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## About the Author

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# Coastal Inundation: Rising Sea Levels Explained

*David R. Legates, PhD*

*Sea level rise is an oft-cited result of anthropogenic climate change. The usual narrative is that sea levels rise due to the thermal expansion of seawater and the melting of ice caps, both due to the rise in air (and ocean) temperature caused by increasing greenhouse gas concentrations. However, the dynamics of why sea levels rise (or fall) relative to the coastal elevation (coastal inundation) are far more complex. This Special Report explains how and why coastal inundation occurs and provides a deeper insight into this complex issue.*

One of the most important and often discussed components of climate change is sea level rise.  Coastal states, countries, and regions—as well as the general public—are fixated on the potential effects of rising sea levels as the primary result of climate change, and for good reason. For societies that depend on coastal life for sustenance or recreation, or simply when their citizens' homes are located in low-lying areas, rising sea levels pose a serious threat, potentially displacing countless people.

Additionally, people who do not live along the coast also can be affected by the influx of displaced people and by salt contamination of soil and groundwater. Even the danger to coastal wetlands and wildlife habitats arises as a result of changes in sea levels.

However, some climate analysts have made dire predictions about the certainty and effect of sea level rise. They suggest drastic changes to public policy.[1] The reality of the situation, however, is that the dynamics of sea level rise are considerably more complex than portrayed in the mainstream media, and thus, these concerns are vastly overstated. Measurements indicate no significant recent acceleration that can be attributed to increases in carbon dioxide.  Moreover, while satellite estimates of sea level rise are markedly greater than direct observations by tide gauges, by about a factor of two, satellite estimates are complicated in coastal areas by other confounding factors contributing to net changes in coastal sea level relative to existing land mass.[2]

## Coastal Inundation (Sea Level Rise)

The definition of sea level rise, as used in the media and even academic circles, is rather ambiguous. For example, a recent article published in *Science Progress* defines sea level rise as

> an increase in the global mean sea level, caused by an increase in the volume of water in the Earth's oceans, primarily as a result of thermal expansion, the addition of further water from the melting of land-based ice sheets and glaciers, and to a smaller degree from changes in land-water storage, including the transfer of groundwater that has been pumped from aquifers.[3]

The National Geographic Society defines sea level rise as "an increase in the level of the world's oceans due to the effects of global warming."[4] In terms of the public policy, however, the Intergovernmental Panel on Climate Change (IPCC) reports are the most commonly referred to documents about climate change and its various manifestations. Although the (most recent) Sixth Assessment Report of the IPCC does not provide a formal definition of sea level or sea level rise, the Fifth Report does:

> Sea level rise from ocean warming is a central part of the Earth's response to increasing greenhouse gas (GHG) concentrations.... The height of the ocean surface at any given location [that] is measured either with respect to the surface of the solid Earth (relative sea level (RSL)) or a geocentric reference such as the reference ellipsoid (geocentric sea level).... RSL is the more relevant quantity when considering the coastal effects of sea level change.[5]

Such definitions are highly limiting and insufficient because they presuppose that sea levels do not change in the absence of warming, or in the absence of ice and snow melt or, most notably, in the absence of human activity. Indeed, estimates of sea level rise have increased since the demise of the last ice age approximately 22,000 years ago, and particularly over the past 10,000 years,[6] despite a significant decrease in air temperature during the Dark Ages Cool Period (ca. 150 AD to 950 AD) and the Little Ice Age (ca. 1350 AD to 1850 AD).

A more useful definition of sea level rise or, as it should be called, coastal inundation, is the increase in water levels relative to the adjacent land. Previously mentioned definitions seem to presuppose that land is immovable; however, as demonstrated in this *Special Report,* it is not. What affects coastal communities is the change in sea level relative to the elevation of the coast. The volume of water in the ocean can vary, either through a change in density (through a change in its temperature) or by a change in the number of molecules (water, salt, or pollution) in the ocean, or the land can change elevation by a variety of land-surface processes. Water levels change relative to the coast through both oceanic and land-based processes. Undeniably, the effect on humans and the biota are often the same whether the water rises one meter or if the land subsides by one meter.

The rise in sea level over the past 10,000 years[7] demonstrates that sea level equilibrium does not exist in nature; the assumption has been that since the last ice age ended so long ago, the ice should have quickly melted—and certainly we must have reached equilibrium by now. In fact, that is not the case. As with a thermostat in a room, changing the thermostat does not immediately change the room's temperature—some delay exists between the impulse given to the thermostat and the response of the temperature to that impulse. The same holds true here. Since the last Ice Age, the Earth has warmed and sea levels have risen as a result of the melting of the Ice Age glaciers, and now the ice caps. It is therefore likely that sea level will continue to rise either until most, if not all, of the ice caps will have melted or until the Earth enters another ice age.

The point is that at the end of the last Ice Age, the Earth warmed. This warming resulted in a melting of the ice that constituted the glaciers and ice caps, and the meltwater (along with the concomitant thermal expansion of the oceans) resulted in rising sea levels. However, the additional energy added to the climate system since the demise of the last Ice Age was insufficient to melt all the ice caps in just a few thousand years; indeed, the ice caps are still melting as a result of the Ice Age demise some 22,000 years later. Thus, the melting of the ice caps will continue until either all of them have melted (or the remnant is at a mean temperature below freezing) or another Ice Age begins and glacier ice and ice caps begin to grow.

The term "global mean sea level" is often bandied about in discussions of long-term changes in sea levels. While this can be a useful metric, it undermines the important fact that sea levels and the rates of their change relative to coastal areas vary globally.[8]

As is the case for mean global air temperature, sea levels change for a variety of reasons, which affect different parts of the globe unequally. This

*Special Report* focuses on the factors that lead to local variability in sea level changes rather than considering aggregate measures of sea level that ignore this critical heterogeneity. Understanding the intricacies of how sea levels rise and fall is considerably more nuanced than simply linking sea levels to changes in temperatures due to carbon-dioxide emissions. Clearly, when news reports highlight locations where coastal inundation has been the greatest (such as in Miami Beach and Virgina Beach), something other than global-warming-driven sea level rise must also be operating.[9] Otherwise, the story would be the same in all coastal areas of the world.

It is disconcerting to many that sea level has been rising for more than 20,000 years and that coastal areas are likely to be inundated in the future, even if air temperatures remain constant. Indeed, the longest record of measured sea levels at The Battery in New York City shows a constant rise in sea level since 1856, but no measurable acceleration that could be attributed to greenhouse gas warming.[10]

Thus, the steady rise in sea level is *not* attributable to an increase in greenhouse gases; rather, it is likely that sea levels are responding to the transition to an interglacial period and have not yet reached equilibrium, as discussed above. This steady rise in sea levels, even without a greenhouse-gas-induced acceleration, will lead to inundation of coastal areas, although the rise is relatively benign. This transition has led to a rise of only about 0.5 meters (m), 19.8 inches, at The Battery from 1856 through 2023.

The following section, "Changes in Water Levels," discusses factors leading to changes in water level while the third section, "Land Subsidence," focuses on land subsidence. Coastal erosion often occurs on dynamic barrier islands but also along other coastlines and thus it will be covered in the fourth section, "Coastal Erosion."

The aspect of sea level rise discussed here is concerned with the long-term change in the relative elevation of the world's oceans. Short-term fluctuations in sea level caused by wind-driven waves and tidal activities (both lunar-induced and solar-induced) are not the focus of this report.

## Changes in Water Levels

Simply put, sea level rise can occur in two ways—the water level can increase, or the level of the ground can decrease. With respect to the former, the water level of the oceans can change by a change in the volume of water in the oceans. Since volume is the mass of water divided by its density, the sea level of the oceans can rise by a change in density (thermosteric, by temperature, or halosteric, by salt content) or through the addition of water (barystatic changes).

**Thermal Expansion of Sea Water.** Generally speaking, as liquids warm, they expand. Water, however, is an exception to this rule in that at temperatures below 4°C, pure water expands as temperature decreases (the reason why ice floats on water). Nevertheless, most of the oceanic mixed layer[11] is substantially above 4°C, such that a warming of the oceans will necessarily lead to thermosteric expansion (expansion of the water column by a change in oceans temperature). The rate of expansion as a function of a change in temperature depends both on the salt content and the temperature of the salt water.[12] Salts, however, increase the salinity of sea water and, accordingly, the density increases (halosteric expansion). The sea level will rise through thermosteric expansion regardless of the source or cause of the warming.

Based on satellite altimetry, sea level is currently[13] rising at about 3.0 millimeters (mm) (plus or minus 0.4 mm) per year with a slight decrease in the rate toward the latter portion of the record due to cooling of the Pacific Ocean arising from the Pacific Decadal Oscillation.[14] Tom Wigley and Sarah Raper[15] estimated that between 1985 and 2025, oceanic thermal expansion would be about 1 mm to 2 mm per year, arising from a temperature increase of between 0.6°C to 1.0°C (although the actual surface air temperature rise has been only approximately 0.625°C). Since the rise in air temperature was at Wigley and Raper's lower bound, their estimate was that about one-third of the currently observed sea level rise was due to thermal expansion of sea water. This estimate is consistent with estimates by researcher Thomas Frederikse and his colleagues.[16] However, the World Climate Research Program (WCRP) Global Sea Level Budget Group[17] suggests a higher value of 42 percent, while Anny Cazenave and William Llovel[18] argue for a smaller value of about one-sixth of currently observed sea level rise.

In particular, Frederikse and colleagues[19] suggest that the thermal expansion of the oceanic mixed layer is all that is required to explain the thermosteric component; an assumption of a large-scale deep ocean thermal expansion is not required to balance the sea level budget. However, researcher Katja Lorbacher and her colleagues[20] argue that the climate models used by the WCRP's Coupled Model Intercomparison Project (CMIP) require roughly half of the multi-model thermal expansion to occur at depths below between 400 m and 580 m. These disagreements illustrate the uncertainty associated with one of the major purported components of sea level rise—the depth of warming of the world's oceans.[21]

**Melting Ice Caps and Glaciers.** Approximately 2.1 percent of the water on the Earth is in the form of ice.[22] Regardless of the cause, as air temperature rises from current levels, ice melts, particularly around the edges of the two ice sheets (one in Greenland and one in Antarctica) where mean air temperature lies near freezing. This meltwater adds to the total volume of water in the world's oceans (a barystatic change), thereby increasing global sea levels.  Paleoclimatic evidence suggests that the ice caps have been melting since the demise of the last Ice Age and that if the Earth does not enter into another glacial period, the complete melting of the Greenland Ice Sheet would contribute to a 5 m to 6 m rise in sea levels. Due to its larger expanse, the Antarctic Ice Sheet will take many millennia to melt[23] and would contribute about two-and-a-half times as much water to the world's oceans as the melting of the Greenland Ice Sheet. Even the annual melt cycle of the Antarctic Ice Sheet causes a variation in global sea levels of about 5 mm.[24]

The current rise in sea level due to the melting of ice sheets and glaciers suggest rates of 0.7 mm per year with melting of the Greenland and Antarctic Ice sheets contributing a bit more than half of that value.[25] Currently, there is some debate about whether rising air temperatures and the subsequent melting of land ice are responsible for an increase in the rate of sea level rise in the past several decades.[26]

Melting sea ice does not directly contribute to rising sea levels. Ice floats in liquid water and, as such, displaces some of the liquid according to Archimedes Principle—any solid object immersed in its liquid, is buoyed by a force equal to the weight of the fluid displaced by the solid object. However, it has been argued that the melting of sea ice *will* change the volume of ocean water due to density (thermosteric or halosteric changes) changes. In particular, changes in density due to the melting of freshwater ice into otherwise salty water will increase the volume of water in the world's oceans from halosteric changes.[27] However, this increase in volume is offset, at least partially, by the cooling of the ocean water (a thermosteric change) due to the melting of colder ice into the relatively warmer water.[28] In particular, the water provides the energy needed to melt the sea ice which, in turn, cools the oceans, albeit slightly and locally.

**Precipitation, Evaporation, and Runoff.** It stands to reason that rain falling over the oceans, evaporation from the oceans, and runoff from the land to the oceans also will affect the ocean water budget. With a warmer atmosphere, the potential for more evaporation from the oceans will exist, thereby decreasing (albeit slightly) the total mass of the global oceans (a barystatic change). But with the enhanced evaporation comes more moisture in the atmosphere, which may cause enhanced rainfall to the oceans and enhanced rainfall over the land surface, which reaches the oceans through additional runoff. Thus, the net contribution of precipitation, evaporation, and runoff are quite complex and, most likely, a local effect.

In particular, relative humidity has decreased over continental regions, but the specific humidity—a better measure of the moisture content of the air—has increased more over the oceans than over land.[29] Global precipitation has remained relatively constant and the changes in both humidity and precipitation are well within their natural variability and measurement error.[30] Regionally, however, precipitation may have changed in some locales, which might lead to local changes in sea level. Over Greenland, in particular, increased snowfall has been observed, due to the enhanced ability of warmer air to transport moisture inland. This process is expected to have cut the Greenland Ice Sheet mass losses in half.[31] Specifically, this is water that otherwise would have been in the oceans but is being stored on land as ice, thereby reducing sea levels.

**Atmospheric Circulation and Local Barometric Pressure Changes.** It is well known that strong tropical cyclone events can produce large storm surges. This is due, in part, to the high winds that drive waves onshore. A lesser, but important, component of the storm surge is due to the lowered atmospheric pressure associated with the tropical cyclone.[32] Of course, this effect is rather short-lived and local, and usually stronger in the right-front quadrant of the tropical cyclone in the Northern Hemisphere or the left-front quadrant in the Southern Hemisphere.

Could changes in atmospheric circulation and barometric pressure cause changes in sea levels on longer time scales? Yes. An example is pressure changes associated with the Southern Oscillation (the Walker Cell circulation) in the tropical southern Pacific Ocean. During the strong El Niño of 1997, positive pressure anomalies and the weakened easterly winds in the western Pacific Ocean caused sea levels to drop considerably.[33] Patterns in pressure, winds, and sea levels were opposite during the La Niña that followed.

Nevertheless, sea levels also are affected by changes in pressure and circulation patterns on smaller spatial scales and longer temporal scales. For example, atmospheric circulation is affected by the Atlantic Multidecadal Oscillation and the Pacific Decadal Oscillation, which varies the intensity of action centers of high and low pressures in the Atlantic and Pacific Oceans, respectively.[34] Changes in the Indian monsoon also have been attributed to additional observed sea level rise in the Maldives, Arabia, Somalia, and the upper Indian Ocean.[35] These and other oscillations in surface air pressure exhibit fluctuations on timescales of several decades and, consequently, sea levels can oscillate at this time scale, as well.[36]

**Oceanic Circulation Changes.** Concomitant with changes in atmospheric circulation, oceanic circulation also will affect regional sea levels due, in part, to the wind-driven effect (the wind-driven large-scale oceanic circulation, not waves seen at beaches) but also to a slowdown of the meridional overturning circulation, particularly in the Atlantic Ocean.[37] These sterodynamic changes in sea levels arise from changes in oceanic circulation, its density (that is, its salt content), and its temperature.[38]

As the oceans cover nearly three-quarters of the planet's surface, they play a key role in redistributing energy from the tropics to the poles, thereby mitigating the equator-to-pole temperature gradient. But ocean circulation is extremely complicated; surface currents interact well with the atmosphere and are largely wind-driven, whereas deepwater currents are more complex and interact with the atmosphere only at the polar extremes. Changes in temperature and density can be affected by oceanic circulation and, by the effect of winds, through atmospheric circulation changes as well as barystatic changes through precipitation, evaporation, and land-surface runoff.

In addition to horizontal circulation changes, the Ekman transport mechanism—the process by which friction of the wind causes ocean circulation—also induces upwelling and downwelling that redistributes temperature and density changes vertically within the mixed water layer. Through the combination of surface wind stress, the Coriolis force, and friction, vertical motions are induced due to the requirement of mass conservation. Thus, changes in ocean circulation can occur vertically, which also serves to redistribute temperature and density gradients throughout the column of water.

Nevertheless, changes in oceanic circulation can account for a non-trivial rise in sea levels. One assessment shows a change between 15 centimeters (cm) and 20 cm in New York City by 2100 due solely to a weakening of the meridional overturning circulation in the Atlantic Ocean,[39] while another suggests about half that for other cities in northern North America.[40]

**Effects of Planetary Rotation and Gravity.** Another possible reason for the global redistribution of water in the world's oceans arises from a concept known as "rotational eustacy."[41] Variations in the Earth's rotation are induced by interactions within the Sun–Earth–Moon system (including the effects of Jupiter and nearby planets) and the solar wind that affects the Earth's magnetosphere. As a result, water is redistributed among the tropics and poles due to the increase in the equatorial diameter of the Earth that occurs when the Earth's rotation increases. Sea levels, therefore, rise in the equatorial Pacific and Indian Oceans during periods of the Grand Solar Minima, while they decrease during the Grand Solar Maxima.[42] Observed variability in sea levels of 20 years to 26 years in duration can be attributed to the Earth's rotation.[43]

The Earth's gravitational attraction also is an important component in global and regional changes in sea levels. Overall, where gravitational forces are stronger, sea levels will be higher,[44] which is counterintuitive. In fact, as an ice sheet melts, sea levels decrease near the melting ice sheet but rise at a considerable distance from the melting ice sheet due to changes in gravitational forces. Since gravity is not constant over the entire planet, local and regional variations exist in sea level resulting from differences in the gravitational force.[45]

## Land Subsidence

In addition to changes in water content of the oceans (barystatic changes), an apparent change in sea level can be induced by changing land elevations. Subsidence (descending land) or rebound (rising land) can occur from a number of processes. Isostatic processes—where the crust returns to a state of equilibrium due to the addition or removal of surface forces—usually occur over long time scales, often involving ice sheet formation and removal. But changes in coastal elevation also can be induced by glacial outwash, channelization of rivers, pumping of groundwater, and changes in land use.

While often overlooked, these four factors can greatly affect interpretation of regional sea level changes. For example, glacial outwash builds coastal regions where ice sheet meltwater exits into saltwater bays and seas or directly into the ocean. This outwash can be used to date changes in sea levels over time when sea levels fall or to minimize the effect of sea levels when sea levels rise.[46] River channelization makes water flow faster and reduces sedimentation on river deltas, increasing relative sea levels by nearly 2 mm per year.[47] Groundwater extraction often leads to coastal subsidence, which can adversely affect streamflow, wetlands, and related ecosystems in areas where groundwater extraction exceeds recharge for large areas and over long time periods. Estimates show that on average, large-scale removal of groundwater reserves for cropland irrigation—particularly in China, India, Pakistan, and the United States—results in a sea level rise of about 0.8 mm per year, about one-quarter of the current global sea level rise as assumed by the IPCC.[48] Moreover, changes in land use resulting in wetland loss and "coastal squeeze" will lead to increasing sea levels relative to the coastline.[49]

While much research has focused on removing these factors from estimates of global and regional sea level changes, they are indeed important because the human effect of coastal variations is the same regardless of whether the land is subsiding or the water is rising. Thus, from a social science perspective, sea level rise is relative.

**Isostatic (Glacial) Subsidence.** The presence of an ice sheet exerts a significant force on the Earth's surface. Consequently, the land deforms and subsides beneath the weight of the ice. As the ice melts, the weight is reduced and isostatic post-glacial rebound occurs as the land responds by rising vertically. This phenomenon is most evident in the Baltic Sea[50] region where the average isostatic rebound is about 4 mm to 5 mm per year [51] with a maximum of 9 mm per year in the Gulf of Bothnia.[52] Beyond the margin of the ice sheet, however, the land is pushed up due to the weight of the ice on the adjacent land. As a result, the land descends as the ice is removed. This can be seen along the Atlantic seaboard where coastal New Jersey, Delaware, and Maryland exhibit the highest rates of sea level rise, largely due to coastal subsidence, as these states were located near the margin of the Laurentide Ice Sheet about 21,000 years ago.[53] The maximum rate of isostatic subsidence is about 1.7 mm per year at Reedy Point in Delaware. Thus, isostatic subsidence and rebound is not trivial.

**Channelization of Rivers and Creation of Impoundments.** To control floods, enhance navigation, decrease erosion, and improve local drainage, river banks are usually reinforced, levies are occasionally built, and the rivers themselves are often straightened or deepened. This enhancement of the river flow, called *channelization,* causes (1) water to move more efficiently down the river and flow into the ocean or lakes and seas and (2) a reduction of sediment replenishment in backwater areas. Through straightening of the river channel and the subsequent increase in the river gradient, water moves faster down the river and provides runoff to the oceans more quickly. Construction of water impoundments in the world's artificial reservoirs has reduced global sea levels by an average rate of approximately 0.5 mm per year since 1960.[54]

Channelization also leads to enhanced erosion of the waterway and a lack of deposition and subsequent subsidence in the flood plain that is isolated by the channelization process.[55] Limited replenishment of sediments occurs due to the isolation of the floodplain from the river itself. As sediments compact over time, they are not replenished by flood events and thus the land surface subsides at a rate faster than if the river was not channelized. Consequently, the ability of the river to provide sediment to the flood plain is dramatically altered.[56]

Along the coast, floodplains and wetlands are not supplied by spillover during flooding events. This causes the wetlands to subside through compaction without ample replenishment and thus the relative sea level rises faster in river deltas[57]—wetlands created when a river empties into a larger body of water.

**Groundwater Pumping.** The largest source of subsidence of land is the compaction of soils that is caused by excessive pumping of aquifer systems.[58] In some regions, groundwater pumping can result in compaction of the subsoil systems where the open pore spaces in the soil collapse due to the removal of water.[59] Coastal cities that are built on soft sediments are most susceptible to subsidence due to groundwater pumping. Khulna and Kolkata in the Ganges-Brahmaputra River Delta,[60] and Hanoi in the Mekong Delta,[61] for example, are coastal and river delta regions that are experiencing significant subsidence due to excessive pumping of groundwater reserves. In the United States, groundwater depletion is responsible for 2.1 percent of the observed sea-level rise between 2001 and 2008.[62]

**Land Use Changes and Loss of Wetlands.** Marshes, swamps, and bogs that are occasionally saturated with water are termed wetlands. Coastal wetlands act as buffers to protect the adjacent land from erosion and flooding due to coastal storm surges, excessive streamflow, land subsidence, droughts, and rising sea levels. In the continental United States, more than 5 percent of the land area is covered by wetlands, nearly all of which are freshwater.[63]

Coastal development, agricultural expansion, and insect or pest reduction have led to many wetlands being filled or drained. For example, changes in coastal land use in Argentina have led to an extensive loss of wetlands.[64] A total of 33 percent of marshes and 6 percent of steppe vegetation have been replaced by mudflats due to rising sea levels as well as harbor development, landfilling, and spoil dredge deposition, in addition to the growth of pastures and forests in the lower Paraná River Delta.[65] Most of this area of development has led to depositional landforms and increased sedimentation.[66]

## Coastal Erosion and Deposition

While land subsidence and rebound are vertical motions associated with the coastal landscape, sand and other coastal material can be transported laterally to reshape the coastline. Many coastal areas exhibit continuing patterns of erosion and deposition as a result of storm surges and littoral drift. Particularly along the North American Atlantic coast (but elsewhere as well), barrier islands are sand deposits that constantly evolve and provide an important contribution to coastal geology and ecology.

Constructive waves are much lower in energy and have a much weaker backwash. They produce depositional landforms and are most prevalent during normal wind and wave action. By contrast, destructive waves contribute to coastal erosion in that their retreat to the sea is much more powerful than their ability to wash waves upon the shoreline. They are high-energy waves and are most prevalent during tropical cyclones and nor'easters. Erosion by destructive waves occur through hydraulic action (the force of the water that dislodges sand and other particles which are removed by the ocean), compression (through trapped air in rock cracks), abrasion (material removed by other processes that subsequently is forced against coastal areas to provide additional erosion), and attrition (dislodged rocks and stones impacting themselves, thereby providing an additional reduction of the size of eroded material).

## Problems with Prognostications of Future Sea Level Rise

Concern over sea level rise and its potential devastating results were forecast even before the IPCC's First Assessment Report was released. Two years earlier, in 1989, Noel Brown, director of the New York Office of the United Nations Environment Program, indicated that rising sea levels would cause entire nations to be wiped off the face of the Earth if the global warming trend was not reversed by 2000. This would cause a mass migration of "eco-refugees" that would threaten to unleash political chaos.[67] This and other disasters forecast by the United Nations never occurred.[68]

Locations that are often cited as being destined to succumb to rising sea levels, accelerated by global warming, include island nations in the Pacific and Indian Oceans, and coastal regions all across the world, including Bangladesh and the deltas of the Padma (Ganges), Meghna, and Jamuna Rivers, for example. The Maldives, the Marshall Islands, Tuvalu, and Kiribati have garnered particular attention as classic island countries that are likely to disappear under rising sea levels.

Tuvalu's alleged descent into the ocean apparently began in the early 1990s when Tuvalu's prime minister announced that Tuvalu was "the world's first victim of climate change" and that "sea level rise [driven by the greenhouse effect] threaten[s] the very heart of our existence."[69] Since then, Tuvalu has been referenced numerous times in the popular press as the classic example of the threat that anthropogenic warming-induced sea level rise poses to low-lying islands and atolls. This would be particularly disconcerting if it were true; it is not. Tuvalu lies near the center of a large region in the Pacific Ocean where sea level is *falling*, not rising.[70] This fall has been ongoing since the beginning of the satellite record in 1993 and has amounted to almost 3 cm over the past two decades.[71] Nevertheless, total land area in Tuvalu has *increased* by nearly 75 hectares (about 3 percent) in the past 40 years.[72] In other areas where sea level rise is supposedly an existential threat—including Bangladesh, Fiji, Goa, and the Maldives—tide gauges show no significant trend.[73]

Bangladesh, by contrast, is a confluence of a number of factors that affect the perception of a rise in sea levels.[74] The Indian Ocean and Bay of Bengal region lies approximately 40 m to 100 m below the surface of a reference ellipsoid and is the lowest of anywhere on the globe.[75] The area also is home to many earthquakes and tropical cyclones, due to its location on the eastern edge of the Indian subcontinent and proximity to the tectonically active Himalayas. Moreover, southern Bangladesh is undergoing tectonically driven subsidence at a rate up to five times the predicted rise in sea levels.[76] Other studies have found that a relationship exists between the intensity of the Indian summer monsoon and substantial sea level incursions that naturally affect coastal Bangladesh.[77] These and other factors (including accelerated ground subsidence due to groundwater withdrawal and hydrocarbon extraction[78]) highlight the fact that attributing all changes in water levels to anthropogenic greenhouse gas concentrations is highly misleading and overly simplistic.

## Three Issues Often Raised About Sea Level Rise

Proponents of aggressive greenhouse gas reduction policies often raise several issues related to sea level rise. The overarching concern is that net zero (zero net production of carbon dioxide) must be achieved to *stop* sea level rise. As noted, sea levels have been rising since the demise of the last Ice Age approximately 20,000 years ago.[79] With all other factors held constant—including concentrations of atmospheric carbon dioxide (and other greenhouse gases)—global sea levels would continue to rise, just as they have for the past 7,000 years. Despite the evidence, the alarmist narrative continues to focus on the correlation between atmospheric carbon dioxide concentrations and rising sea levels, even though any attribution of causation is speculative.

Following are three issues that are commonly raised about sea level rise and atmospheric greenhouse gas concentrations.

**Example 1.** *The most serious potential adverse effects of human-induced climate change are the increased risk of storm surge and flooding in coastal areas from sea level rise. The observed sea level rise is already increasing the risk of storm surge and flooding in some coastal areas.*

Coastal inundation arising from the natural rise of sea levels, coastal subsidence, or the reshaping of coasts and barrier islands from storm-induced erosion are undoubtedly leading to serious potential risk. These processes are sudden and without much warning, which makes them more dangerous in their own right. Nevertheless, coastal warning systems are far more beneficial to the protection of life and property from these events than reducing the amount of carbon dioxide in the atmosphere. This is especially important since sea levels are rising from natural, non-anthropogenic causes and the influence of greenhouse gases on sea level rise is exceedingly small. Moreover, even if the United States could stop all anthropogenic greenhouse gas emissions today, there is no evidence that this would mitigate whatever processes—natural or otherwise—that are currently affecting sea level rise. For example, even if the United States were to completely abate all carbon-dioxide emissions, the result by the end of the century would be less than 0.2°C (about 0.4°F) of global temperature mitigation.[80]

**Example 2.** *In areas where an increase in water flow is projected, water resource issues will still arise from problems associated with air temperature rise and precipitation variability.*

Sea level rise is only one of a number of water quality and quantity issues that affect coastal areas around the world. Aside from the lack of causal connection between incremental greenhouse gas emissions and sea level rise, there is no reason to assume that if sea levels stopped rising or if net zero were achieved, that most coastal problems would be alleviated. Instead, given the natural variability associated with air temperature and precipitation, it is to be expected that floods and droughts, in particular, will continue to have a substantial effect on coastal water resources.

**Example 3.** *The risk associated with industry, infrastructure, and settlements to climate change are generally greater in vulnerable locations, particularly coastal and riverine areas, and areas whose economies are closely linked with climate-sensitive resources. These areas are generally subject to natural factors and forces that have far more direct and measurable effects.*

This is unsurprisingly true, since risk is always greater when vulnerabilities increase and when economies are tied closely to the cause of the increasing risk. Vulnerability is a pre-existing fragile condition that sets the stage for the effect of a natural risk on the local economy.[81] But, given that storms and coastal events will disproportionately affect the locations that are the most vulnerable to these events, it stands to reason that climate-sensitive resources will be most affected. Human-induced climate change through sea level rise *would* exacerbate this influence *if* it were significant. So, while the risk to vulnerable coastal communities and economies is real, the anthropogenic component of climate change does not significantly alter that risk.

The main factors associated with coastal effects are present, regardless of whether carbon dioxide has any influence on sea level rise. Land loss occurs not only from rising ocean levels and coastal subsidence, but also from inundation effects and beach erosion during storm and high wave events. Rising sea levels also lead to wetland submergence and habitat loss. But the key issue to note is that the effect of sea level rise from rising concentrations of atmospheric carbon dioxide is speculative and uncertain. Therefore, efforts to reduce carbon-dioxide emissions and other greenhouse gases will have no measurable effect on the coastal impact of storms and natural effects that lead to rising sea levels and the risks related to such rises.

## Conclusion

The popular misperception is that the oceans are like an immense bathtub—water volume is increased through melting ice (barystatic changes) or by changing density, largely through an increase in its temperature (thermosteric changes). Thus, the premise is, as the oceans warm and increase mass through melting ice, sea levels should rise globally and relatively evenly. Such is clearly not the case.

While these two processes dominate on a global scale, they are measurably exceeded by other influences that affect relative sea levels at regional or local scales. The atmosphere and ocean water are both dynamic and their currents and subsequent changes in them play a key role in creating relative changes in sea levels. The hydrologic cycle of ocean evaporation, precipitation, and runoff also contributes to variations in sea levels both in space and time. Even the effects of planetary rotation and gravity play a non-trivial role in sea level fluctuations and variability.

Moreover, an apparent rise in sea level can be induced by changes in the elevation of the adjacent land. Isostatic subsidence and rebound due to glacial loading or unloading is a main reason for changes in coastal elevation. Groundwater pumping can also lower elevations due to compaction of water-bearing soil layers while the channelization of rivers and land-use changes prohibits replenishment of sediments in floodplains behind manmade levies and along coastal wetlands. In addition, littoral drift changes barrier islands, which reshapes coastlines and affects local sea levels.

Complicating the problem of local changes in relative sea levels is that nothing occurs by itself. The interface between land and water changes with sea level, which affects the processes that create, mitigate, or exacerbate sea level rise. Even the change in sea level can, in turn, affect the Earth's rotation and influence the local gravitational field.[82] Thus, the issue of coastal inundation (sea level rise) is not a simple question solely driven by changing air temperatures due to carbon-dioxide emissions, as it is often presented in the mainstream media.

Although the mean global sea level does not comprehensively describe the spatial distribution of sea level rise, mean global sea level, like the estimate of mean global air temperature, is a way of summarizing this distribution. When compared with the Keeling Curve of carbon-dioxide concentrations taken at the Mauna Loa Observatory (temporarily moved to Maunakea due to the eruption of the Mauna Loa shield volcano in 2022), a strong correlation exists with the mean global sea level. However, this correlation does not imply causality.

As demonstrated here, the rise in mean global sea level has been ongoing since the demise of the last Ice Age, approximately 20,000 years ago.[83] Sea levels were rising at an accelerated rate between 7,000 years and 15,000 years ago, and that change in the rate of global sea level rise was *not* solely due to atmospheric carbon-dioxide concentrations. A much better explanation is that most sea level rise is a response to the interglacial period and that equilibrium of the polar ice caps has not yet been attained.

But is the rate of sea level rise increasing such that sea levels will rise between 4.6 m and 9.1 m (15 feet and 30 feet) from 2023 to 2100 as some alarmists claim?[84] This extreme estimate is clearly political hype and does not represent the science, even as advocated by climate alarmists. The largest estimates of mean global sea level suggest the rate will increase during the 21st century to about 3 mm per year (about 9 mm by 2100), more than 50 percent more than the rate in the 20th century.[85]

However, Nils-Axel Mörner argues that the estimated rate for the 21st century is exaggerated, with a more appropriate value being about a third of that.[86] Satellite altimetry, in particular, suggests rates of increase that are much higher than direct observations, but they rely on calibrations that are biased and subjective.[87] When coastal subsidence and uplift is taken into account, extreme rates of the increase in sea level rise appear erroneous. Regardless, as pointed out in this *Special Report*, these levels are driven by myriads of factors other than carbon-dioxide emissions. In vulnerable areas, the potential for any impression on coastal communities by virtue of sea level rise over a human time scale is dwarfed by storms and other natural influences of great variability, and so, is of insignificant marginal effect.

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