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Sea level rise, storms, and fate of barrier islands: Lessons from more than fifty years of research on US East and Gulf Coasts

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ABSTRACT

Sea levels may rise by up to a meter by the end of the 21st century, thus endangering coastlines worldwide. Coastlines with barrier islands are especially vulnerable to erosion because of this rise. Along the US East Coast and the Gulf of Mexico, barrier islands line almost two-thirds of the coastline, thus making this region the prime location for studying the impact of sea level rise on barrier islands. One of two scenarios might happen: the barriers regress landward as the sea level rises (*shoreface retreat*) or the barrier may be overwhelmed by waves during a major storm event and may be "*drowned in place*". Both of these scenarios have taken place along the US East Coast during the last 8,000 years of sea level rise.

Impact of sea level rise on barriers is especially critical now because during the last few decades, the population living full-time or part-time on barrier islands has increased tremendously. Major storm events, occurring more frequently as the sea level rises, endanger human lives, property and infrastructure. While the impulse is to “replenish or restore the beach” after such natural events (storms, hurricanes), the results are always short-term. In the long term, only engineered retreat towards the land or complete abandonment might be the only solutions. However, rather than responding to each natural disaster one-by-one as it affects the coastal areas, a comprehensive national plan, with state- and local-level buy-in, needs to be adopted.

INTRODUCTION

The purpose of this paper is to review the scenarios that coastlines with barrier islands would face as sea level rise leads to a transgression (drowning) of coastal areas worldwide (Lindsey, 2021). This paper focuses on the US East and Gulf Coasts, where barrier islands fringe the mainland shoreline (Linhoss, 2018; Nienhuis and Lorenzo-Trueba, 2019). These islands are elongate, shore-parallel accumulations of unconsolidated sediment that are separated from the mainland by bays, lagoons, or wetland complexes (Hayes, 2005). Depending upon the sediment supply and the rate of sea level change, they may be transgressive (retrograding, moving landward) or regressive (prograding, moving seaward). They might aggrade and remain “in place” for intervals lasting a few hundred years, but eventually the rate of sea level change affects the barrier movement. Worldwide, barrier islands occur along approximately 10 percent of coastlines (Linhoss, 2018). Stutz and Pilkey (2011) catalogued barriers worldwide from satellite imagery and counted 20,783 km of shorelines worldwide, segmented into 2,149 islands (2,100 barrier islands according to NASA Earth Observatory, 2020). Along some coastlines, such as the US East Coast and the Gulf Coast, they are very prevalent, and form about 3,700km, or almost 60% of the coastline (Zhang and Leatherman, 2011; 4,685km according to Stutz and Pilkey, 2011). Therefore, the fate of the barriers along these shorelines in the US is very critical and is the primary focus for this review (Fig. 1). The map shown in Figure 1 (from Zhang and Leatherman, 2011) shows the barrier islands along the U.S. Atlantic and Gulf Coasts (barrier coasts shown in red and shoreline in blue). As shown in this map, a great majority of these shorelines are “barrier

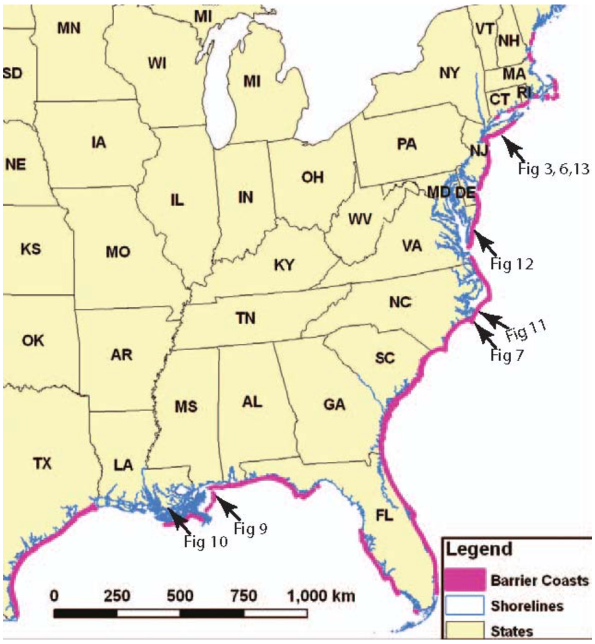

Fig 1. Map showing the “Barrier Coasts” along the US East Coast and the Gulf coast. Various barrier-island locations discussed in the paper are marked (modified from Zhang and Leatherman, 2011).

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coasts". The location of various examples of barrier-island migration discussed in this paper is marked on Figure 1.

This review was undertaken because the rise of sea level worldwide is bound to affect millions of people who either live at the coast or use it for recreation. Major natural events, such as storms and hurricanes, cause increasingly more damage during sea level rise and although the examples provided here are from one of the most studied areas in the world (US East and Gulf Coasts), coastal management is a worldwide concern. Although some studies (e.g., Ohenhen et al., 2024) have recently pointed out the particular vulnerability of major cities along the US East and Gulf Coasts because of *land subsidence* in addition to the sea level rise, they have not covered the fate of barrier islands in their work. In addition, this review provides a historical background for the work carried out on the fate of barrier islands *before* modern technologies such as GPS (Global Positioning System) or high-resolution satellite imagery or GIS (Geographic Information System) or LiDAR (Light Detection and Ranging) were available and applied to coastal research. However, discussion of the work carried out even early in the 20th Century provides a historical background and shows that some of the fundamental ideas have remained unchanged, while the latest technology has provided highly accurate mapping and imaging tools to substantiate those ideas.

Barrier islands perform a very important task: protecting the mainland areas from hurricanes and storms by absorbing much of their force and reducing wave energy (Linhoss, 2018). At the same time, because of their sea-facing locations, barrier islands are also attractive places to live, full- or part-time (except during storms and hurricanes). Thus, it stands to reason that these natural features must be protected and maintained in order to prevent loss of life and property. However, unless overstepped, they also naturally migrate landward in response to rising seas. If a house or road is built on the island, this change will appear as a loss of beachfront and there would be a call for its "protection". However, when man-made structures are built for such protection, the natural process is hampered (Burke et al., 2001; Nienhuis and Lorenzo-Trueba, 2019). The population density of these islands is almost three times that of the adjacent mainland coastal areas (Zhang and Leatherman, 2011). Moreover, during the fair weather, the daytime population of a barrier island could increase manyfold. For example, one of the barrier islands in New Jersey (USA) with a year-round population of 5,325 could see its daytime population increase to more than 250,000 during the summer months (Dempsey, 2021). Thus, the infrastructure has to be able to accommodate the "peak" traffic.

Most of the barrier beaches along the US East and Gulf Coasts have undergone erosion during the last few decades (Luijendijk et al., 2018). Although local factors such as sediment supply, subsidence, wind action and tides, as well as frequency of storms, control the rate of regional erosion, sea level rise is the primary controlling factor (Passeri et al., 2015). Some of the factors other than sea level rise could be local and might be caused by anthropogenic factors, such as water or oil withdrawal during the last few decades, especially surrounding major population centers (Mentaschi et al., 2018; Nicholls et al., 2021; Ohenhen et al, 2024). This sinking of the coastal land area is bound to exacerbate the effects of the sea level rise. Nonetheless, the focus in this paper is on the fate of the barriers during the Holocene sea level rise.

BARRIER ISLAND MIGRATION DURING HOLOCENE TRANSGRESSION

One of the ways we can predict the future of barrier islands is to reconstruct how they have behaved in the past. At the peak of the last ice age, worldwide sea level was approximately 120m lower than today and it has risen in various pulses since then (Gornitz, 2012, Fig. 2). The most recent accelerated rise in sea level is associated with meltwater added to the oceans from 8,200-7,600 years ago (Gornitz, 2012, Fig. 2, MWP 1C). By 6,000 to 5,000 years BP, glacial melting had essentially ceased. Thus, the areas that had experienced a rapid rise (such as the US East Coast) slowed to a few tenths of millimeters per year. However, as mentioned earlier, the rate has increased again at least since the 1900s (Gornitz, 2012; Frederikse et al., 2020).

Reconstruction of barrier island migration during the last 8,000 years suggested that both "shoreface retreat" and "drowning in place" took place during historical times on the south shore of Long Island, NY (Fig. 3, Kumar, 1973; Sanders and Kumar, 1975). Additional examples of barrier migration from the U.S. East Coast and the Gulf Coast have also been described (Moslow and Heron, 1979; Houser, 2012).

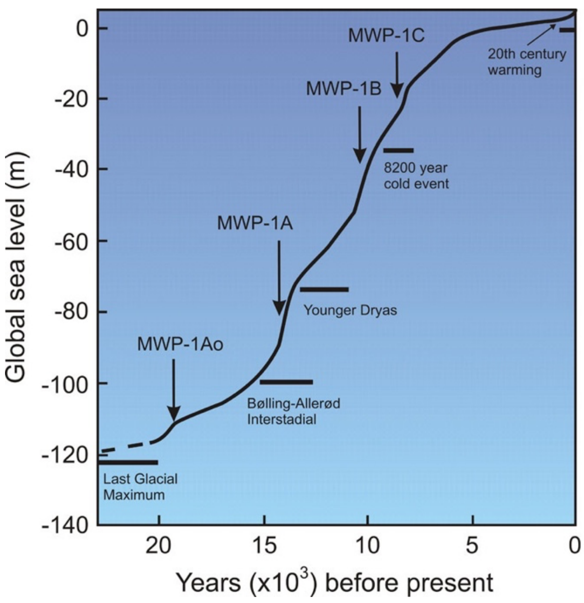

Fig 2. Generalized curve of sea-level rise since the last ice age. Abbreviations: MWP = meltwater pulse. MWP-1C, ~8,200-7,600 years ago. Since then, the rise has been very slow, except in most recent years (from Gornitz, 2012).

Fig 3. (A) Map showing the current coastline of Long Island, New York City and adjacent areas of New Jersey. Location of profile in Fig 6 is marked on the map. (B) Same coastline if the current mean sea level rose by 1.5m, a possibility by the year 2100. The drowned areas are shown in light green (both maps from Surging Seas Risk Zone Map, 2021). Fig 1 locates the Long Island area on the US East Coast.

The history of barriers during the last few thousand years should give us a model for what could happen to the barriers along modern shorelines as the sea levels rise (Frederikse et al., 2020). Strategies proposed to protect the barriers are described later in the paper (Titus, 1990). Unfortunately, most of those are only short-term solutions.

Sea level rise is a cause for concern wherever there is infrastructure along barrier islands, especially as the eustatic sea level appears to be rising at an increasing rate during the last few decades (Gornitz, 2012; Frederikse et al, 2020) (Fig. 2). Figure 4 shows various potential scenarios to the year 2100 (Sweet et al., 2017) for sea level rise ranging from less than one-half meter to 2.5 meters. For this paper, the “intermediate” scenario with a possible rise of up to one meter is assumed (Sweet et al., 2017). Increasing sea levels would lead to higher-than-normal tides, waves and storm surges. Furthermore, in the recent report from the Intergovernmental Panel for Climate Change (IPCC, 2021), it is stated that "with gradual sea level rise, those extreme sea level events that have occurred in the past, just once per century, will occur more and more frequently, perhaps once or twice per decade" (McGrath, 2021). Additionally, even modest mean sea level rise can enhance the effects of tidal surge and wave action, increasing the frequency of extreme water-level events in many places (Idier et al., 2019). Thus, a science-based plan of action to “protect” these barriers in the near future is imperative.

Although there is considerable new literature on barrier migration (see Rosati, 2009; Cooper et al., 2018; Barrineau et al., 2015), as early as 1885, Gilbert (1885) and later, Johnson (1919) proposed models for barrier migration during a transgression. Gilbert (1885) suggested that if the sea level rises fast enough, the barrier remains in place as the back barrier area expands until the barrier "drowns" in place and a new barrier system is established farther landward (Figs. 5A and B). On the other hand, Johnson (1919) suggested that barriers migrate through a process of "shoreface retreat" as they move across lagoonal marshes and muds until these "backbarrier" sediments are exposed or covered by thin nearshore sediments under the retrograded barrier established as a result of the sea level rise (Figs. 5C and D). These models follow the "Bruun Rule" (Bruun, 1962) only in a general way because this rule conserves all eroded material from the shoreface during a sea level rise and carries it all offshore to build up the base level. However, it does not account for material transported across the barriers into the lagoons as washover fans or through tidal inlets during major storms. Swift (1975) made a case for the barriers on the Central Atlantic Shelf having retreated from the shelf edge during the post-glacial transgression. According to Swift (1975), this retreat left a lagoonal carpet on the shelf as the barriers retreated to their present positions. Sanders (1963) argued that barriers could be “drowned” in place by a rising sea whereby the shoreline would “jump” landward to the inner margin of the former lagoon. The models mentioned above (Fig. 5) were not rigorously tested until much later. Kumar (1973) carried out studies of Fire Island Inlet on the south shore of Long Island

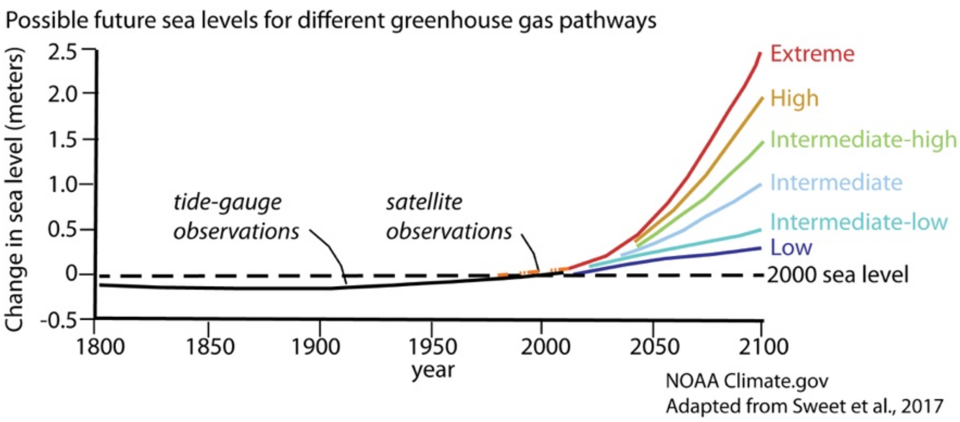

Fig 4. Observed sea level from tide gauges (solid line) from 1800-2015 and satellites (orange dashed- approx. from 1980s to 2010s). The other six colored lines show predicted future sea levels through 2100. The scenarios differ based on potential future rates of greenhouse gas emissions and differences in the plausible rates of glacier and ice sheet loss. The "intermediate high" curve (green) projects a rise of almost 1.5 m by the year 2100 (from Lindsey, 2021).

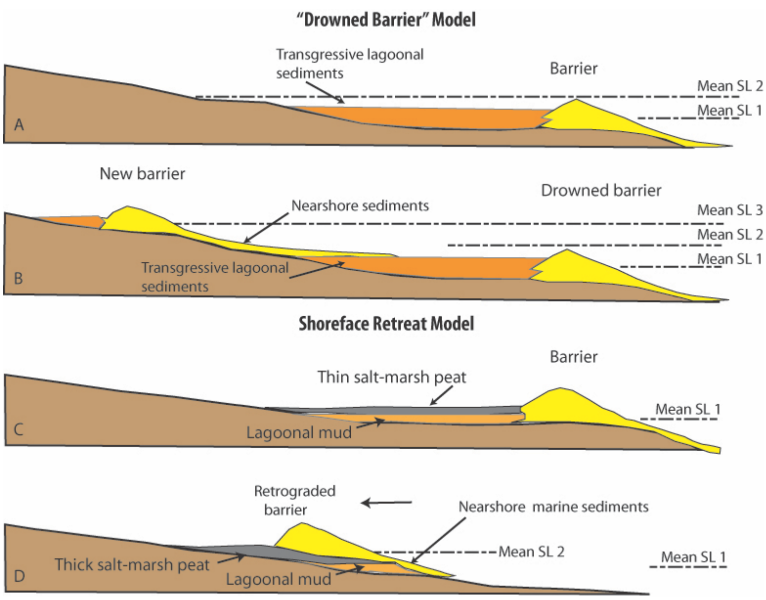

Fig 5. The "Drowned Barrier Model" proposed by Gilbert (1885) (A & B): As the sea level rises the lagoon may expand on the backbarrier side until eventually the new shoreline is established farther inland. In the "Shoreface Retreat Model" as proposed by Johnson (1919) (C & D), as the sea level rises, the front of the barrier is eroded and the barrier moves landward until the "backbarrier" salt-marsh peat and lagoonal mud might be exposed on seaward side of the barrier (modified from Kumar, 1973).

(New York) and the adjacent shallow continental shelf (see also Sanders and Kumar, 1975). Their data included shallow boreholes on the barrier island, cores from the adjacent shelf, shallow seismic imaging, and aerial photography. The environmental interpretation of various sediments was carried out using sedimentary structures, grain-size analyses and habitat interpretation of foraminifera and molluscs found in the sediments. Radiocarbon analysis allowed for the absolute dating of some of the associated organic material.

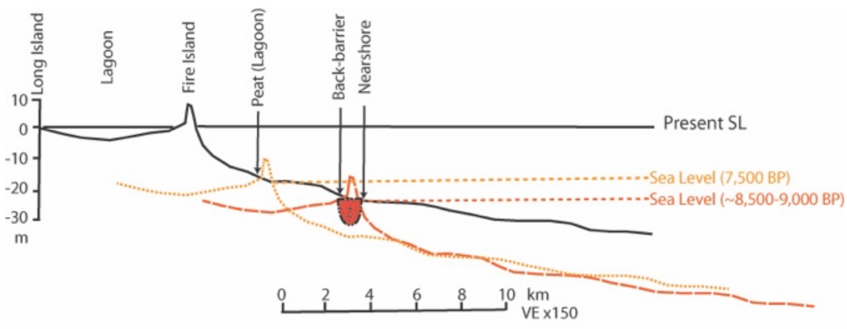

Fig 6. Sea-floor profiles across the south shore of Long Island (NY) (location on Figs 1, 3). Black line is the present-day profile whereas the red line is the same profile at 24m below current mean sea level (~8,500 - 9,000 yrs. BP) and the orange line displays the same profile at 16m below the present mean sea level (~7,500 yrs. BP). The red lenticular structure below the barrier at -24m barrier is interpreted as a body of inlet-filling sediments after the protruding part of the barrier is eroded after the transgression (modified from Sanders and Kumar, 1975). Further details in text.

The two scenarios mentioned above are not mutually exclusive to a coastline during an extended period of transgression (thousands of years) (Kumar, 1973; Sanders and Kumar, 1975). Interpretations from sedimentary environments of cores led Kumar (1973) and Sanders and Kumar (1975) to suggest that when the sea level was at -24m (~8,500-9,000 years ago, Fig. 1), a barrier island, perhaps similar to that of today, existed on the Long Island shelf. They interpreted the nearshore environment in some of their cores, and in another set of cores about one km landward, they interpreted a backbarrier environment. Although no protrusion or "bar" exists at the sea floor today, on shallow-seismic (SPARKER) records, they mapped a lenticular body less than a kilometer wide and about 8m thick. This evidence led the authors to conclude that there was a "drowned-barrier" transgression at 8,500-9,000 years ago (location on Fig. 3, Fig. 6: Red dashed profile). The location marked "nearshore" (Fig. 6) was sampled with cores interpreted to contain lower-foreshore sands. The location marked "back-barrier" (Fig. 6) included several cores interpreted to contain lagoonal deposits (Kumar, 1973). Lack of a bar suggests that the sand body probably consists of inlet sediments, deposited as the inlet migrated laterally (Kumar, 1973). As the current barrier is about 8m in elevation, these authors suggested that the sea level "jumped" to -16m during this phase. Since then (about 7,500 years ago), the barriers have transgressed through shoreface erosion as another set of cores has yielded lagoonal peat on the shelf, which was radiocarbon dated to approximately 7,500 years BP (orange profile, arrow marking "peat", Fig. 6). This shoreface retreat appears to have continued until the present. Rampino and Sanders (1981) for the same area also inferred a set of submerged sand bodies in seismic records when the sea stood about 24 m below the present level (about 9,000 years ago). These inferred barriers stood about 7 km offshore; with the continued sea level rise, the -24m barrier built upward until the sea reached about -15 m, just prior to 7,000 yr BP. This barrier chain was submerged (drowned) as a result of rapidly rising sea level, and the surf zone shifted rapidly landward to a position about 2 km from the present shoreline. Since then, the barriers have moved landward as a result of shoreface retreat (Rampino and Sanders, 1981).

Coincidentally, Moslow and Heron (1979) reconstructed the long-term migration of the Core Banks in North Carolina, which migrated landward approximately 6.7 km over a 7,000-year period. Moslow and Heron (1979) identified overwash as the dominant process of barrier migration between 7,000 and 4,000 yr BP whereas from 4,000 to almost the present day, the rate of migration slowed considerably as the rate of sea level rise slowed (Fig. 7). The dates interpreted by Moslow and Heron (1979) for "fast" (possibly drowning) and later "slow" (mostly by shoreface retreat) for barrier migration are compatible with those suggested by Kumar (1973).

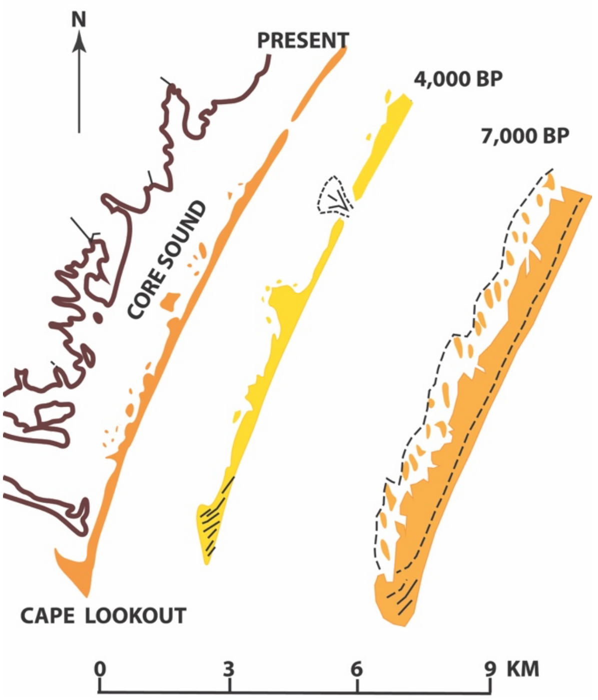

Fig 7. Shoreward migration of barriers at Cape Lookout in North Carolina (after Moslow and Heron, 1979, see location in Fig 1). From 7,000 BP to 4,000 BP, the barriers moved "fast" (possibly drowning) and since 4,000 BP, they have transgressed "slow" (most likely shoreface retreat). These dates are very comparable to those at Fire Island, NY as interpreted by Sanders and Kumar (1975, Fig 6).

PROCESSES OF BARRIER MIGRATION DURING FAIR-WEATHER AND STORM EVENTS

Pierce (1969) and Leatherman (1979) identified dune migration, sediment transport through inlets, and overwash as the three major processes for landward barrier migration. During relatively fair weather (a majority of the time), the first two processes dominate. However, during storms, the dominant process is overwash: the erosion and transport of foreshore and dune sediment into the backbarrier or lagoon and its deposition as washover fans. Storms also erode the foreshore and carry the sediment farther offshore. A storm event could also breach the barrier, creating an inlet which may or may not later close as the fair-weather returns (Larson et al., 2003). As the sea levels rise, washover activity would be expected to become more intense. However, Sherwood et al. (2023) have documented at least one incident where the loss of barrier volume occurred from the lagoon side in the Outer Banks of North Carolina through erosional washout channels. However, most of these channels recovered during the post-storm period.

More recently, Rosati (2009) has developed a comprehensive numerical model to predict the evolution of barrier island systems overlying a poorly consolidated substrate. This model considers many variables accounting for the consolidation of sediments in the bay (silt, clay, peat, etc.), which would tend to lower the profile of the landward-migrating barrier island. Rosati (2009) concentrated on developing her model for the Gulf Coast barriers. However, she has reviewed the literature and history of barriers along the US East Coast as well. Whereas much of the shoreface retreat takes place by overwash, the frequency, volume and the path of the sand from shoreface to overwash across the dunes depends on a multitude of factors along the length of a barrier (Matias et al., 2014). Morton et al. (2004) discussed shore processes along the Gulf of Mexico coastline and discussed the formation of barrier islands as proposed by a variety of authors over almost a century. Formation of barriers through "dune drowning" (McGee, 1890) would lead to retreat of barriers as the sea levels continue to rise.

Morton et al. (2004) also categorized barriers as "high profile" and "low profile" (Fig. 8). Obviously, the low-

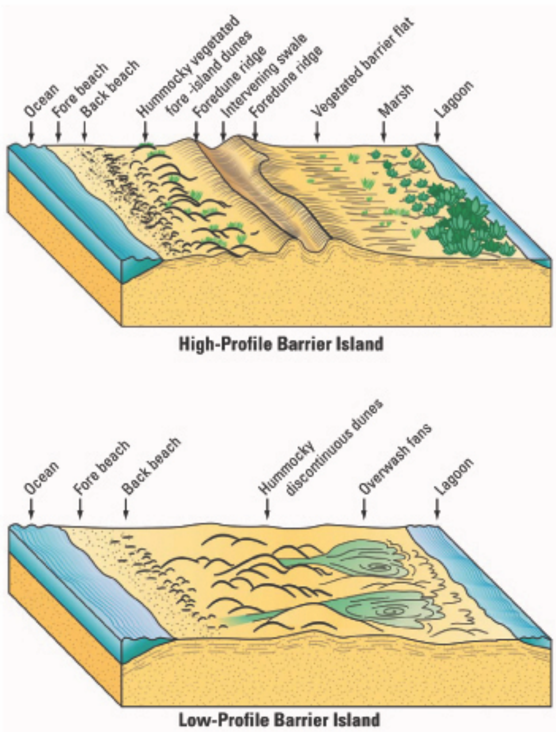

Fig 8. Geomorphological characteristics of high- and low-profile barrier islands (from Morton et al. 2004). Low-profile barriers are expected to be more susceptible to washover fans, especially as the sea-levels rise.

profile barrier islands are more susceptible to sand transfer across the dunes by washovers and thus prone to migrating landwards through shoreface retreat. However, as discussed below, during extreme weather events, low-profile barriers would also be subject to in-place drowning and creation of a new barrier island system near the newly elevated shoreline (Fig. 8). Leatherman (1979, 1985) has summarized the literature on barrier migration through a comprehensive bibliography of barrier-island migration. Leatherman's

(1985) review also included several papers that suggested that low- frequency, high-magnitude storms may contribute more to long-term barrier island morphologic change as compared to high-frequency, low-magnitude storms or "fair-weather" events. The impact of major storms is discussed below.

Infrequent, intense storms cause much more changes to barrier islands than years of "normal" or "fair-weather" systems. The impact of storms on barrier islands has been recently modeled by Sallenger (2000) and Elsayed (2017). During "extreme" storms (Sallenger, 2000: his Impact Levels 3 or 4), initially storm waves (coupled with tidal surge) may overwash the barrier and carry sediments across the dunes, thus causing the barrier to retreat. At Impact Level 4, the barriers may be completely and continuously submerged and may also breach, creating a new inlet through the barrier. At this stage, the barrier "drowns" and the quantities and distance of landward transport of sediment may be much greater than the less severe Impact Level 3 (Overwash Regime: Sallenger, 2000). Several examples of post-storm barrier impacts are mentioned below. These include examples from the U.S. Gulf Coast and the eastern shoreline of the United States, in that order.

Hurricane Katrina (2005), provided a recent demonstration of what a severe storm would do to barrier islands. Katrina caused extreme changes to the barrier islands along the central Gulf of Mexico coast (Sallenger et al., 2007). Dauphin Island, Alabama, migrated landward by washover fans by several hundred meters and the Chandeleur Islands, Louisiana, were completely stripped of their sand. Thus, it appears that both "shoreface retreat" and "in-place drowning" took place along the Gulf of Mexico coast during Hurricane Katrina (Fig. 9).

During 2005, the US Geological Survey documented coastal changes resulting from several hurricanes that year, but of course, Katrina caused the most substantial life and property damage that year (Sallenger et al., 2007). The objective of these studies was to be able to predict where maximum impacts would be felt during future extreme storm events. These studies monitored where the waves and storm surge overtopped beaches, where sand dunes retreated landward, and where the barrier islands were breached. Specifically, Sallenger et al. (2007) monitored the Chandeleur Islands, offshore Louisiana and Dauphin Island, offshore Alabama (Fig. 9, Locations A and B on the map, respectively). Photos A and B of the Chandeleur Islands (lower left) show that all the visible sand was stripped from the island after the storm and the island was essentially completely "drowned". Sallenger et al. (2006) reported that the Chandeleur Islands lost 84% of their surface area. However, in the subsequent years, the sand has come back and the island appears to have partially recovered as a result of natural recovery and restoration efforts (Coastal Restoration, 2020).

On the other hand, at Dauphin Island (Images C and D, lower right, Fig. 9), during the same storm, extreme erosion took place on the Gulf of Mexico side of the barrier (left in image C) and deposition took place on the right. Image C shows the elevation difference pre- and post-storm as determined by Light Detection and Ranging (LIDAR); red patches to the left show net erosion and red "rectangles" on the island are foundations of houses that were washed off. The green areas to the right are where sand was added and the white "peaks" are the houses that survived the hurricane.

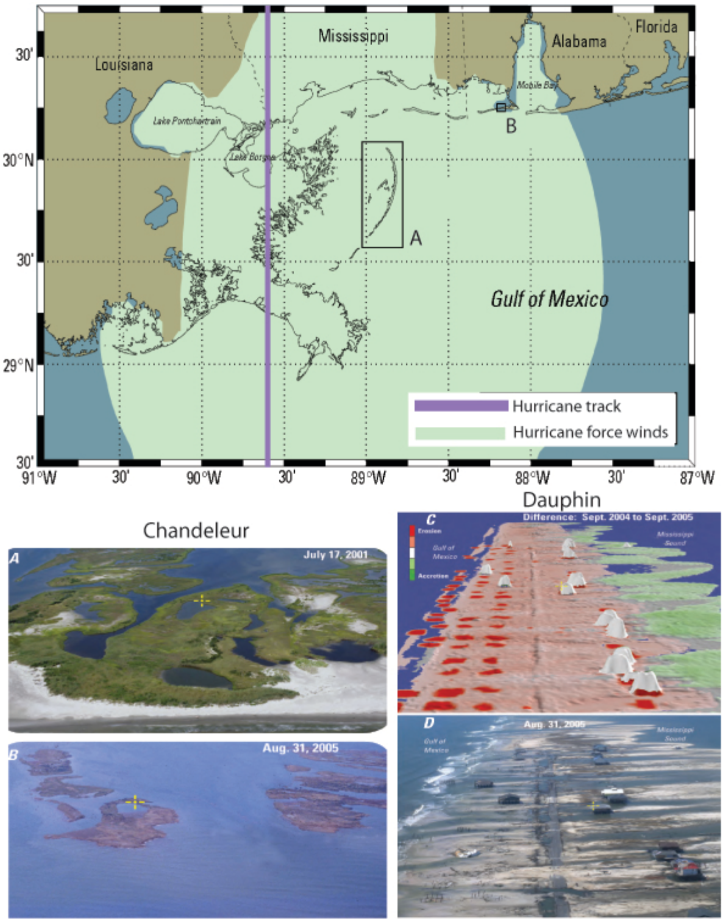

Fig 9. Location of Chandeleur Islands (A on map) and Dauphin Islands (B on map) and the changes at these locations after Hurricane Katrina. Photographs A and B are pre- and post-Katrina photographs of Chandeleur Islands (July 17, 2001 and August 31, 2005, respectively). The islands essentially "drowned" immediately after the hurricane and lost almost all of their sand. C is the difference in topography between Sept 2004 and Sept. 2005 on Dauphin Island as shown by LIDAR (Light detection and ranging). Reds are loss in topography and greens are gains. Photograph D is an aerial view on August 31, 2005 showing the erosion on the Gulf of Mexico (left) side of the island and deposition by washover fans on the Mississippi Sound (right) (see location on Fig 1, modified from Sallenger et al., 2007).

Photograph D was taken right after the hurricane on August 31st 2005, showing the erosion on the left and washover fans on the backbarrier side of the island. NASA (2005) has described this process as "barrier island rollover" or shoreface retreat, as termed in this paper.

Other islands along the Mississippi-Alabama region have also undergone changes during extreme events (Morton, 2008). This study across more than 100 years of history showed that almost all of the coastal islands in this area have lost their areal extent, especially since the 1960s. The primary agents for these changes are storm cycles, sea level rise, subsidence, and a decrease in sand supply as a result of human activities. Hence, the US Army Corps of Engineers (2009) has carried out studies to propose improvements to protect these barrier islands. Farther west, along south-central Louisiana, along the periphery of the Mississippi River delta plain, the barrier shoreface has retreated up to 3 km in places during a 120-yr period (Fig. 10, Miner et al., 2009). As shown in Figure 10 (d), the barrier islands from Grand Isle in the east to Timbalier Island in the west, the islands have moved anywhere from one to 4 km landwards between 1884 and 2005. However, the shoreward migration has not been linear. Miner et al. (2009) demonstrated that these trends were enhanced by major hurricane impacts and that these impacts are an order of magnitude greater than the average trends. Moreover, when extreme events are separated by a few years, newer and "more resilient" structures are built but suffer the same fate later under subsequent storms, which only adds to the cost of restoration (Pilkey and Young, 2005). For example, 70% of Dauphin Island was inundated and the Chandeleur Islands were breached in many places earlier in 1969 during Hurricane Camille. Most of the effort on restoration was probably nullified when Hurricane Katrina took its toll on the same two islands in 2005.

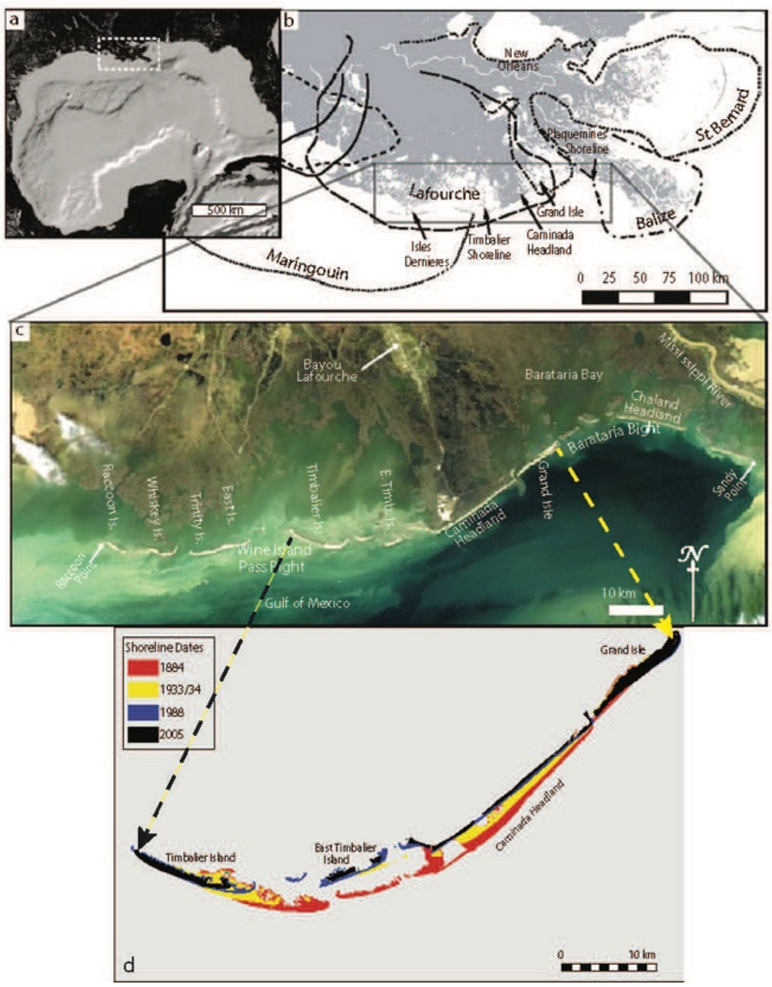

Fig 10. Shoreward migration of barriers in South Central Louisiana, from Timbalier Island to Grand Isle. The barriers have migrated from 1 to 3 km during a 120-yr period from 1884 to 2005 (Location on Fig 1, modified from Miner et al., 2009)

Mallinson et al. (2011) have documented that the evolution of North Carolina Outer Banks (Fig. 11B, Location on Fig. 11A) has been primarily controlled by storms during the last 4,000 years, primarily by enhanced activity of hurricanes (during the Medieval Warm Period from about 1,300 to 800yr BP) and "northeasters" (during the Little Ice Age from about 700 to 100 yr BP). During these periods of enhanced storm activity, many more inlets opened than are there now and a general reduction in storm activity has allowed the system to evolve into a more continuous barrier with relatively few inlets (Mallinson et al., 2011). As shown in Figure 11C, the shoreline just north of Oregon Inlet has migrated landward by almost one km since at least the 1850s, suggesting a rollover in this part of the barrier chain. Using examples from the North Carolina Outer Banks, Paris and Mitasova (2014) traced barrier island dynamics during a relatively short interval (about 15 years) through "Mass Center Analysis" as compiled by Geographical Information System (GIS) using LIDAR data. They were able to establish that during this short interval, the primary change in barrier "mass center" was along shore, but there was a minor cross-shore component as well. However, after a major storm in 2003 (Fig. 11D), washover fans crossed the barrier ridge and filled part of the back barrier bay. Some of this landward shift in the barrier's center of mass was healed once the fair weather returned, but the effect of storms causing landward transport of material from the front of the barriers to the back (rollover) was definitely established.

Just north of the area shown in Figure 11, Nebel et al. (2013) documented the cyclone frequency and erosion rates on Cedar Island, Virginia (Fig. 12). Tropical Storm Ernesto struck the area in 2006 and surveys were carried out 1.5 months before and 3 weeks after the storm. On average, the southern section of the island retreated 25.4 m as a result of the storm (Nebel et al., 2013). Although the shoreline recovered somewhat one year after the storm, comparisons of shoreline position just after the storm and 9 months after the storm revealed that the shoreline had not recovered to its post-storm position but had undergone a net erosion of almost 18.3 m. Record of more than 150 years of tropical storms and cyclones passing through

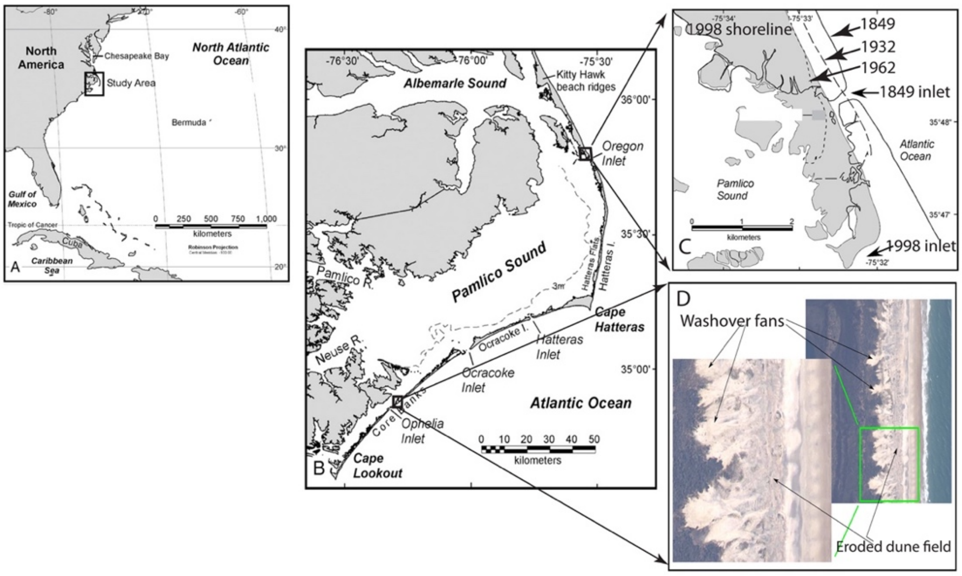

Fig 11. Location map of barriers offshore North Carolina (A, B) and detailed map (C). The original location of Oregon Inlet was almost 3 km to the north in 1849. Since then, as the inlet migrated downdrift to the south, the shoreline has migrated landward by almost one km or more. Stabilization efforts might have affected the recent shoreline position (modified from Mallinson et al., 2011). Photo D (see box in B for location) from Paris and Mitasova (2014) showing washover fans and eroded dunes immediately after hurricane Isabel in 2003. Further details in text.

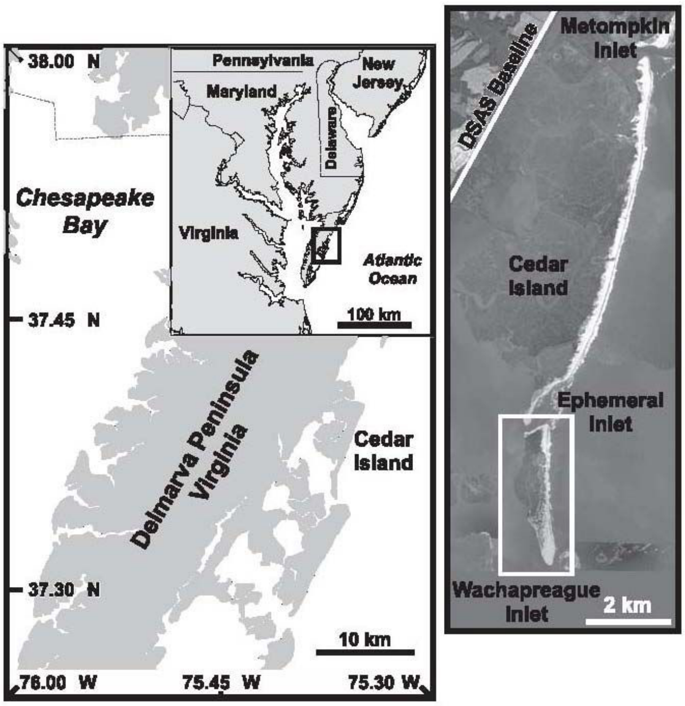

Fig 12. Location of Cedar Island, part of barrier islands along the Virginia shore (see inset, and Fig 1). The location of Cedar Island is shown in the expanded view (lower left) and the photograph to the right locates the barrier island and some of the inlets at the southern tip of the island (from Nebel et al., 2013).

the area shows an increased frequency of storms starting in 1980 until the end of the study in 2007. This increased frequency coincides with increased rates of island retreat. Obviously, if the storms occur frequently enough before the barriers have a chance to recover, the impact would be cumulative from multiple storms (Houser and Hamilton, 2009). See Table 1 for a summary of various examples of modern and ancient barrier migration mentioned here.

This review demonstrates that during extreme-weather events (storms), the entire barrier may be submerged with partial recovery at a later date. Figure 13 shows that these events are not rare, at least when measured over a time span of thousands of years. Since 1858, at least 9 major hurricanes have passed over the south shore of Long Island (Tanski, 2012). This map does not show some of the more recent hurricanes, e.g., Sandy (2012) or Ida (2021, which caused extensive rainfall and damage in the New York/New Jersey area. It is clear that over a time span of several thousand years, numbers of such events would be in the hundreds and a majority of the shoreline changes would probably be caused by these events.

Although this paper is focused on the U.S. East and Gulf coasts, admittedly, the trends in worldwide sea level change are not uniform. During the 27-year period between 1993 and 2016, through satellite data NASA (2016) has mapped sea level trends worldwide. According to NASA's map, sea level rise along the US East Coast and Gulf Coast has been in the 6 to 10 mm/yr range, while in other parts of the globe, such as Equatorial Africa and South America, the rate is in the 2-4 mm/yr. A discussion of these regional variations is beyond the scope of this paper. However, regional variations, of course, impact the effects on shorelines, and particularly, the barriers as we trace their history and project their near future. For example, Barboza et al. (2021) have demonstrated that along the southern coast of Brazil, the sea level was at a maximum level of 1.9m above the present day about 5,000 years ago and has continued to fall until recent times. Consequently, instead of retreating, the barriers have shown a pattern of progradation caused by

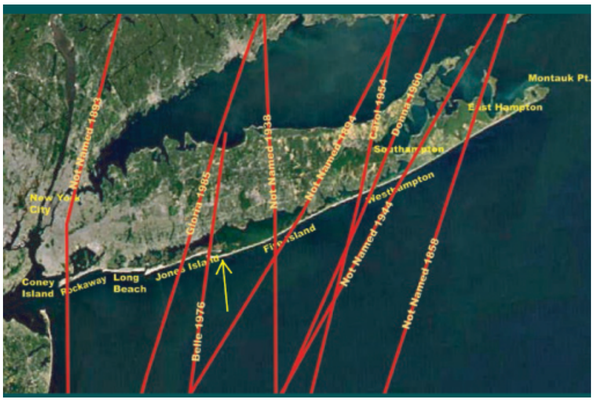

Fig 13. Tracks of hurricanes passing through New York city/Long Island area since 1858. Yellow arrow shows the location of Fire Island Inlet (Figures 3 and 6). Image modified from Tanski (2012).

falling sea level along more than 600 km of coastline. However, this trend is neither uniform nor continuous, as shown by Nicolodi et al. (2021) along the same shoreline. They found that about 43% of the shoreline was stable and only 12% was moderately or strongly prograding between 2002 and 2013. However, the remainder, about 45%, was undergoing moderate or pronounced erosion. Additionally, they modeled the sea level rise of about 0.89 m for the years 2030 to 2100, which suggested that the southern part of this coastline (hundreds of kilometers) is subject to the greatest erosion and even the sectors that have historically prograded can become vulnerable under conditions of sea level rise in the long term (Nicolodi et al., 2021). The sea level projection tool developed by NASA/IPCC (NASA, 2021) shows that even under most optimistic scenarios of climate change (net zero CO_2 emissions around the middle of the 21st Century and the warming to approximately 1.5^0 C above 1850-1900 in the year 2100), the mean sea level will rise in almost all parts of the world. Hence, there is a need to review the risks and possible mitigation for barriers around the world.

FUTURE OF BARRIER ISLANDS

After every disaster, a discussion of resilience or "rebuilding" takes place (National Research Council, 2013). As early as the Middle Ages, instead of being part of nature, man attempted to become the exploiter of nature (Haila, 2000). When the populations worldwide were much smaller, it was relatively easy to adjust to natural phenomena, but as the population has rapidly increased, adjustment to natural adversities has become increasingly difficult, if not impossible. This reality has dawned only in the last 60 years or so as part of the conversation on the ecological movement (Martin et al., 2016).

Access to the ocean for our ancestors meant the availability of food and travel to distant places during the earliest days of human development. However, there is evidence that during the Pleistocene sea level lowstand, the earliest migrants to North America lived and clustered on the present-day shelf and as the sea level rose during the Holocene, they gradually relocated landward, eventually locating near the present-day shorelines (Pilkey and Pilkey, 2019). As the population grew, more and more human settlements along shorelines developed worldwide. In fact, almost 600 million people (slightly less than 10% of the world's population) live in coastal areas that are less than 10 meters above sea level, including some of the most populous cities in the world (Ocean Conference, 2017; Pilkey and Pilkey, 2019). As described in this paper, the rise in sea level is obvious along various shorelines around the world. The strategies for "dealing with it" are fraught with political, economic, and emotional issues that transcend geological reality.

Table 1: Summary of selected Barrier Responses along US East and Gulf Coasts cited in this paper

Barrier Location	Event/Date	Shoreface Retreat	In-place drowning	Reference/Comments
US East Coast: Ancient barriers South shore, Long Island, NY	8,500 yr to 9,000 yrs BP 7,500 yr BP to modern	From -16m SL to present	-24m to -16m SL	Kumar (1973), Sanders and Kumar (1975), Rampino and Sanders (1981)
Core Banks, North Carolina	7,000 to 4,000 yrs BP 4,000 yr BP to modern	Shoreface retreat	Likely in-place drowning	Moslow and Heron (1979)
US East Coast: Modern barriers Outer Banks, North Carolina Oregon Inlet	1850 to present	Shoreface retreat		Mallinson et al (2011), Paris and Mitasova (2014)
Cedar Island, Virginia	Recent 25 years	Shoreface retreat		Nebel et al (2013)
US Gulf Coast: Modern barriers Dauphin Island, Alabama	Hurricane Katrina (2005)	Shoreface retreat		Sallenger et al (2007,2006)
Chandeleur Island, Louisiana	Hurricane Katrina (2005)		In-place drowning	Sallenger et al (2007,2006)
Mississippi, Alabama, S. Central Louisiana	Last 100 years, particularly since 1960s	Shoreface retreat		Morton (2008), Miner et al. (2009)

In the Dutch Wadden Sea, with its extensive system of barrier islands and backbarrier lagoons, the rates of future sea level rise predicted are comparable to early Holocene rates (Oots and de Boer, 1994). However, during the early Holocene, the complete system was "unimproved" and could retreat landwards in response to the sea level rise. However, construction of dikes currently blocks the landward migration of the coastal system, and it is expected that under conditions of accelerated sea level rise, a percentage of the intertidal flats will change into subtidal areas (Oots and de Boer, 1994). According to these authors, "fixing" of the Wadden Sea barrier islands artificially in their present position might, in the long run, lead to washover channels on the barriers and a permanent drowning of the backbarrier region.

There are two potential responses to sea level rise: mitigation and adaptation (Passeri et al., 2015). While mitigation at a global scale is very desirable, most of the immediate action has to be undertaken at a local level. Also, a mitigation effort through overcoming climate-change consequences, even if successful, may be too late for many of the barrier islands. Annual damages from coastal flooding, including loss of infrastructure and rebuilding plus additional socio-economic costs, may reach tens of billions of dollars within the next few decades (Passeri et al., 2015). Because the sea level rise along barrier islands is inevitable, there are various strategies that could be employed: no

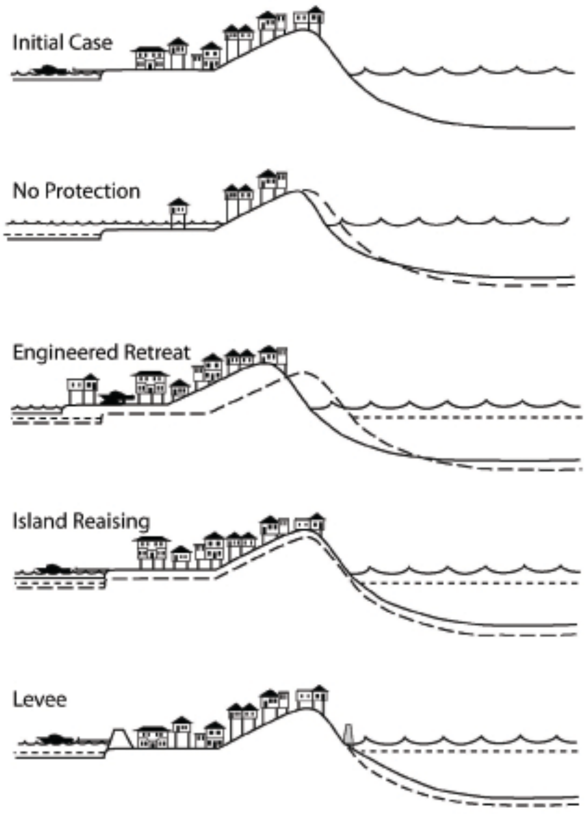

Fig 14. Various strategies possible for adapting to the rising sea levels at barrier-island coastlines. Each of these possibilities have economic, social and political consequences (after Titus 1990). See that publication for detailed discussion of each of these strategies

coastal protection, engineered retreat, island raising, or shoreline protection with seawalls and jetties (Titus, 1990, Fig. 14). Titus (1990) has discussed each of these strategies and their pros and cons in detail and therefore, these options are only briefly discussed here.

In reality, "no coastal protection" is not an option for most places (except undeveloped and protected barrier islands), because when the ocean front is subjected to the effects of sea level rise with flooding and enhanced storms, "coastal protection" becomes the first step demanded by the property owners and generally provided by the civil authorities. This is attempted either by replenishing the eroded sand or by constructing seawalls and jetties. Valverde et al. (1999) have documented the coastal replenishment projects around the U.S. East Coast since the 1920s. They calculated that almost 350 million cubic yards (~268 million cubic meters) have been placed along the coast, a great majority of which has been placed in the most recent decades. In recent years, replenishment by sand has been preferred over the construction of hard structures. However, the availability of suitable sand has become a problem and the environmental damage to the source areas remains considerable. Whether hard or soft protection, it becomes a continuous and ongoing expensive project, and offers no permanent solution. In March 2024, a Massachusetts beach community lost its $600,000 sand reclamation project just three days after its completion. Yet, some of the residents claim that it is worthwhile even if it has to be done after each major storm because "it protects $2 billion worth of property" (Casey and Assoc. Press, 2024).

Another approach discussed by Titus (1990) is to raise houses and roads in flood-prone areas and to maintain the original profile of the island on the bay side, as well as on the open-ocean side, by dredging and pumping sand. But as mentioned earlier, damage to the ecosystem from dredging and pumping cannot be easily mitigated and the cost of such a strategy would be a major ongoing societal expense. Charlier et al. (2005) describe the cost of maintaining Miami Beach (a barrier island) with fine coral sand at US $60 million of taxpayers' money (it lasted sixteen years). However, in some cases, the replenished beach is swallowed up within a year or two when the next storm strikes. These authors cite a figure of US$366,000 for restoring one km of beach in the United States. Today, that figure would be obviously higher in 2026 dollars. Losses from coastal storms have only increased during the last few decades (Dean, 2014; Grambling, 2021). A cost-benefit analysis (Bralower, 2021) might indicate that the cost of restoration/nourishment may be offset by economic benefits provided by the coastal environment. However, because the severity of the next storm event is almost impossible to predict, such approaches may still be insufficient. An ambitious example of barrier island protection is a proposed $29 billion project to build a series of floodwalls to protect Galveston Island, Texas: a ring levee on the bay side of Galveston, restoration and elevated buildings in Galveston Bay and a set of storm surge barrier gates at the entrance of the bay (Irvine, 2022). Even if funded, this project would take 10 to 15 years to complete, while a major storm could strike the area during the construction and not only cause extensive damage but also destroy the partially constructed project (Irvine, 2022).

The discussion on preservation or restoration has to be primarily concerned with areas where infrastructure for habitation and entertainment exists and where life and property would need to be protected during a major storm event. Gorstein (2021) found that the annual economic benefits of recreation alone on South Carolina's beaches and barrier islands were in the $1.5 to $3.0 billion range (2019 dollars). This did not include other benefits such as coastal protection or water supply protection, etc. Thus, the argument can be made that spending a certain percentage of the economic benefit on restoration or protection is a valid investment. Surveys suggest that people living in communities on the barrier islands support certain expenditures to restore to the existing footprint or a higher amount to restore to a previous, larger extent of a barrier island (Petrolia and Kim, 2009).

O'Donnell et al. (2016) have provided pros and cons for various options shown in Figure 14, but in reality, an engineered retreat or abandonment of the barrier island as a place for permanent settlement might be the only option in the coming decades for locations with extensive infrastructure. However, these two options are probably also the most expensive and "politically" the most difficult to achieve. It appears that the insurance industry might be forcing homeowners (and thus other entities involved) to take decisive steps by cancelling or not renewing home-insurance policies for up to 25% of the properties in some of the localities in North Carolina, Louisiana, and Mississippi (Flavelle and Rojanasakul, 2024). Without insurance, homeowners may not have a choice but to move to other, less vulnerable locations. Perhaps the "free market" system will work where other solutions have not worked so far. As most of the money for these efforts, directly or indirectly, comes from the federal government, a national dialogue is needed to create a plan (National Research Council, 2014). Fortunately, some states are already taking a "holistic" system approach to manage their barrier islands and headlands, as carried out by Dalyander et al. (2021) for the State of Louisiana.

CONCLUSIONS

- This review has focused on the fate of barrier islands during a eustatic sea level rise, which also enhances the effects of coastal storms, hurricanes, and tides.

- Barrier islands occur along almost 60% of the US East and Gulf Coasts. Hence, the impact of sea level rise has been predominantly felt along these "barrier coasts." Because these barriers act as the "first line of defense" for the mainland coastline, they are of primary importance in protecting the population and infrastructure not only on the barrier islands but also on the adjacent mainland.

- As the sea level rises, one of two consequences might happen to the barrier islands. Either they may regress landward gradually (*shoreface retreat*) or they may be overwhelmed by the rising sea (*drowned in place*). Table 1 is a summary of selected case histories described in this paper. Both of these scenarios have taken place at the same shoreline during historical times (the last 10,000 years) or both of these events have occurred during the same storm at different parts of the same shoreline.

- Catastrophic events along the coastlines have become more frequent during the last few decades. As the population and infrastructure along the barrier islands have also increased in recent years, calls for "beach protection" or "beach nourishment" have become louder and the ensuing projects more expensive.

- Only a long-term view of a regional solution and recognition of the full array of economic, social, environmental, and life-safety benefits that come from risk-reduction efforts need to take place. These efforts will avoid reacting to events after the fact and instead lead to investing in building resilience among coastal communities for the short- and long term. However, the efforts and their outcomes need to be monitored by independent panels, rather than by the same agencies that developed and executed the plans.

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DECLARATION OF INTEREST

The author has no competing interest to declare.

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