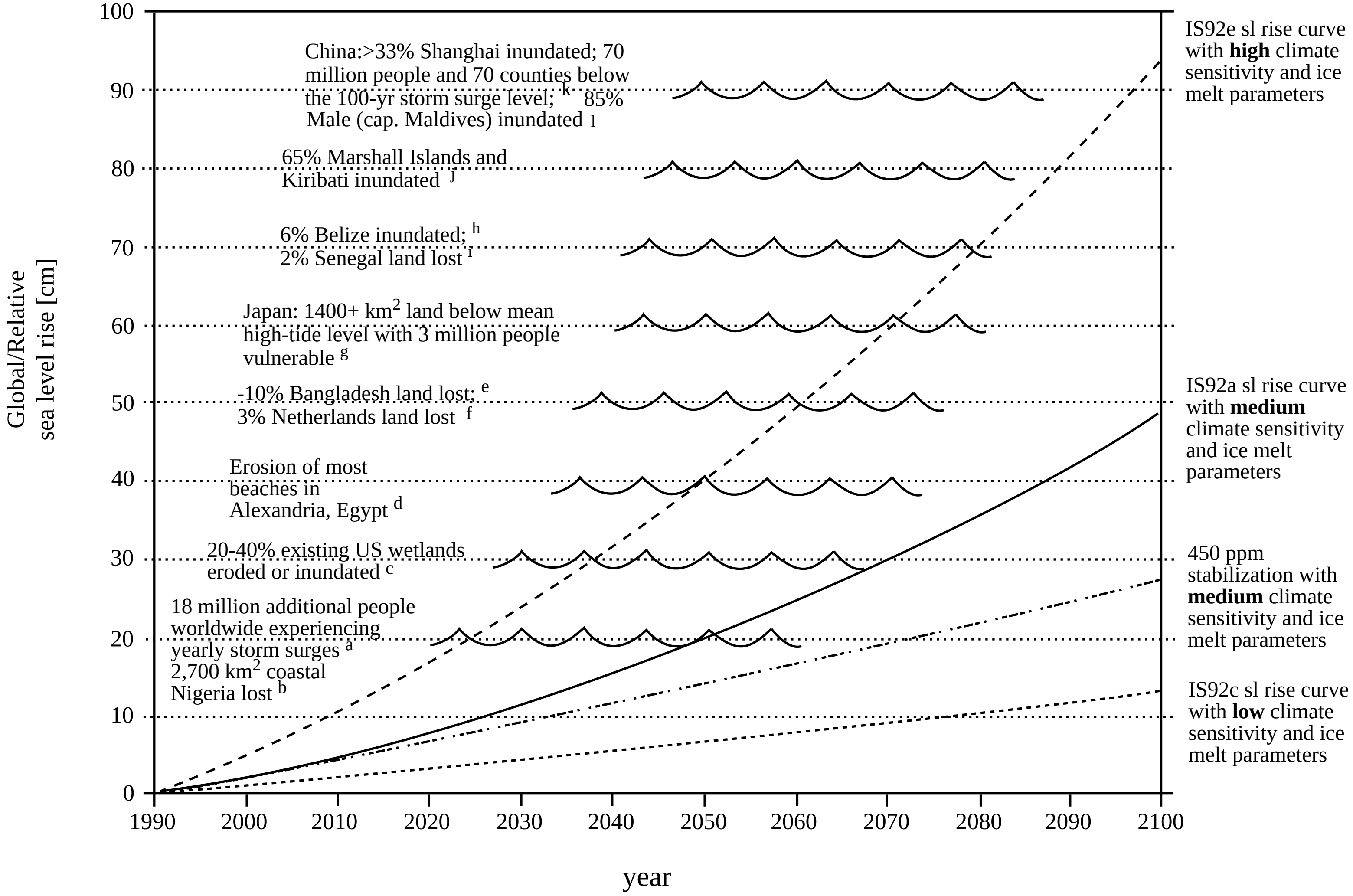

FIGURE 1

Figure 1. Impacts of global and relative sea level rise on selected coasts and islands. Some land loss estimates are based on linearly interpolating the effects discussed in case studies for a different sea level rise (usually 0.5 or 1 meter). Most impacts studies are based on a *relative* sea level rise of the given magnitude. In addition, all the projections assume no coastal protection measures. Unless otherwise noted "land lost" includes dry land and wetland lost to inundation or erosion. *(a)* Linearly interpolated from an estimate that 46 million more people would be vulnerable to yearly storm surges as a result of a 0.5 meter sea level rise; does not take into account future population growth (IPCC 1995 WG2, p. 311); *(b)* estimate of land loss taken directly from a 20-cm-rise scenario (G. T. French, L. F. Awosika and C. E. Ibe, “Sea Level Rise and Nigeria: Potential Impacts and Consequences, “ *Journal of Coastal Research* [Special Issue] 14 [1995]: 224-242; *(c)* estimate based on linear interpolation of U.S. land loss resulting from a 50-cm sea level rise, assuming no protection measures and no new wetland formation on formerly upland areas (IPCC 1995 WG2, p. 309); *(d)* estimate of beach loss based on a 0.5-meter sea level rise (M. El-Raey, S. Nasr, O. Frihy, S. Desouki, and K. Dewidar, “Potential Impacts of Accelerated Sea Level Rise on Alexandria Governate, Egypt,” *Journal of Coastal Research* [special issue] 14 [1995]: 190-204; *(e)* estimate of land loss based on a 1-meter relative sea-level rise (S. Haq, S. I. Ali, and A. Atiq Rahman, “Sea Level Rise and Bangladesh: A Preliminary Analysis,” *Journal of Coastal Research* [special issue] 14 [1995]: 44-53; *(f)* estimate of land loss based on a 1-meter rise (IPCC 1995 WG2, p. 308); *(g)* estimate of land loss based on a 0.5-meter sea-level rise (N. Mimura, ed., *Data Book of Sea Level Rise* [Onogawa: National Institute for Environmental Studies, Environmental Agency of Japan, 1996], p. 68); *(h)* interpolated downward from an estimate of a 1-meter rise (IPCC 1995 WG2, p. 308); *(i)* interpolated between land-loss estimates for a 0.5- and a 1-meter sea-level rise and including land lost to inundation and erosion (K. C. Clements, I. Niang-Diop, and R. J. Nicholls, “Sea-Level Rise and Senegal: Potential Impacts and Consequences,” *Journal of Coastal Research* [special issue] 14 [1995] 243-261, esp. Table 3, p. 252); *(j)* estimate of land loss based on a 1-meter sea-level rise,

resulting in 80 percent island losses (IPCC 1995 WG2, p. 308); *(k)* Shanghai is subsiding by almost 1 meter a century; estimate of land loss based on a 1-meter relative sea-level rise so a global rise of 1 meter will add to the local subsidence (M. Han, J. Hou, and L. Wu, “Potential Impacts of Sea-Level Rise on China’s Coastal Environment and Cities,” *Journal of Coastal Research* [special issue] 14 [1995]: 79-95; *(l)* J. C. Pernetta, “Cities on Oceanic Islands: A Case Study of Male, Capital of the Republic of Maldives,” in *Impacts of Sea Level Rise on Cities and Regions,* proceedings of the first annual international meeting “Cities on Water,” edited by R. Frassetto, pp. 169-182 (Venice: Marsilio Editori, 11-13 December 1989).

Impacts of Global/Relative Sea Level Rise on Selected Sites in the U.S.

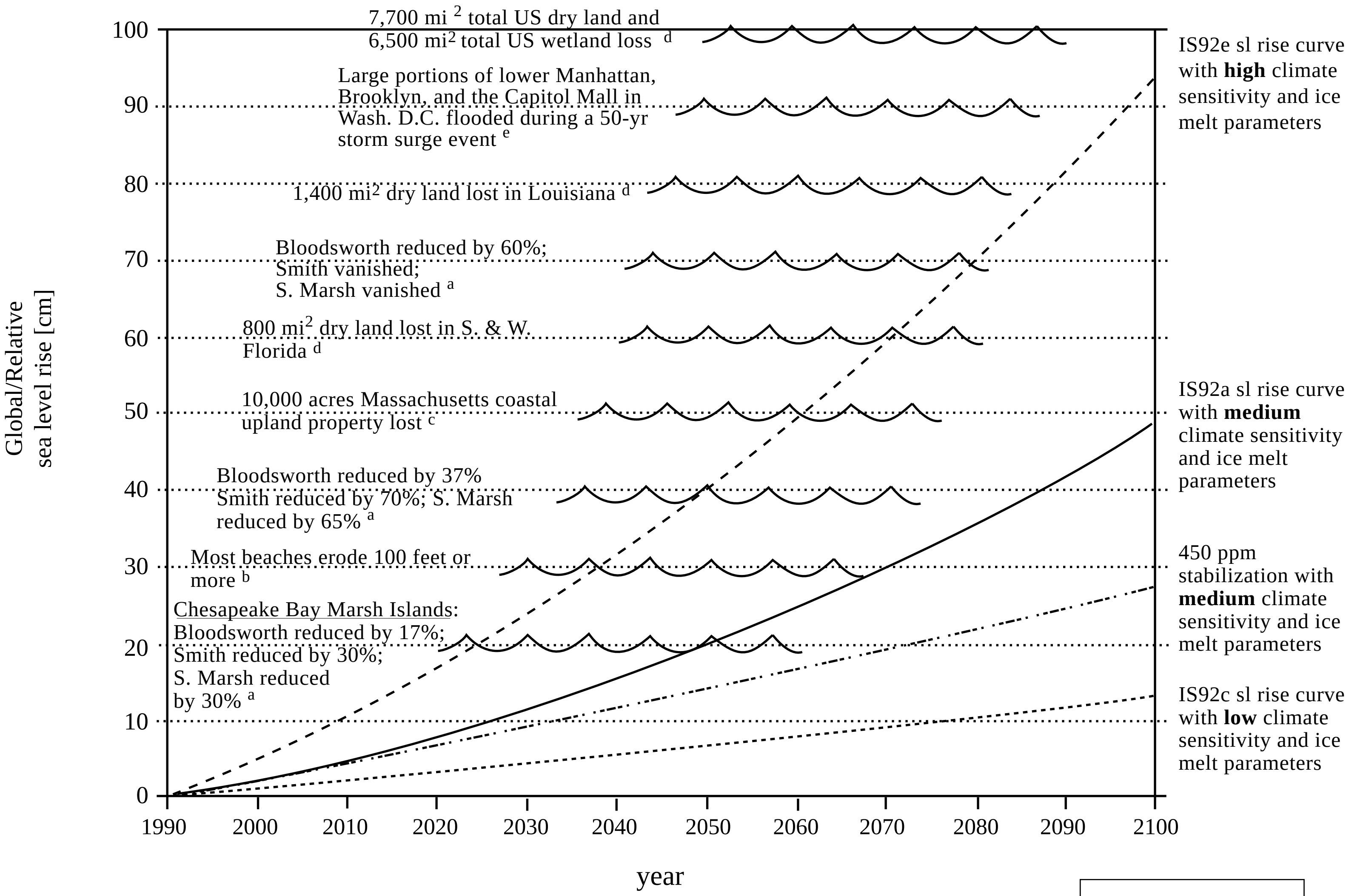

FIGURE 2

Figure 2. Impacts of global and relative sea level rise between 20-cm and 1 meter on selected sites in the United States. Even a 10-cm rise would eliminate the majority of estuarine beaches in the US. (J. G. Titus, personal communication). *(a)* Adapted from R. D. Wray, S. P. Leatherman, and R. J. Nicholls, "Historic and Future Loss for Upland and Marsh Islands in the Chesapeake Bay, Maryland, USA," *Journal of Coastal Research* 11 (1995): 1195-2103; *(b)* J. G. Titus, "Rising Seas, Coastal Erosion and the Takings Clause," *Maryland Law Review* (in press). (*c)* estimate, using hypsometric curves, of land loss based on a 47.9-cm (1.57-foot) relative sea level rise; losses for smaller rises scale linearly, so 35-cm and 14-cm relative rises are estimated to result in losses of 7,500 and 2,900 acres, respectively; estimates are conservative, as they do not take into account upland loss due to increased rates of coastal erosion or rising water tables (upland is all land other than wetland and other inland areas) (G. S. Giese and D. G Aubrey, "Loss of Coastal Upland to Relative Sea Level Rise," Woods Hole Oceanographic Institution, Electronic Coastal Brief 1994-02 [Website: www. whoi.edu / coastal-briefs / Coastal Brief-94-02.html); *(d)* estimates of land loss include the effects of ongoing coastal submergence, so impact relates to global sea level rise (J. G. Titus, R. A. Park, S. P. Leatherman, J. R. Weggel, M. S. Greene, P. W. Mausel, S. Brown, C. Grant, M. Trehan, and G. Yohe, "Greenhouse Effect and Sea Level Rise: The Cost of Holding Back the Sea," *Coastal Management* 19[1991]: 171-204; *(e)* S. P. Leatherman, "U.S. Cities Subject to Sea Level Rise," in *Impacts of Sea Level Rise on Cities and Regions*, proceedings of the first annual meeting "Cities on Water," edited by R. Frassetto, pp. 104-108 (Venice: Marsilio Editori, 11-13 December 1989).

Principal Areas of Land Subsidence, Uplift and Plate Tectonics

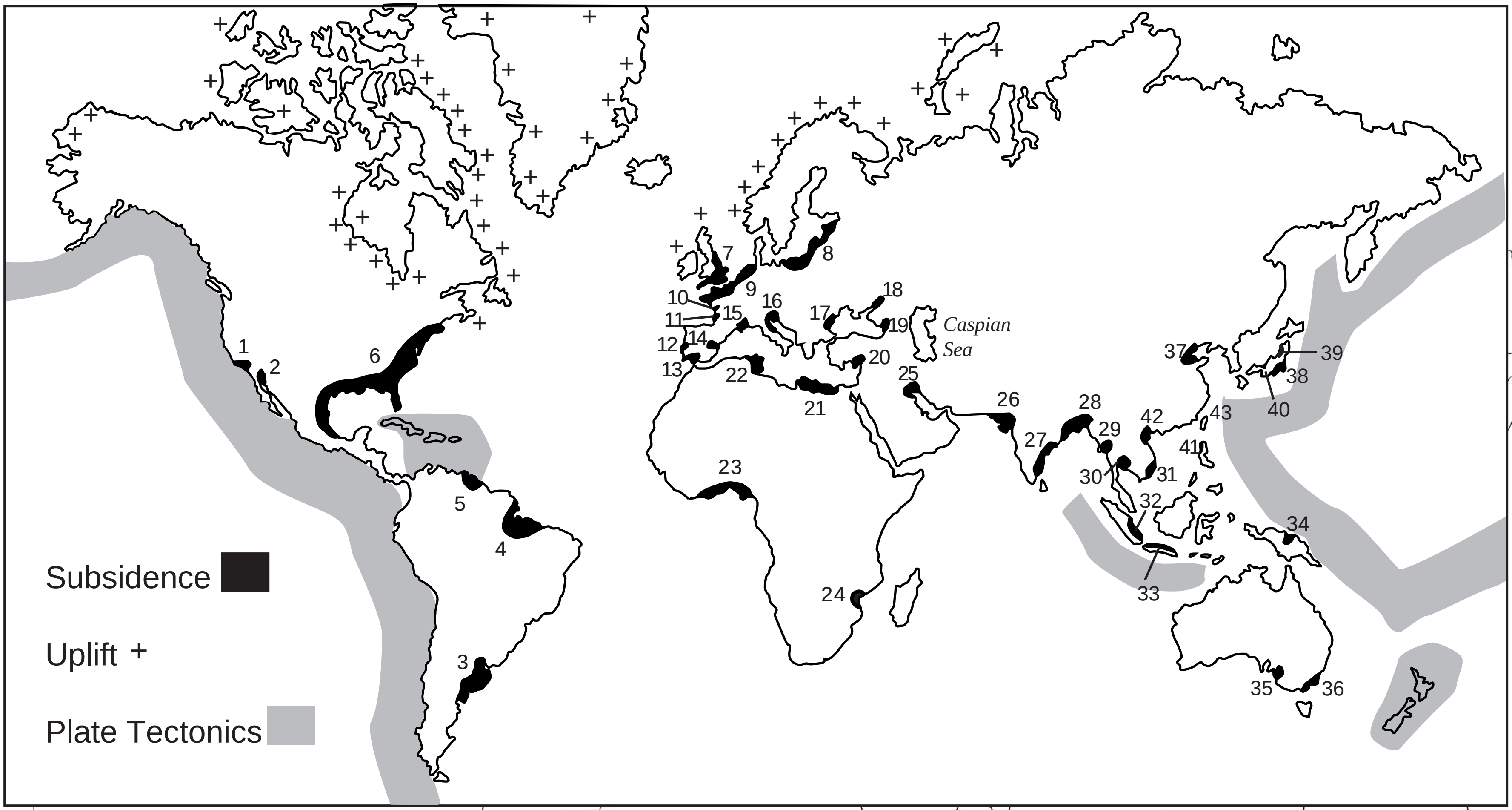

FIGURE 3

Figure 3. Principal areas of land subsidence, uplift and plate tectonics worldwide. Subsiding areas determined by evidence of tectonic movements, increasing marine flooding, geomorphological and ecological indications, geodetic surveys, and groups of tide gauges recording a rise of mean sea level greater than 2 mm per year over the past three decades. Subsidence is shown by black areas; uplift, by plus sign; plate tectonics, by shaded areas within the oceans.*Key to subsiding areas on map*: *(1)* Long Beach area, southern California; *(2)* Columbia River delta, head of Gulf of California; *(3)* Gulf of La Plata, Argentina; *(4)* Amazon delta; *(5)* Orinoco delta; *(6)* Gulf and Atlantic coast, Mexico and United States; *(7)* southern and eastern England;

(8) the southern Baltic from Estonia to Poland; *(9)* northern Germany, The Netherlands, Belgium and northern France; *(10)* Loire estuary, western France; *(11)* Vendée, western France, *(12)* Lisbon region, Portugal; *(13)* Guadalquavir delta, Spain;

(14) Ebro delta, Spain; *(15)* Rhône delta, France; *(16)* northern Adriatic from Rimini to Venice and Grado; *(17)* Danube delta, Romania; *(18)* eastern Sea of Azov; *(19)* Poti Swamp, Georgian Black Sea coast; *(20)* south-east Turkey; *(21)* Nile delta to Libya;

(22) north-east Tunisia; *(23)* Nigerian coast, especially the Niger delta; (24) Zambezi delta; (25) Tigris-Euphrates delta; *(26)* Rann of Kutch; *(27)* south-eastern India; *(28)* Ganges-Brahamputra delta; *(29)* Irrawaddy delta; *(30)* Bangkok coastal region; *(31)* Mekong delta; *(32)* eastern Sumatra; *(33)* northern Java deltaic coast; *(34)* Sepik delta;

(35) Port Adelaide region; *(36)* Corner Inlet region; *(37)* Hwang-ho delta; *(38)* head of Tokyo Bay; *(39)* Niigata, Japan; *(40)* Maizuru, Japan; *(41)* Manila; *(42)* Red River delta, North Vietnam; *(43)* northern Taiwan.

Sources: Map and caption information from E. C. F. Bird, *Submerging Coasts: The Effects of a Rising Sea Level on Coastal Environments* (New York: Wiley, 1993), p. 184. Reprinted by permission of the publisher; uplift and tectonic-activity areas adapted from S. Jelgersma, M. Van der Zijp, and R. Brinkman, “Sea Level Rise and Coastal Lowlands in the Developing World,” *Journal of Coastal Research* 9 (1993): 958-972. Reprinted by permission of the publisher.

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Stuart R. Gaffin is a staff scientist in the EDF New York office. He was trained as a climatologist and, prior to joining EDF, his scientific publications dealt with analyzing climate clycles during Earth's geologic history, including ancient sea level changes.

Since joining EDF in 1990 he has focused on atmospheric science policy issues and their interface with socio-economic concerns. He is currently serving as a lead author for the next IPCC Scientific Assessment report and is part of a team preparing a new generation of greenhouse gas emissions scenarios that will be used to make global warming forecasts over the coming century. In this work he is also clarifying the role of population growth in emissions and in quantfying how effective population policies will be in stabilizing the climate of the Earth.

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