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Journal

Water, 13(16)

ISSN

2073-4441

Authors

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Publication Date

2021

DOI

10.3390/w13162151

Coastal Adaptation to Climate Change and Sea-Level Rise

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Abstract: : The Earth's climate is changing, ice sheets and glaciers are melting, and coastal hazards and sea level are rising in response. With a total population of over 300 million situated on coasts , including 20 of the planet's 33 megacities (>over 10 million people), low-lying coastal areas represent one of the most vulnerable areas to the impacts of climate change. Many of the largest cities along the Atlantic coast of the U.S. are already experiencing frequent high tide flooding, and these events will increase in frequency, depth, duration and extent as sea levels continue to rise at an accelerating rate throughout the 21st century and beyond. Cities in Southeast Asia, or islands in the Indo-Pacific and Caribbean are also suffering the effects of extreme weather events combined with other factors that increase coastal risk. While short-term extreme events such as hurricanes, El Niños, and severe storms come and go and will be more damaging in the short term, sea-level rise is a long-term permanent change of state. Yet, the effects of sea-level rise compound with other hazards, such as increased wave action, or loss of ecosystems. As sea-level rise could lead to displacement of hundreds of millions of people, this may be one of the greatest challenges that human civilization has ever faced, with associated inundation of major cities, loss of coastal infrastructure, increased saltwater intrusion and damage to coastal aquifers among many other global impacts, as well as geopolitical and legal implications. While there are several short-term responses or adaptation options, we need to begin to think longer term for both public infrastructure and private development. This article provides an overview of the status on adaptation to climate change in coastal zones.

Citation:

Academic Editor:

Received: date
Accepted: date
Published: date

Keywords: 1. sea-level rise; 2. climate change; 3. shoreline erosion; 4. adaptation; 5. Managed retreat.

1. Introduction

Climate has been changing as long as we have had an Earth and the Sun. The amount of solar radiation we receive from the Sun has varied over tens of thousands of years due in large part to the Milankovitch Cycles, which control the distance between the Earth and the Sun. Sea level is intimately tied to ocean warming and therefore climate change. As temperatures rise during warm or interglacial periods, seawater expands, and the ice covering Antarctica, Greenland and the mountain glaciers of the planet melts, increasing sea levels globally. During cooler (glacial) periods, sea level is lowered as seawater cools and takes up less volume, and more precipitation falls as snow, freezes to ice, and allows ice sheets and glaciers to expand.

Geological evidence, primarily from sediments and fossils collected from the continental shelf, provides clear global confirmation that the rapid rise of sea level following the end of the last ice age about 20,000 years ago, slowed nearly to a halt about 7-8,000 years ago (Griggs and Patsch, 2019). From that time until about the mid-1800s, sea level rose at less than 1 mm/yr. With the onset of the Industrial Era and the increasing combustion of fossil fuels (coal, oil, and natural gas), the greenhouse gas content of the atmosphere gradually increased. Since the onset of the industrial revolution, the content of carbon dioxide in the atmosphere has increased from natural levels varying from about 175-275 ppm to 419 ppm today, an increase of about 50 percent. Greater greenhouse gas concentrations have amplified the Earth's natural greenhouse effect leading to a gradually warming planet. Over the past 100 years the Earth's climate warmed by about 1º C (1.8º F; Figure 1). As temperatures rose, ice sheets and continental glaciers melted at an increasing rate and seawater warmed and expanded. Global sea levels rose in response, raising sea levels at a more rapid rate than over the previous 7,000-8,000 years (Church et al. 2013).

Today, hundreds of tidal gauges around the coastlines of the world are recording sea water levels, but the first measurements date from the mid-1800s. Tide gauges track local or relative sea level, which is the elevation of local sea level relative to land motion, including uplift and subsidence. Globally averaging historic records documented sea-level rise values ranging from ~1.2 to ~1.7 mm/year (4.7 to 6.8 in./century) over much of the 20st century (Griggs, et al, 2017). These tide gauges are not evenly distributed, however, with most in the northern hemisphere (U.S. and Europe). While tide gauges provide relative or local sea-level rise rates, a recent evaluation of 32 tide gauge records from all U.S. coastlines revealed that, with the exception of the U.S. Northeast Coast and Alaska, every coastal location in the continental U.S. has experienced an upturn in relative sea-level rise rate since 2013-2014, despite wide differences in the magnitude and trending direction of relative sea-level rise acceleration (Boon, et al, 2018).

In 1993, two satellites were placed in orbit (Topex and Poseidon), followed by Jason-1, -2, and -3, with the objective of measuring global or absolute sea level accurately and precisely from space using lasers. The average sea-level rise rate from these satellite measurements over their 27 years of operation is now 3.4 mm/year (13.4 in./century), but this rate is accelerating (Nerem, et al., 2018). More recently, Veng and Andersen (2020) utilized independent data from European satellites to increase both the time period covered (1991-2019) as well as the geographic distribution of data (from 66 degrees to 82 degrees latitude). The European satellites extended the spatial coverage from 66º to 82º-north latitude. Satellite-based observations now allow us to measure that the average acceleration of sea-level rise has been 0.1 mm/year^2 between 1991 and 2019. The average rate of rise of 3.4 mm/year from satellite measurements over the past 26 years has now increased to approximately 4.8 mm/year, or about 18.9 in./century (Figure 2), based on new observations of the past 10 years (https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html).

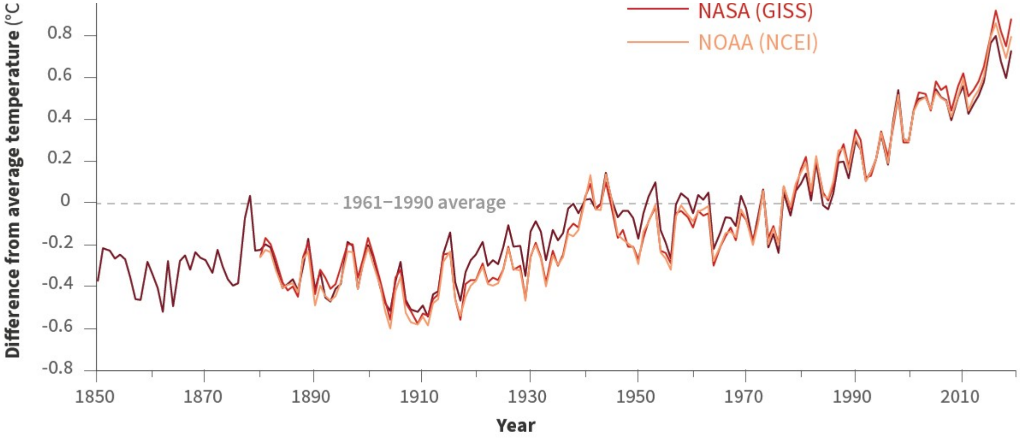

Figure 1. Annual global surface temperature 1850-2019. Source: (National Academy of Sciences, 2020)

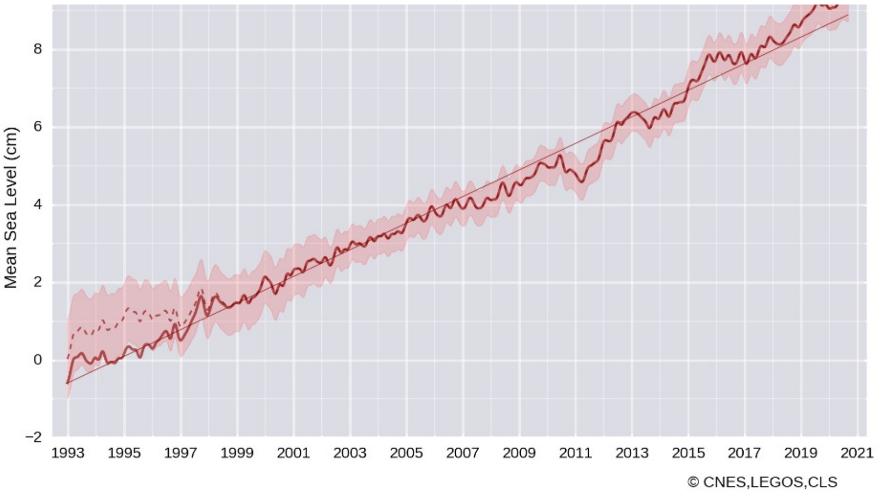

Figure 2. Sea-level rise from satellite altimetry 1993-2020. Source: based on Ablain et al (2017), obtained from: https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html

2. Future sea levels

Tidal gauges and satellite-based observations provide a good understanding of past and present sea level. However, the challenge for coastal regions around the planet is projecting sea-level rise and its impacts into the future. This is an important objective of the Intergovernmental Panel on Climate Change (IPCC), but individual geographic entities (local to national governments) are simultaneously involved in developing future sea-level rise projections for their own regions (USGCRP 2017). Future climate projections are developed through global climate models, which include uncertainties and assumptions of future greenhouse gas emissions (i.e. Representative Concentration Pathways) and model the inputs or factors that will affect global climate, including ice melt, and consequently sea-level rise (Church et al. 2013). Today, the predictions or projections for the next few decades are in general agreement but estimates for the end-of-century vary between models and depending on Representative Concentration Pathways (RCPs), with increasing wider uncertainties and ranges by 2100. The latest estimates indicate that values for the end of the century (2100) range from a low of ~50 cm (~20 inches) to as high as ~310 cm (~10 feet), as a function of greenhouse gas emission scenarios and various probabilities or uncertainties, especially concerning the extent of Greenland and Antarctica ice melt (IPCC, 2014; DeConto and Pollard, 2016; NOAA, 2019; Figure 3).

Understandably, while projections of future sea levels typically only extend out to 2100 due to increasing uncertainties, sea-level rise will not stop then, but will likely continue for decades and even centuries into the future. Even in the absence of further greenhouse emissions, the sea-level rise inertia will continue, and sea levels will increase in the future. There are approximately 66 meters (~216 feet) of potential sea-level rise contained in the ice sheets and glaciers of Antarctica, Greenland, and the mountain glaciers of the planet (http://www.antarcticglaciers.org/glaciers-and-climate/estimating-glacier-contribution-to-sea-level-rise/). No one believes that these will all melt this century, but this is the total potential that exists if it were all to melt.

In just this century, raising sea level just 1 meter will create substantial issues for developed shorelines around the planet. A recent global assessment determined that about 110 million people live below present high tide today, and 250 million occupy land below current annual flood levels (Kulp and Strauss, 2019; McGranahan, et al., 2006). For the first few meters of sea-level rise, more than 3 million more people are at risk with each vertical 2.5 cm (one inch) of rise. One billion people today, approximately 13% of the entire global population, live less than 10 m (33 feet) above today's high tide.

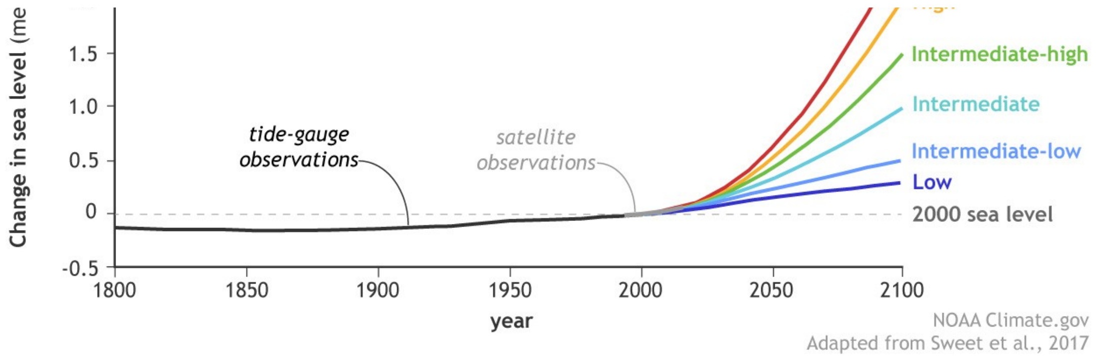

Figure 3. Possible future sea levels for different greenhouse gas emission pathways. Observed sea level from tide gauges (dark gray) and satellites (light gray) from 1800-2015 show historical trajectory. The scenarios differ based on potential future rates of greenhouse gas emissions and differences in the plausible rates of glacier and ice sheet loss. Source: NOAA Climate.gov graph, adapted from Figure 8 in Sweet et al., 2017.

3. Effects of Climate Change and Sea-Level Rise in Coastal Areas

3.1. How future sea-level rise will affect coastal areas

Looking to the future, the potential loss of public infrastructure and private development due to sea-level rise will have enormous economic impacts on coastal nations globally (Nicholls & Cazenave 2010). Different coastal environments face unique hazards, however, as a result of their geology and topography, regional climatic settings, and development patterns. Coasts display a variety of landforms (e.g. estuaries, beaches, dunes, low bluffs, high cliffs and steep mountains) and also differing development patterns (low to high density). Lower-lying shoreline areas are more vulnerable to flooding from wave action, hurricanes, large storm waves acting simultaneously with very high tides, and atop the higher sea levels of the future. Higher-elevation areas, such as bluffs, cliffs and coastal mountains are more vulnerable to coastal erosion from wave attack during high tides or elevated sea levels (Anderson, et al., 2020). Nonetheless, higher sea levels in the future will mean: 1) more frequent and higher elevation flooding of low relief shoreline areas, followed by permanent inundation and loss of beaches and coastal wetlands (Vitousek, et al., 2017; Thorn, 2018); and 2) waves reaching and impacting the base of coastal cliffs, bluffs, and dunes more often, leading to increased erosion rates.

The economic impacts of coastal hazards will also vary with the degree and type of development and whether public or private. Passive erosion, or the gradual loss of beaches from continuing sea-level rise where the back beach has been fixed by a seawall, rock revetment or some other structure, will be a major challenge along highly developed and armored coasts (Griggs, 2005; Vitousek, et al., 2017b; Leo et al. 2019). Along the intensively developed ~325 km (233-mile) coastline of southern California, for example, where millions of people use the beaches, 38 percent of the entire shoreline has now been armored (Figure 4), and with rising sea levels, the issue of passive erosion and beach loss will become more pressing (Griggs and Patsch, 2019).

3.2. Nuisance flooding

To date, much of the research on the impacts of sea level rise has focused on the occurrence and damage of sea level extremes, such as from tropical cyclones or other storms (Hallegatte et al. 2013; Reguero et al. 2015; Hsiang et al. 2017) as sea-level rise contributes to more flooding by increasing the probability of extreme floods (Menéndez & Woodworth 2010; Losada et al. 2013; Vitousek et al. 2017a). However, nuisance flooding (also known as sunny days floods) has increased on U.S. East coasts in recent decades due to sea-level rise (Union of Concerned Scientists, 2017 and 2018).

Figure 4. Rip-rap revetment armoring a section of the Malibu, California, shoreline. Courtesy: California Coastal Records Project)

Coastal nuisance flooding is considered to be minor flooding from the seas that causes problems such as flooded roads and overloaded stormwater systems, which can be major inconveniences for people and provide habitat for bacteria and mosquitoes. Based on over 70 years of observations from the U.S., a study found that the total number of nuisance flooding caused by tidal changes increased at an exponential rate since 1950, adding 27% more nuisance flooding events in 2019 (Li et al. 2021). Estuaries show the largest changes because of tide changes associated to anthropogenic alterations such as dredging of channels, land reclamation, other development and changes in river flows.

Frequent high-tide flooding also affects local economic activity. For example, a study found that frequent high-tide flooding in Annapolis, Maryland, found that frequent high-tide flood has reduced visits to the historic downtown by 1.7% but with 3 and 12 inches of additional sea-level rise, high-tide floods would reduce visits by 3.6% and 24%, respectively (Hino et al. 2019). The impacts of high-tide flooding should also be better characterized and understood to help guide efficient local responses and include them in urban planning.

3.3. Short-term coastal hazards versus long-term sea-level rise

Climate change will also influence coastal hazards beyond sea-level rise. While considerable research and planning effort today is focused on increasing the accuracy of future sea-level rise projections, in the short- or near-term (until perhaps mid-century), it will likely be the extreme events that will be more damaging to coastal development and infrastructure (Griggs and Patsch, 2019). These events include cyclones, typhoons and hurricanes, large storm waves arriving simultaneously with very high tides or elevated water levels, and tsunamis.

- Interannual changes

For example, the large El Niño of 1982-83 raised sea levels along the California coast, as recorded at tide gauges, to the highest values ever registered, ranging from 29 cm (11.4 in.) above predicted tidal heights at San Diego, 32.3 cm (12.7 in.) at Los Angeles, and 53.9 cm (21.2 in.) at San Francisco. These extreme El Niño related tides were the highest water levels recorded during the prior 77 years in San Diego, 59 years in Los Angeles, and 128 years in San Francisco. Using average rates of global sea-level rise from satellite altimetry (3.4 mm/yr. or 13.4 inches/century), these elevated 1983 El Niño water levels were equivalent to 85, 95, and 158 years of sea-level rise at recent rates, respectively, at these three locations. In addition to elevated water levels, seven major storms brought large waves during periods of high tides. These combined to produce $265 million in coastal damage to oceanfront property (in 2020 dollars). Damage was not restricted to broken windows and flooding of low-lying areas – 33 oceanfront homes were totally destroyed and dozens of businesses, parks, roads and other public infrastructure were heavily damaged (Figure 5).

Figure 5. Storm waves arriving simultaneously with high tides broke through the front of these homes built along the northern Monterey Bay, California, shoreline

Yet again, in mid-January 1988, very large waves struck the southern California coast suddenly and left $62 million in losses (Griggs and Patsch, 2019). A decade later, during the El Niño winter of 1997-98, intense rain storms hit southern California, washing out roads and railroad tracks, overflowing flood control channels and battering the coast, leading to 17 fatalities and over half a billion dollars in damage (Storlazzi and Griggs, 1998). Recent El Niños along the US West Coast and Pacific have also setting new records and cause widespread flooding and erosion (Barnard et al. 2011, 2015a, 2017).

- Hurricanes, Cyclones and Typhoons

While other coastal areas around the planet do not experience the impacts of El Niños, they have their own extreme events to contend with. On November 8, 2013, Typhoon Haiyan, the strongest tropical cyclone ever to make landfall based on wind velocities, cut a devastating swath across the central Philippines in the tropical western Pacific. The storm strength was equivalent to a Category 5 hurricane (the highest level of intensity) with sustained wind speeds at landfall of 195 mph, the highest ever recorded, and gusts up to 235 mph.When wind speed reaches about 120 mph, it is no longer possible for a human being to stand up. Thirteen percent of the nation’s entire population, nearly 13 million people, was affected. There were at least 6,300 fatalities and 28,700 injuries. Because of the lightweight construction materials commonly used in the Philippines and the extreme wind velocities, over 281,000 houses were reported as destroyed, with 1.9 million people displaced (Figure 6).

Figure 6. Damage from Typhoon Haiyan in The Philippines, 2013.

A year earlier Superstorm Sandy produced a record storm surge in New York City. The water level at the southern tip of Manhattan, topped 13.9 feet, exceeding the 10.2-foot record set by Hurricane Donna fifty-two years earlier, driven by the size and angle of superstorm Sandy along the US East Coast. For perspective, the average long-term sea-level rise rate for the NOAA tide gauge at the southern end of Manhattan Islands has been 2.87mm/yr. since 1856. Seventy-two lives were lost and losses reached $50 billion from damage to homes and other buildings, roads, boardwalks and mass transit facilities in low-lying coastal areas of both New York and New Jersey from storm surge and large waves.

Tropical cyclone induced-coastal flooding will worsen under climate change from the combined effects of sea-level rise and changes in storm activity. For the U.S., the compound effects of SLR and tropical cyclone climatology changes will turn the historical 100-year flood levels into annual events in New England and mid-Atlantic regions and 1–30 year events in southeast Atlantic and Gulf of Mexico regions in the late 21st century (Marsooli et al. 2019). Even in regions where the effect of strengthened storms could be compensated with displacement of storm tracks, as in New York, the effects of higher mean sea levels will drive significant increases in flood levels (Garner et al. 2017), with important consequences for coastal risk and adaptation needs.

Apart from geographic coastline variability and sea-level rise, whether climate change will drive a future increase in the frequency and magnitude of climatic patterns such as El Niños or hurricanes events remains uncertain. There seems to be an emerging consensus, however, that warmer surface ocean water will raise evaporation rates and increase the frequency and magnitude of hurricanes, cyclones and typhoons, potentially delivering more damage when they make landfall. NOAA has suggested that an increase in Category 4 and 5 hurricanes is likely (https://www.gfdl.noaa.gov/global-warming-and-hurricanes/), with hurricane wind speeds increasing by up to 10 %, and with 10-15 % more precipitation in a 2 degree C scenario. Recent storms such as Hurricane Harvey (2017), that dropped over 60 inches in some locations near Houston; Florence (2018) with over 35 inches, and Imelda (2019; 44 inches), in addition to the impacts of wind, storm surge and wave action as demonstrated with Hurricanes Irma and Maria in the Caribbean in 2017, demonstrate the devastating effects that can be triggered by more frequent, intense or wetter hurricanes. The connection between climate change and hurricane frequency is less straightforward. It is likely the number of storms will remain the same or even decrease, with the primary increase being in the most extreme storms. Areas affected by hurricanes are also shifting poleward, likely with expanding tropics due to higher global average temperatures. The changing patterns of tropical storms (a shift northward in the Atlantic) could also put more property and human lives at risk, but much more research is required to better characterize and predict how such patterns will change in the future. Independently, historic data shows how the cost of hurricanes is also increasing globally, associated with a conjunction of climate, more intense coastal development and other factors (Reguero et al. 2020).

- Wave action

Changes in wave action can be one of the most important drivers of coastal change. Recent research indicates increasing wave energy across ocean basins (Reguero et al. 2019) and higher waves, especially in high latitudes and for the larger waves (high percentiles) (Young & Ribal 2019). Future projections also point to increases in wave heights along many coastlines, but with strong spatial variability (Morim et al. 2020; Song et al. 2020). Local changes in wave action, as well as the strong influence of interannual patterns such as El Niño or the North Atlantic Oscillation (Wang et al. 2009; Izaguirre et al. 2011; Mentaschi et al. 2017) necessitate including local projections and effects when predicting and forecasting wave-driven impacts in coastal areas. Furthermore, recent research has also indicated that wave forces could drive important impacts, especially for low-lying areas, sandy shorelines and islands (Barnard et al. 2015b; Storlazzi et al. 2015). Changes in wave action will accelerate coastal erosion (Figures 7, 8 and 9), require upgrading and increased costs of coastal defenses (Jonkman et al. 2013; Burcharth et al. 2014), port activity and operations (Izaguirre et al. 2021), and alter sediment transport and beaches (Hanley et al. 2014; Vitousek et al. 2017b; Mentaschi et al. 2018). Local changes in wave action, as well as the strong influence of interannual patterns such as El Niño or the North Atlantic Oscillation (Wang et al. 2009; Izaguirre et al. 2011; Mentaschi et al. 2017) need local projections for predicting these local impacts. These impacts are occurring globally, in developed regions such as the U.S., but also represent important challenges in developing countries and island nations (Figures 7 and 8).

Figure 7. Beach erosion in Saint Louis, Senegal, threatens houses and the livelihood of many.

Figure 8. Saint-Louis, the old colonial capital of Senegal, faces a flooding threat that has already seen entire villages lost to the Atlantic . Source: The Guardian - https://www.theguardian.com/environment/2020/jan/28/how-the-venice-of-africa-is-losing-its-battle-against-the-rising-ocean

Figure 9. Collapose of road from beach erosion and wave action (left) and wave overtopping during high tides (right) in Seychelles.

3.4. Other effects of climate change in coastal areas

In addition to flooding and erosion, sea-level rise will also produce other effects in coastal areas. The six main concerns for low-lying coasts from sea level rise include (IPCC 2014): (i) permanent submergence of land by mean sea levels or mean high tides; (ii) more frequent or intense extreme flooding; (iii) enhanced erosion; (iv) loss and change of ecosystems such as wetlands; (v) salinisation of soils, ground and surface water; and (vi) impeded drainage.

Salinisation is caused by rising sea levels that drive seawater intrusion into coastal aquifers and surface waters and soils. Salinisation also increases with land-based drought events, decreasing river discharges in combination with water extraction and SLR. Seawater intrusion is already contributing to conversion of land or freshwater ponds to brackish or saline aquaculture in low-lying coastal areas of Southeast Asia such as the Mekong Delta (Renaud et al. 2015). SLR will also affect agriculture mainly through land submergence, soil and fresh groundwater resources salinisation, and land loss from permanent inundation and erosion, with consequences on production, livelihood diversification and food security, especially in coastal agriculture-dependent countries such as Bangladesh (Khanom 2016). Salinisation is already a major problem for traditional agriculture in deltas and low-lying island nations (Wong et al. 2014; Tessler et al. 2015).

SLR may also affect tourism and recreation through impacts on landscapes (e.g., beaches), cultural features and critical transportation infrastructures such as harbors and airports (Monioudi et al. 2018) Coastal areas' future tourism and recreation attractiveness will however also depend on changes in air temperature, seasonality and sea surface temperature. Although ocean warming and acidication will be more influential in global fisheries and aquaculture, sea-level rise may produce indirect effects through adverse effects in habitats or facilities.

4. Responses to the inevitable and accelerating rise in sea level.

With the thousands of kilometers of developed beaches, dunes, barrier islands, bluff and cliff tops around the planet, there are countless locations in virtually every coastal nation where development of all types, whether private or public, whether new or old, where erosion or flooding are already threatening that land, or will in the decades ahead. What can or should be done with the communities and cities, homes and hotels, streets and parking lots, airports and power plants, wastewater treatment plants, pump stations and transmission lines, or other infrastructure built on the beach or at the edge of a cliff or bluff? This challenge has affected and will increasingly affect nearly every coastal community on Earth and will only become more acute and costly over time.

There are a limited number of options, however, and all come with some costs, benefits, and impacts. Depending on location, some of these may require successfully navigating and negotiating through a complex, expensive, and time-consuming permitting and environmental review process. Future losses will be high. The threat from future sea-level rise to coastal cities and low-lying areas around the world, combined with storms, erosion and inundation, will be one of the major societal and infrastructure challenges of this century (Hinkel et al. 2014; Hoggart et al. 2014; Neumann et al. 2015; Hsiang et al. 2017; Vitousek et al. 2017b). Threatening levels of sea-level rise, however, are a longer-term issue, at least for now, but require mainstreaming adequate planning and rethinking of how coastal communities plan for new development in coastal areas as well as existing development, manage ecosystems and other coastal resources, and prepare action to mitigate the impact of existing hazards, such as El Nino, hurricanes or tsunamis.

4.1. Short to Intermediate-Term Responses

Throughout the 20th century, developed coastlines around the world have been responding to the hazards of shoreline flooding and coastal erosion or shoreline retreat in several ways:

1) Do nothing (or wait and see)
2) Beach nourishment or adding sand to beaches
3) Preventive actions to maintain the shoreline (i.e. hold the line) through either soft or hard solutions that may include armoring or hardening the shoreline
4) Managed or unmanaged retreat or realignment
5) Regulatory and restriction options on new development

Each of these options has its positives and negatives and different geographic areas, political entities, communities, cities, states, or nations have either intentionally or unintentionally made decisions to use one or several approaches:

(1) Do Nothing or Wait and See

This strategy may have the lowest cost upfront, but also the greatest risk of potential consequences. Whereas it is difficult to predict when any particular structure built on the back beach or on the edge of an eroding bluff will be inundated, damaged or collapse, doing nothing almost guarantees that the day will come when it's too late and damage or complete loss will result. This approach incurs no costs until a major event finally does occur, which usually cannot be predicted very far in advance, and then the losses may be high or catastrophic as last-minute protection might not be permissible, possible, or effective. Depending on the setback of a particular structure from the shoreline or bluff edge, its elevation relative to sea level and wave runup (also known as freeboard), age or condition, past erosion or flooding problems, maintenance level, and the future actions from local sea-level rise and storm impacts (which may exceed their original design conditions), this approach may work for a limited period of time

(2) Beach Nourishment

Approximately 80% to 90% of the sandy beaches along the U.S. Atlantic and Gulf coasts are experiencing erosion with rates averaging 0.6 meters per year (Heinz Center, 2000); While many factors contribute to shoreline recession, sea-level rise is the underlying factor accounting for nearly ubiquitous coastal retreat (Leatherman, et al, 2000). This land loss has enormous economic impacts because some of the most expensive real estate in the United States is beachfront property.

One approach used for temporarily forestalling shoreline retreat or beach erosion is to artificially widen a beach with sand from some outside source, usually from the offshore continental shelf. Beach nourishment is usually carried out as very large-scale projects, where thousands of meters of shoreline are at least temporarily widened with thousands or millions of cubic meters of sand. Restoring beaches through beach nourishment can greatly increase their attractiveness to tourists (Houston 2008). Beach nourishment has been employed for decades along the low relief, typically barrier island-backed sandy shorelines of the Atlantic and Gulf coasts of the U.S. Over 1.35 billion m3 of sand has nourished the beaches of 475 U.S. communities since 1923 at a 2020 real cost of $10.8 billion (https://beachnourishment.wcu.edu/). While several states have long-term beach management plans, the great majority of the funding for placing sand on beaches comes from the federal government through the Army Corps of Engineers.

Whether New Jersey, New York or Florida, while literally billions of federal dollars have been spent moving sand from offshore to the shoreline for both recreational and shoreline protection benefits, the lifespan of the sand added artificially to these beaches in many cases has been relatively short, in some instances less than a year. For some perspective on lifespans of individual nourishment projects, Florida has 15 beaches that have each been nourished 15 or more times, and Palm Beach has been nourished 51 different times (https://beachnourishment.wcu.edu/). It is clear that beach nourishment should not be seen as a permanent or even long-term solution to beach or bluff erosion, but simply buys a little more time at great public expense.

Yet, beach restoration can have important benefits too. The resurgence of Miami Beach was largely attributed to saving the Art Deco architecture in South Beach, which was a significant achievement, but beach restoration was paramount to the recovery (Leatherman, 2015). Beach nourishment in the late 1970s and early 1980s rejuvenated Miami Beach , which brought back the visitors and hence the economy (Houston, 2013; Leatherman, 2015). The massive beach nourishment project, which was the largest such project of its kind undertaken in the world at that time, cost $51 million. White coral sand was pumped from deposits a few kilometers offshore at the cost of only a few dollars per cubic meter. Miami Beach was widened by about 60 meters along the 16 km of barrier shoreline. This beach nourishment project is often cited as the most successful beach restoration in the United States because of its longevity and positive economic impact. Most recently, Miami is investing $16 million in fresh sand to push back against erosion, while also maintaining a dune belt. The economic benefits of these projects are clear but face challenges from the costly maintenance, the duration, and the rising threats from sea levels and storm action (Figure 10).

Figure 10. The U.S. Army Corps of Engineers dumps new sand from Central Florida along the Miami Beach shoreline. Source: U.S. Army Corps of Engineers.

In the U.S.A., six states account for over 83% of the total volume of sand placed on beaches: California, Florida, New Jersey, North Carolina, New York, and Louisiana (Elko et al. 2021). The largest recipients have been Florida, New York and New Jersey, who have received about 500 million m^3 of sand since the 1930s, much of this funded by the federal government. Adding in the remaining Atlantic and Gulf Coast states, the amount of sand dredged from offshore and dumped on the beaches totals about 1.3 million m^3 (ASBPA). This is a difficult volume of sand to visualize but is enough sand to build a beach 50m wide, 3m deep, and 8,667 km long, or a beach extending all the way down the Atlantic seaboard from Maine around the southern tip of Florida and west across the entire state of Texas and beyond. Much of this sand has been moved around at federal expense and in recent years, with federal budgets being stressed, these projects have been more difficult to fund.

Overall, beach nourishment remains controversial. Shorefront cities and development have come to rely upon continuing projects funded by the federal government to restore and maintain beach values. While maintaining the beach is essential for recreation, storm protection of property and beach-dependent economic activities, re-nourishment projects are a costly intervention, paid by taxpayer money and maintain high real estate interests for those who live by the beach, which can be considered a form of subsidy to the wealthy (U.S. Commission on Ocean Policy, 2004).

Traditional approaches to beach nourishment that merely add sand have also had important limitations in effectiveness. Beach replenishment success and environmental impacts may arise when one or more of the following factors is lacking: (1) a realistic assessment of potential borrow area sand volume; (2) compatibility of added sand to the beach being nourished, (3) construction costs; (4) all vulnerable geomorphic elements of the coastal zone; and (5) environmental impacts. Additionally, pre- and post-replenishment monitoring studies have frequently been inadequate to answer the questions of environmental impacts (Peterson and Bishop, 2005). Ecological consequences of beach replenishment can also be significant (Woodbridge, Henter, and Kohn , 2016). To be effective, beach nourishment needs to be combined with sediment management techniques, ideally sand retention efforts (Griggs, et al., 2020), whether groins or some other mechanism to hold the sand in place so that it survives for a longer period of time and avoids frequent and costly sand feeding cycles. This requires understanding and characterizing the historic causes of erosion, either episodic or chronic, the long-term littoral drift rates and directions (Capobianco et al. 2002; Hanley et al. 2014), as well as the natural processes and landscape.

With sea-level rise and increased wave action, beach nourishment will also need to be combined with other options, including adequate setback zones that can naturally nourish the system. Although the Army Corps of Engineers as well as many local beach communities and coastal organizations continue to put forward beach replenishment as a “soft” solution to coastal erosion or beach loss, a comprehensive study by Parkinson and Ogurcak (2018) concluded that beach replenishment (alone) may not be a sustainable strategy in the long term to mitigate climate change. For example, projections in California indicate that beach replenishment will only marginally delay the long-term inevitable loss of southern California beaches due to sea-level rise (Vitousek et al. 2017b; Figure 11).

Figure 11. A number of beaches on the northern San Diego County coastline, California, have been nourished twice with a total of 2.7 million m3 of sand at a total cost of $46 million. Beach surveys showed most of the sand had moved downcoast with littoral drift with a year or two (Courtesy: SANDAG Regional Beach Sand Project).

(3) Armoring or Hardening the Shoreline.

Whether rock revetments, seawalls, levees or floodwalls, or any of a variety of other engineered or non-engineered structures, hardening or armoring the shoreline has been the most common historical approach to coastal erosion, shoreline retreat or flooding. These solutions aim to protect the shore by defending against elevated water levels or wave impacts. There is a long global history of coastal armoring, but in most cases, these structures were not built with their potential impacts to the surrounding environment and shoreline in mind. The potential effects of hardening the shoreline include visual impacts; loss of public beach due to placement of the structure on the beach; loss of the sand previously provided by the eroding cliff, bluff or dune being armored; passive erosion or the gradual loss of the beach fronting the armor with a continuing rise in sea level (Griggs, 2005; Figure 12)

Figure 12. Passive erosion (loss of beach) in front of a rock revement in central Monterey Bay while a beach continues to exist on either side where there is no armor. Courtesy: California Coastal Records Project.

It is important to understand that coastal armoring (including seawalls and revetments) protects what is behind the armor, at the cost of the fronting beach. Combating erosion with a hard structure parallel to the shoreline is a choice to not protect the beach at that location. It is only a matter of time before beaches in front of hard armoring structures will be flooded or disappear with a rising ocean (Griggs, 2005; Vitousek, et al., 2017b; Figure 12). Structures also produce shoreline encroachment and coastal habitat squeeze (Leo et al. 2019). Coastal development and coastal armoring present physical barriers for the natural inland migration of coastal habitats, and changes in hydrological connectivity reduce sediment inputs and the potential for vertical accretion. Encroachment is also a term used to describe the advancement of structures, roads, buildings, and other development into natural areas including the shoreline and the buffers around these areas. The term encroachment encompasses the placement of fill, the removal of vegetation, or an alteration of the natural topography. This causes impacts to the functions and values of natural areas, such as water quality, loss of habitat (both aquatic and terrestrial), loss of flood attenuation potential, or modifications in ecological processes.

However, there are many locations where coastal structures have historically been deemed necessary to protect critical infrastructure and other important assets. They will no doubt be used in the future to protect high value coastal infrastructure (large international airports, for example, Griggs, 2020) that will be prioritized for protection as long as possible. For many other oceanfront development locations, however, hard armoring structures eventually will become increasingly impractical, costly, unaffordable or unacceptable. The effectiveness of existing armoring will vary depending upon the age, engineering, foundation depth, height, and lateral extent of the individual seawall or revetment as well as exposure to wave energy and elevated water levels. Overtopping of current armoring structures during moderate to extreme events may demonstrate the need for existing seawalls and rock revetments to be engineered to stand taller. As proposed seawalls become larger and stronger, this will inevitably bring new concerns and conflict in the regulatory process concerning increased environmental impacts.

In the U.S.A., some coastal states have essentially banned any new hard structures altogether, while others have made it more and more difficult to get a permit unless the primary structure (a house for example) is under imminent threat. The era of routine armoring of any eroding stretch of coastline in the United States is ending, as the negative impacts of protective structures have been increasingly documented, recognized and understood and the inevitability of future sea-level rise becomes more obvious (Griggs and Patsch, 2019). While armor can provide short or intermediate term protection for private property and public infrastructure, with a changing climate and a rising sea, there are no future guarantees that today's armor will survive far into the future. Review of research and experience also demonstrate that there exist a range of financial, policy, planning and management tools, often used for different purposes, that can be readily implemented or modified to address coastal squeeze and enable inland habitat migration. Awareness of approaches/solutions can assist in accommoding migration of habitats as a necessary component of coastal management in an era of increasing rates of sea-level rise (Leo et al. 2019).

(4) Soft protection approaches and working with natural processes rather than against them

The rising costs of coastal armoring, and its intrinsic challenges in a changing climate, has driven an increasing interest in other soft approaches, which include new engineering and ‘building with nature’ approaches, which go beyond managing natural ecosystems for their coastal protection value. (Judge et al., 2017; NOAA 2015). New ‘soft’ approaches that use managed sediment relocation, beach and dune restoration with plants and landscape reshaping, as well as other living shorelines alternatives (e.g., oyster reefs) show examples that can work with natural processes and strategic management to avoid some of the failures of the past. For example, the Spanjaards Duin in the Netherland is one of the first example of constructing artificial dunes to create natural dune habitats as a compensation measure for port development. The project leverages natural processes to shape the dunes by ensuring proper grain size for aeolian dynamics and maintaining the groundwater level to support vegetation. Experiences on the U.S. Gulf Coast also demonstrate successes with soft protection in low energy environments (Bridges et al. 2018a). Given the dynamic nature of these solutions, monitoring must be a critical component in maintaining and expanding cost-effective approaches that use soft coastal protection solutions.

Another strategy along many coastlines where coastal ecosystems provide coastal protection is maintaining and enhancing this ‘‘natural infrastructure’’. The term ‘natural infrastructure’ includes recognizing the value that ecosystems like coral reefs, mangroves, salt marshes, beach and dune systems and other emerged or submerged vegetation offer in coastal protection by attenuating waves, reducing the impacts of sea-level rise, at least over the short term, and retaining sediment or building land (Temmerman et al. 2013; Temmerman & Kirwan 2015). For example, reefs (Scyphers et al. 2011; Quataert et al. 2015; Harris et al. 2018; Chowdhury et al. 2019), seagrasses (Ondiviela et al. 2014) or saltmarshes and beach and dune systems can also be effective in protecting against the impact of storms (Hanley et al. 2014; Narayan et al. 2017; Gracia et al. 2018), under certain conditions, which can be very valuable. Recent research shows that U.S. coral reefs provide over $1.8 billion in flood mitigation benefits every year, with much of the protection being highly concentrated in certain reef-lined coastlines, including the most vulnerable communities in island territories (Reguero et al. 2021). For many of these coastlines, maintaining this natural infrastructure may be one of the most cost-effective strategies, at least over the short term, for tropical nations and small island states at the forefront of the impacts of climate change. For some context, throughout the millions of years that these coastal ecosystems have existed, they have been able to keep pace with sea level fluctuations of more than 100m, as evidenced by the very existence of these habitats or ecosystems today. However, added pressures on these ecosystems currently threatens their potential to keep pace with sea-level rise and affects their resilience to storm impacts (Rodriguez et al. 2014; Lovelock et al. 2015; Sasmito et al. 2015; Perry et al. 2018), and therefore, threatens their future effectiveness for flood and erosion reduction.

Many organizations in civil works research, development and technology programs, as well as conservation and environmental organizations are increasing the momentum and knowledge base for embracing nature-based solutions for climate adaptation to more sustainably to deliver economic, social, and environmental benefits associated with water resources infrastructure (Orton et al. 2015; Bridges et al. 2018b; Reguero et al. 2018; Whelchel et al. 2018). These approaches also leverage key characteristics of natural systems to adapt and change with environmental conditions.

However, some of these ecosystems are restricted to particular latitudes and energy conditions (Figure 13). For example, salt marshes and similar wetland ecosystems require fine-grained sediment and cannot tolerate or survive high wave energy conditions. Where wave energy is low, estuary and lagoon environments, for example, vegetation that inhabits those shorelines should be protected and even restored, but in the long run, these approaches will be affected by long-term sea-level rise unless they have the space and conditions (e.g. hydrological conditions, sediment supply, etc.) to self-adapt. For example, where the landward edges of these coastal environments are urbanized or developed (i.e. coastal squeeze), eventual shoreline migration with future sea-level rise will be compromised. Living shorelines, such as vegetated shorelines and dunes, also have limitations, however, and can be quickly eroded or removed under severe wave and storm conditions (Figure 14).

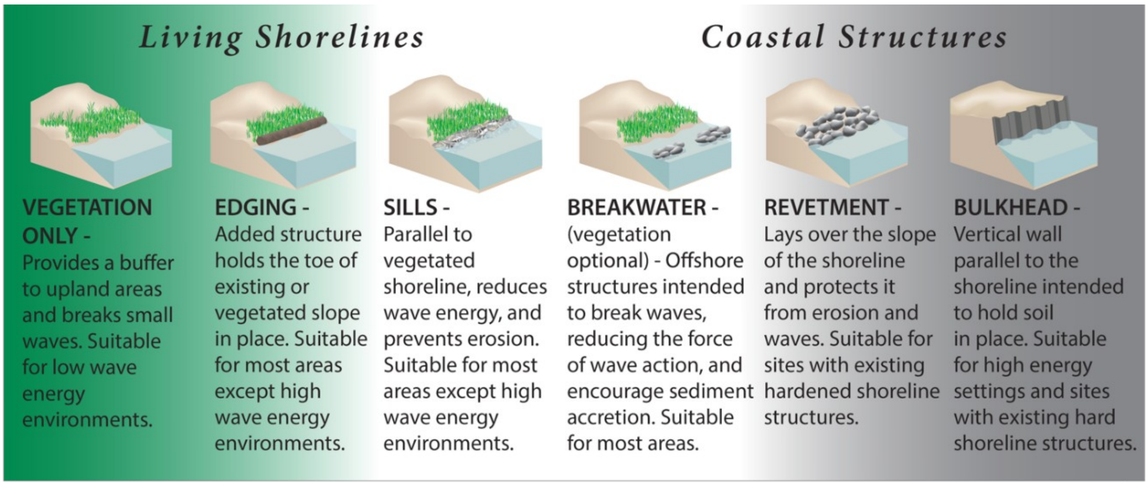

Figure 13. Range in coastal protection approaches from green to gray with those on the left ("living or partially living") suitable only for low wave energy environments. Source: NOAA 2015.

Figure 14. Storm waves along the U.S. Atlantic coast have removed a major portion of a newly built and vegetated dune at Bay Head, New Jersey.

(5) *Managed retreat, realignment, and setbacks.*

Managed retreat or managed realignment is a coastal management strategy that involve the controlled flooding of low-lying coastal areas, the abandoment or relocation of assets and people, and allows the shoreline to move inland, instead of attempting to 'hold the line' (Neal et al. 2005). For example, flood defenses can be set back from the shoreline to allow erosion or flooding in certain areas. Often, this approach also offers opportunities for enhancing coastal habitats and their ecosystem services, including coastal protection. Climate-induced relocation and managed retreat are increasingly considered as part of the adaptation planning process in many coastal areas although deciding whether, where, when, and how to move is very complex and controversial. Managed retreat requires interweaving science and governance for community decision-making (Wible 2021). California has invested significantly in planning to respond to sea-level rise, and managed retreat is being actively debated in dozens of communities (Anderson et al 2021). Some cities in California are beginning to discuss, consider, and plan for how they will adapt to higher sea levels while others are resisting. Managed Realignment and Sacrificial zones are also a form to battle flood risk and erosion (Williams et al. 2017).

Managed retreat may include various approaches include: planning and setback zones; relocation of buildings; buy-back and buy-out programs; setbacks (horizontal or vertical) with regulations on new development or no-build areas; restoration of shoreline and habitats; green spaces and controlled flooding areas and erosion setbacks. Some important factors affecting the feasibility of managed retreat include (Neal et al. 2005; Gardiner et al., 2007; Rupp-Armstrong & Nicholls 2007): presence of coastal defenses, availability of low-lying land, flood or coastal defense need, coastal management frameworks, intertidal habitats benefits, societal awareness.

7. Main challenges to adaptation

Local, regional, central, and federal governments need to continue their efforts to reduce greenhouse gas emissions, but it is important also to adequately prepare for the climate impacts that are already underway. Mitigation is needed to reduce and slow down global warming and sea-level rise, but adaptation has to be part of the solution to climate change as there are inevitable impacts that societies will have to face, especially along coastlines where so many natural and socioeconomic interests intersect. Yet, adaptation to sea-level rise have found key types of constraints (Moser & Ekstrom 2010; Hinkel et al. 2018) that involve technological, social conflict, economic and financial barriers and limitations.

One of the critical challenges for upscaling adaptation efforts is finance. Many governments, especially in developing countries, need to balance pressing needs with limited budgets, especially during the global pandemic recovery. A revision of climate finance in 2019 determined that climate finance flows in the cycle 2017-2018 left $30 billion investments in adaptation versus $537 billion in mitigation (CPI 2019). Most of the adaptation investments fell within programs dedicated to Disaster Risk Management, Water and Waste Management, and Land Use. This also shows the cross-sectoral nature of adaptation. However, adaptation financing rose significantly from its previous level in 2015/2016, making up only 5.6% of funding and with no change from 2015/2016 as a percentage of tracked finance. Multilateral funding is the second source of adaptation funding after national sources. Globally, the Multilateral Development Banks committed collectively US$ 61,562 million in climate finance in 2019 – US$ 46,625 million (76% of total for climate change finance) and US$ 14,937 million (24 % of total) for climate change adaptation finance (Joint Report of Multilateral Development Banks, 2019). Therefore, while climate finance is steadily increasing, it still falls far short of the needed investments and makes clear the large global adaptation funding gap.

Economic barriers are another critical limiting factor. They reflect the complex balance between socioeconomic benefits and costs of adaptation versus the impacts they avoid. Cost benefit analyses, which are prescribed for coastal projects in some countries like the U.S., can be challenged by limitations related to the difficulty or impossibility to monetize benefits, the consideration of long timeframes and materialization of the benefits, and potential differences arising from public versus private interests and social versus individual preferences, including the social discount rates considered.

Technological limits refer to when there are no adaptation options available to effectively reduce the impacts of SLR or they are not enough to keep risk in acceptable levels (Dow et al. 2013). Protection and accommodation measures have been in societies for centuries as communities have used coastal engineering to adapt to environmental change and local hazards, e.g. seawalls from the colonial era in the Indo-Pacific. Furthermore, some technologies are not feasible or possible in some countries and coastal environments. There are also limitations in local availability of materials, knowledge or construction, especially in developing countries and small island states. Another important technological aspect is the capacity and ability to maintain, repair, and rebuild adaptation infrastructure beyond its construction. In many developing regions, for example, adaptation projects are implemented by external parties and leave no local capacity or knowhow to maintain or expand such measures over time.

Coastal adaptation is also a clear collective action problem: a group benefits from an intervention but no individual has sufficient incentive to act alone (Nyborg et al. 2016) . Social conflict barriers may arise whenever stakeholders hold conflicting interests that may be overcome through governance to develop norms, laws or policies to resolve conflicts or achieve gains (Bisaro & Hinkel 2016; Nyborg et al. 2016). Formal institutions can help but other informal means and community involvement is needed. Social barriers remain challenging and difficult to overcome and can be further aggravated when local needs, contexts, and priorities are not adequately considered (Narayan 2020). For example, solutions that are considered effective in some regions can be ignored or perceived negatively in other areas. One clear example is found in low crested and submerged structures that have been amply used in Europe, including with environmental benefits (Airoldi et al. 2005), but can be perceived as negative in, for example, tropical regions. Social challenges to adaptation can also be driven by diverging interests between parties, including who benefits and who pays, which can be a major decision factor when planning adaptation. Other social barriers are related to conflicts around cultural and social priorities and constraints.

Barriers to adaptation can be overcome through efforts to address gaps in technology, economic and human resources, management and institutional change. Understanding risk, planning and finance adaptation are key aspects for accelerating adaptation (Global Commission on Adaptation 2019). Furthermore, the process known as ‘Paris alignment', which refers to the alignment of finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development (article 2.1c, Paris Agreement), also represents an opportunity to expand adaptation efforts across activities in the global coastal zones.

8. Deciding the strategy and planning Long-Term Responses

Broadly speaking, the main responses in coastal adaptation involve protect, manage/accommodation, and retreat (Nicholls and Casenave, 2010). Retreat can be pre-emptive, just-in-time, or reactionary (Gibbs, 2016). Pre-emptive planned retreat or proactive abandonment would involve the systematic relocation of buildings or communities well before they are impacted by major coastal flooding or threatened by cliff or bluff erosion. Just-in-time retreat involves delaying retreat as long as possible, but prior to major damage or loss. This approach would take place when many of the involved property owners or entities realize the risk is unacceptable or when sea level reaches some threshold level that has been established and agreed upon in advance. Reactive retreat can be implemented following a major flooding or disaster event, and could be designated as unplanned retreat, where this is the only option left. This would require local, state, or national government legislation preventing reconstruction in high-risk areas that have recently been devastated and potentially implementing some type of partial buyout program.

Along many coastlines it is only a matter of time before resisting the advance of the sea will no longer be possible. Whether through soft solutions such as living shorelines, beach replenishment or hard armoring, maintaining the present position of the shoreline will become infeasible in many areas. Timing may depend on the local hazards, consequences, existing protection, management plans, funding and geomorphology of each coastline, but it is not a question of whether it will happen, but when. In many communities, it is already happening (Rush, 2018; Union of Concerned Scientists, 2017 and 2018).

There is an alternative and longer-term approach. With sea-level expected to rise between ~50 cm (~20 inches) and ~310 cm (~10 feet) by 2100, and continuing on for centuries into the future, and also expected changes in wave action and hurricane frequency and magnitude, virtually every shoreline development, community and city in the world needs to begin to think for the long-term. Communities can start by looking at current management practices, the history of storm damage and erosion, the exposure or vulnerability of both public infrastructure and private development and both present and future hazards and challenges (Griggs et al. 2019). Where structures are located in vulnerable coastal locations and have experienced or are threatened by frequent flooding or cliff retreat, relocating or removing the structure is going to become a more realistic and important consideration or response. There are many existing developments where there are no other reasonable or acceptable alternatives, where future damage or destruction is almost guaranteed, and where rebuilding or protection is simply not possible or cost-effective. In these coastlines, managed retreat should be considered, as well as the associated costs and opportunities (see previous sections). Certainly the size, condition and physical setting of the building or infrastructure will beportant considerations. Yet, there are still a limited number of examples of successful relocation or planned retreat, whether homes or other structures. The Cape Hatteras Lighthouse in North Carolina is a good example of what can be done for $17.5 million, when the tallest lighthouse in the U.S., weighing 4800 tons, was moved inland 2900 feet in 1999. 'Hold the line' coastal protection, in many other instances, can buy time to prepare other responses to realign or relocate critical infrastructure (e.g. airports, power plants,wastewater treatment facilities, etc.).

The choice between protect, manage/accommodation, and retreat will be a local one and undoubtedly include a range of options. Coastal regulation so far has largely failed in part by not including projected rates of sea-level rise and erosion, and could be improved by consistent political oversight, will and enforcement (Neal et al. 2017). New initiatives such as multiple response pathways can provide flexibility in difficult adaptation investment choices, which can be more adequate from a socioeconomic perspective than a single adaptation strategy. Adaptation pathways are defined as a sequence of adaptation actions or strategies over time, such as beach nourishment, building new levees, and floodproofing or elevating buildings, which anticipate uncertain and changing risk conditions, such as sea-level rise (Haasnoot, 2013; Kwakkel et al., 2016). Identifying 'investment tipping points', after which a transition could decrease the economic efficiencies, should be a critical part of adaptation planning (de Ruig et al. 2019). How much risk is tolerable and when a pathway should be taken is also a complex issue. For example, there is also the increasing issue of obtaining insurance for at-risk coastal homes along the U.S. Atlantic coast where insurers are beginning to cancel or no longer insure high risk properties. Without insurance coverage, however, homeowners will not be able to obtain mortgages, which is beginning to further impact the risks facing coastal homeowners. Economics is beginning to lower home values along the Eastern Seaboard. The First Street Foundation (2019) conducted housing market research for 18 states along the East and Gulf Coasts. From Maine to Texas. Data show that increased tidal flooding driven by sea-level rise has lowered property values by $15.9 billion between 2005 and 2017. Among the states evaluated, Florida has witnessed the greatest loss in relative home value at $5.4 billion followed by New Jersey at $4.5 billion, New York with $1.3 billion and South Carolina with $1.1 billion. As property values have continued to decline, and extreme events and tidal flooding have gradually flooded and damaged more cities more frequently, insurance companies are now looking carefully at which policies to cancel, which properties not to insure, and for those that appear to be insurable, what are realistic premiums that will cover projected losses. These forces are all well beyond homeowners' power to influence, and will have increasingly negative effects on both insurance and loans for coastal homeowners.

9. Conclusion

Given the inadequacies to date in our efforts to significantly reduce global greenhouse gas emissions, and the reality that anything we are able to implement or accomplish in the near future to mitigate climate change and its impacts will not have immediate effects, we must also continue to direct our energy and creative thinking towards adaptation strategies that can prepare the coastlines and cities of the world for sea-level rise (Nerem et al., 2018; Boon, et al., 2018).

There is no question that sea levels are rising globally, and the uncertainties revolve around not "if" it is rising, but rather how much it might rise in specific locations and at what future times. The science is clear and the future is, unfortunately, increasingly certain; we need to act and we need to act now. There are no simple answers or solutions, but we need to involve all stakeholders in planning and implementing well-thought out plans and policies for the inevitable future with agreed upon-thresholds for when action will be taken.

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