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Potential implications of global warming and barrier island degradation on future hurricane inundation, property damages, and population impacted

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ABSTRACT

Hurricane flooding is a leading natural threat to coastal communities. Recent evidence of sea level rise coupled with potential future global warming indicate that sea level rise will accelerate and hurricanes may intensify over the coming decades. In regions fronted by barrier islands, the protective capacity of these islands may diminish as they are degraded by rising sea level. Here we present a hydrodynamic and geospatial analysis of the relative role of barrier island degradation on potential future hurricane flooding. For the City of Corpus Christi, Texas, USA, hurricane flooding is projected to rise between 20% and 70% by the 2030s, resulting in an increase in property damages and impacted population. These findings indicate that adaptive management strategies should be developed and adopted for mitigating loss of natural barrier islands when these islands act as protective features for populated bayside communities. Finally, this study illustrates a method for applying models to forecast future storm protection benefits of barrier island restoration projects.

1. Introduction

Inundation by storm surge from hurricanes and other tropical cyclones is one of the leading natural threats to coastal communities. Since 2004, the United States of America (USA) has experienced some of its highest hurricane surges on record with the surges generated by Hurricanes Ike, Rita, Katrina, and Ivan matching or exceeding previous measurements [1–3]. Possible acceleration of sea level rise (SLR) and intensification of hurricanes as a consequence of global warming [4,5] can lead to increased hurricane flooding and damages. In regions protected by natural barrier islands, this potential acceleration in hurricane inundation with global warming is expected to be amplified, as the barrier islands themselves are vulnerable to degradation from SLR. This potential escalation in hurricane flooding inundation can lead to an increased land area threatened by storm surge, potentially increasing hurricane-induced economic damages, the number of evacuees prior to landfall of a hurricane, and demand on resources for post-storm recovery, among other factors. Thus, it is prudent to quantify the potential impact of global warming on future hurricane flooding to improve and develop adaptive engineering, planning, and evacuation strategies for communities at the coast.

In this paper, we investigate the potential implications of global warming on future hurricane inundation and damages with emphasis on the relative role of future degradation, with SLR, of protective barrier islands. Here we present a generalized method for assessing these potential implications at any worldwide location exposed to coastal storms. Our analysis for the City of Corpus Christi, Texas, located on the northern Gulf of Mexico, USA, shows that, if future global warming scenarios are realized and if protective barrier islands degrade over time, hurricane flooding inundation and associated damages will increase during the next century.

Below, we discuss recent climatic research on global warming with an emphasis on those factors with the potential to increase hurricane inundation, and we discuss barrier island processes and the potential for natural barrier island degradation with SLR. The numerical modeling and geographic information methods used for evaluating the potential rise in future hurricane inundation, damages, and population affected are then introduced. Finally, we

Abbreviation: ADCIRC, ADvanced CIRculation model; IPCC, Intergovernmental Panel on Climate Change; MSL, mean sea level; MSL_{2000s}, present-day mean sea level; $MSL_{2030s\text{-}high}$, high projection of 2030s mean sea level; $MSL_{2080s\text{-}middle}$, mid-range projection of 2080s mean sea level; NOAA, National Oceanic and Atmospheric Administration; SLR, sea level rise; SRF, surge response function; SST, sea surface temperature; SWAN, Simulating WAves nearshore.

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present our results and conclusions regarding future hurricane inundation as a consequence of potential barrier island degradation, sea level rise, and hurricane intensification.

2. Background

The hurricane flooding probability and damage risk assessment that forms the basis for much coastal engineering and planning depends on climate statistics including hurricane track, frequency, and intensity and mean sea level. Since these climate statistics can vary on short (decadal) and long-term time scales [6], it is important to understand how the coastal landscape and flooding responses change as a result of climate variability. Here, we will focus on the implications of long-term global warming projections.

The climate projections presented by the Intergovernmental Panel on Climate Change (IPCC) [4] indicate that sea surface temperature (SST) over the next century will rise between 1.1 °C and 6.4 °C. In this analysis, to span a range of future climate possibilities, we consider three of the IPCC future global warming scenarios:

1) B1, which assumes a low rate of greenhouse gas emissions,
2) A1B, which assumes a moderate rate of greenhouse gas emissions, and
3) A1FI, which assumes a high rate of greenhouse gas emissions and represents the highest emission scenario considered by the IPCC [7].

By assuming that the expected global change in sea level rise and the expected hurricane intensification are correlated with SST rise, each of these warming scenarios can be used to project future sea level rise and hurricane intensification.

2.1. Potential sea level rise with global warming

Observed mean sea level (MSL) data over time show a net rise in global, or eustatic, sea level [4,8–10]. Observed eustatic SLR rates over the last century are between 0.17 and 0.18 cm/year [4]; however, these observations also indicate an acceleration in SLR over the last couple of decades, with an SLR rate of 0.30 cm/year [4]. Global climate projections made by the IPCC also indicate a future acceleration in SLR, with respect to historical observations, projecting rates as high as 60 cm over the next century for the three climate scenarios listed above [4,11]. Other researchers suggest eustatic SLR over the next century may be as much as 1 m if major ice-sheet melting occurs [12–14].

2.2. Potential hurricane intensification with global warming

The historical hurricane record and climate projections both suggest that major hurricanes (Category 3 to 5 on the Saffir–Simpson scale [15]) may become more intense with SST rise [5,16–19]. By evaluating several convective parameterizations [20–22] and considering thermodynamic impacts, Knutson and Tuleya [16,23] estimated that, on average, a hurricane's central pressure would increase 8% per 1 °C of SST rise:

$$p_{\Delta SST} = p_o - 0.08(\Delta SST)\left(p_{far} - p_o\right) \quad (1)$$

where:

$p_{\Delta SST}$ is the future projected hurricane central pressure,
p_o is the present-day (2000s) hurricane central pressure,
ΔSST is the sea surface temperature change in °C, and
p_{far} is the far-field barometric pressure, and all pressure parameters are in consistent units.

Because Eq. (1) does not account for wind shear, among other factors, it should be considered representative of possible hurricane central pressure change with SST change for a future tropical system, if that tropical system develops fully.

2.3. Potential barrier island degradation with sea level rise

To understand the potential changes to barrier island morphology with increasing sea level, we first considered how barrier islands have formed and evolved over the past 3000 to 7000 years. Barrier islands were able to form during this period because the eustatic sea level rise rate was relatively slow (~0.1–0.2 cm/year) [24]. Prior to this time, eustatic sea level rise was rapid (1–2 cm/year) and barrier islands were unable to form because the destructive processes of erosion and overwash were greater than constructive processes such as a net influx of long shore sand transport, Aeolian transport and dune building, and onshore transport.

Over the past 100-years, for example, barrier islands in Louisiana have experienced a relative SLR of approximately 1 m (rate of 1 cm/year). Morphologic response of these islands to this rapid rise has been to form breaches, islets, permanent inlets, resulting in island break up and drowning in place [25]. A similar response has been documented in the geologic record offshore of Fire Island, New York, whose islands formed 9000 years ago were drowned in place as sea level rose rapidly. These islands were overstepped as new islands formed in a more landward position [26,27]. Based on this long-term evidence, we infer that a future rise in relative sea level exceeding 1–2 cm/year would likely break up and drown barrier islands fronting Corpus Christi Bay.

With relatively slow rates of relative sea level rise, natural barrier islands can respond in two ways: (1) with sufficient supply of littoral sand, barrier islands can be stable or migrate landward through inundation and overwash processes; or (2) without sufficient supply of sand, islands can either drown in place, which will occur with extremely rapid relative SLR, and break up or disintegrate, forming islets and breaches as occurred in the Isle Dernieres, Louisiana [25].

The Bruun Rule [28] is the simplest model for long-term evolution of the shoreface. It predicts equilibrium shoreface retreat given the rate of relative SLR and the vertical and horizontal extents of the active beach and nearshore profile. The relationship is formulated by equating the volume eroded by an increase in relative sea level to the sediment required to increase the elevation of the active profile, and the profile retreats parallel to itself. Dean and Maurmeyer [29] modified the Bruun Rule for barrier islands, including terms relating the active extent of the lagoon (or bay) in the vertical and horizontal dimensions. Dean and Maurmeyer [29] noted that if the zone of active cross-shore movement of sediment is equal for both the ocean and bay (e.g., same active depth), there would be no potential for building up of the island during landward migration and the barrier island would narrow, essentially drowning in place.

List et al. [30] examined the applicability of the Bruun Rule to predict shoreline response due to relative SLR for 150 km of Louisiana coastline west of the Mississippi River. The authors eliminated approximately half the profiles that did not maintain an equilibrium form over the 50- to 100-year period considered. For the remaining profiles tested, the authors assumed between 31% sand (for deltaic shorelines) and 100% sand (for sand spits) to calculate volumetric losses of fine sediment as the beach retreated. The Bruun Rule could not accurately predict shoreline response in a hindcast evaluation for the Louisiana coast. Long-term massive redistribution of sediment in the nearshore and on the shoreface was used as evidence of changes to the long-term regional sediment budget that decreased applicability of the Bruun Rule. Also, relative SLR has increased the size of the bays behind barrier islands, thus increasing the tidal prism of adjacent inlets and their associated ebb and flood tidal deltas. As the barrier retreats, the redistribution of sand into the deeper bay, as well as into deltas, suggest that the barrier islands cannot maintain their subaerial form.

There is an exacerbating response to an increase in sea level for barrier islands that protect a bay or estuary, for cases in which the bay area can increase. As relative sea level increases, the bay area and tidal prism increase, causing an increase in adjacent inlet area. With larger tidal prism and inlet area, ebb and flood shoals become larger, removing sand from the barrier island beaches. Thus, sea level affects the barrier island sand budget in three ways: apparent retreat of the shoreline because of higher water level; migration of the island itself because of an increased propensity for overwash; and an increased sink for sand in formation of the tidal shoals. FitzGerald et al. [31–33] presented a conceptual model of barrier island evolution with relative SLR, for the case in which a sufficient source of sediment is not available. This model shows the break up of a barrier island fronting a bay as relative water level increases, bay area increases, and sand in the littoral budget is transported to meet the demand of the newly-forming inlet shoals. The response of a barrier island to the additional loss of sand to the inlet shoals is to erode, followed by an increase in overwash and formation of small breaches or islets. For the situation in which sufficient sand is available to maintain a subaerial barrier island, migration of the island into the bay may reduce the bay area to some degree, and may offset the otherwise increase in bay area, tidal prism, inlet area, and shoal volume.

2.4. *Potential implications of global warming on coastal communities*

Hurricanes over the last decade have resulted in widespread damages and loss of life. For example, Hurricane Katrina in 2005 devastated the northern Gulf of Mexico coastline, from Louisiana through Alabama, resulting in more than 1500 deaths and $81 billion in damages [34]. If potential acceleration in SLR and potential hurricane intensification with global warming occur, such hurricane events will result in more severe impacts at the coast.

Several recent studies have considered the effect of SLR on hurricane flooding probability in the USA. For example, Cooper et al. [35] concluded that 1%–3% of New Jersey could be permanently inundated within a century, and a moderately high 0.61-m rise in sea level, based on IPCC projections [4], could result in the present-day 100-year flood level increasing in likelihood to a 30- to 40-year flood level. Kleinosky et al. [36] considered SLR of 30, 60, and 90 cm in Hampton Roads, Virginia. The authors found that the flooding probability zones for major hurricanes (Category 3 and higher) increased between 7% and 28%, while the flooding probability zones for critical facilities (hospitals, schools, etc) increased between 1% and 19%. In a case study for New York City, Gornitz et al. [37] determined that the return period of the present-day 100-year storm flood could increase in likelihood to between 19 and 68 years by the 2050s and to between 4 and 68 years by the 2080s. The authors also found that the 100-year flood would increase from 2.96 m, today, to between 3.0 and 3.5 m by the 2020s and up to 4.2 m by the 2080s.

Among studies of sites in the USA, Frey et al. [38] and Frey [39] are the only studies to consider the combined impact of SLR and hurricane intensification. Frey et al. [38] considered both acceleration in SLR and hurricane intensification in quantifying potential increases in property damage and population affected by hurricane inundation under several IPCC global warming scenarios. Frey et al. [38] reported that if the highest greenhouse gas emission scenario reported by the IPCC is realized, by the 2080s, property damages by hurricane inundation could increase by more than 250% per hurricane event. Under this same high rate of warming scenario, by the 2080s this study showed that population impacted would increase by more than 200% per event.

Church et al. [40] considered tropical cyclone intensification and SLR in Australia. They found that in Cairns, the 100-year storm event increases in elevation from 2.5 m to 2.9 m by 2050 and the average return interval for the 2.5 m event increases in likelihood from a 100-year event to a 40-year event as a result of SLR and tropical cyclone intensification. Karim and Mimura [41] recently studied the effects of tropical cyclone intensification and SLR from climate change on coastal Bangladesh, and showed that flooded area increases by 13% when the SST increases 2 °C and that flooded area increases by 25% when the SST increases by 4 °C. Ali [42,43] also conducted a similar study in Bangladesh and found that a 2 °C SST rise and an SLR of 0.3 m resulted in a 20% increase in flooding, while a 4 °C SST rise and an SLR of 1.0 m resulted in a 40% increase in flooding.

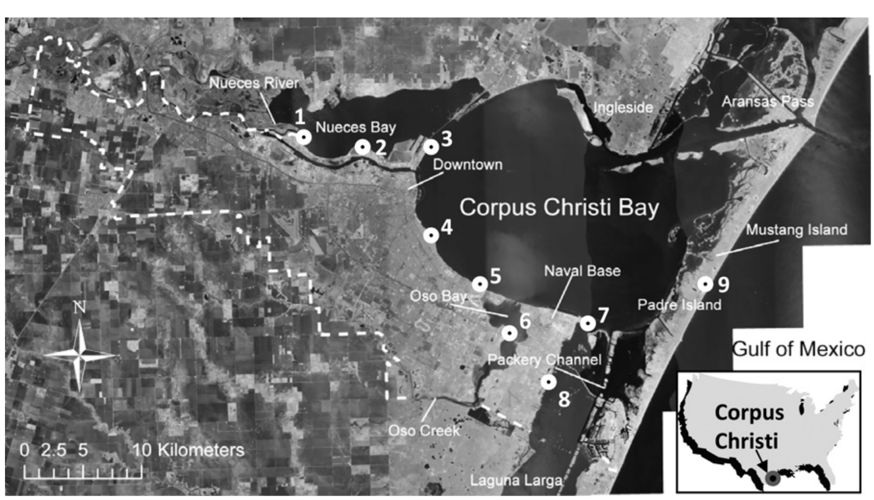

Fig. 1. Location map for Corpus Christi, Texas USA (aerial imagery from U.S. Geological Survey [67]). Dashed line represents the City of Corpus Christi boundary, and numbered circles are selected locations for surge results discussion (Section 5.2).

While the potential implications of global warming on coastal storm impacts is evidenced in the literature discussed above, it is worth noting that none of these studies considered the potential implications of future barrier island degradation on future storm impacts. Yet, barrier islands are known to provide some level of protection against hurricane surge and wave action (e.g., [44]). Because barrier islands can act as natural surge barriers, their potential degradation with SLR can result in higher flood elevations within coastal bays. As an example, Canizares and Irish [45] showed that for coastal storms in Long Island, New York, surge waters passing over the barrier islands during hurricanes can raise flood levels on the order of 1 m within coastal bays. In this paper, we focus on the role of barrier island degradation on future hurricane flooding.

3. Study area

The City of Corpus Christi, along the Texas, USA Gulf of Mexico coastline (Fig. 1) was selected for evaluating the potential impacts of global warming and barrier island degradation on hurricane inundation and its relation to population affected and economic damages. This region of the Texas coast is regularly subjected to high hurricane surges, and the population of Corpus Christi is vulnerable to hurricane damage because of the extensive coastal infrastructure serving tourism, commerce, and energy. More than 275,000 people reside on both the mainland and the barrier islands, this urban community supports a strong tourism industry, multiple oil refineries, the Corpus Christi Naval Air Station, the Port of Corpus Christi, and Texas A&M University – Corpus Christi.

3.1. Historical sea level rise

Historical observations of relative SLR in this region include substantial contributions from both eustatic rise and land subsidence. Based on water level observations reported by the National Oceanic and Atmospheric Administration (NOAA) near Corpus Christi, historical relative SLR in this region is 0.46 cm/year [46]. Using the abovementioned historical eustatic SLR rates, observed land subsidence due to fluid withdrawal and soil consolidation (e.g., [47]) is estimated to contribute 0.29 cm/year to the historical relative SLR. Studies of land subsidence in Texas [48–50] indicate that subsidence rates for this region have slowed somewhat in recent decades, most likely in response to reduced groundwater extraction [51]. However, land subsidence is projected to accelerate in many locations around the world as demands on groundwater increase with population growth [52]. Due to the uncertainty in projecting such processes as groundwater extraction, it is assumed here that land subsidence in Corpus Christi will continue into the future at its average historical rate of 0.29 cm/year. However, if fluid extraction in the future slows or ceases due to mitigation measures, land subsidence may decrease correspondingly. Conversely, if fluid extraction increases as is likely with population growth, land subsidence may increase correspondingly; the United Nations projects the U.S. population to increase 18% by the 2030s [53].

3.2. Hurricane history

Ten major hurricanes (Category 3 or higher) have made landfall along the Texas coastline since 1950 [54]. Of these storms, Hurricanes Beulah (1967), Allen (1980), and Bret (1999) generated high flood levels at Corpus Christi. Observed maximum flood levels along the open coast for these three hurricanes were between 1 m and 3 m [55–57]. It is worth noting that while Hurricane Ike (2008), which made landfall about 300 km to the north of Corpus Christi, generated more than 1 m of surge at Corpus Christi [46], this storm made landfall as a Category 2 hurricane and thus is not classified as a "major hurricane."

3.3. Role of barrier islands for surge protection

The City of Corpus Christi is divided into two geographic sections: a mainland portion, situated on Corpus Christi Bay, and a barrier island portion, Mustang and Padre Islands, which separates Corpus Christi Bay from the Gulf of Mexico. The natural barrier island system fronting Corpus Christi Bay acts as a natural surge barrier to mainland Corpus Christi and other bayside communities. If surge overtopping of the barrier islands is limited, flood levels along mainland Corpus Christi are generated predominantly by locally generated wind surge within Corpus Christi Bay and by ocean flood waters passing through Aransas Pass at the northeastern end of the Bay. Much of this barrier island system is low-lying (Fig. 2), however, with long stretches of elevations as low as 1.25 m above present-day (2000s) mean sea level (MSL_{2000s}) and some areas with elevations between 0 and 0.5 m above MSL_{2000s}. During major hurricane flooding events, ocean flood waters flow over these low-lying portions of this barrier island system,

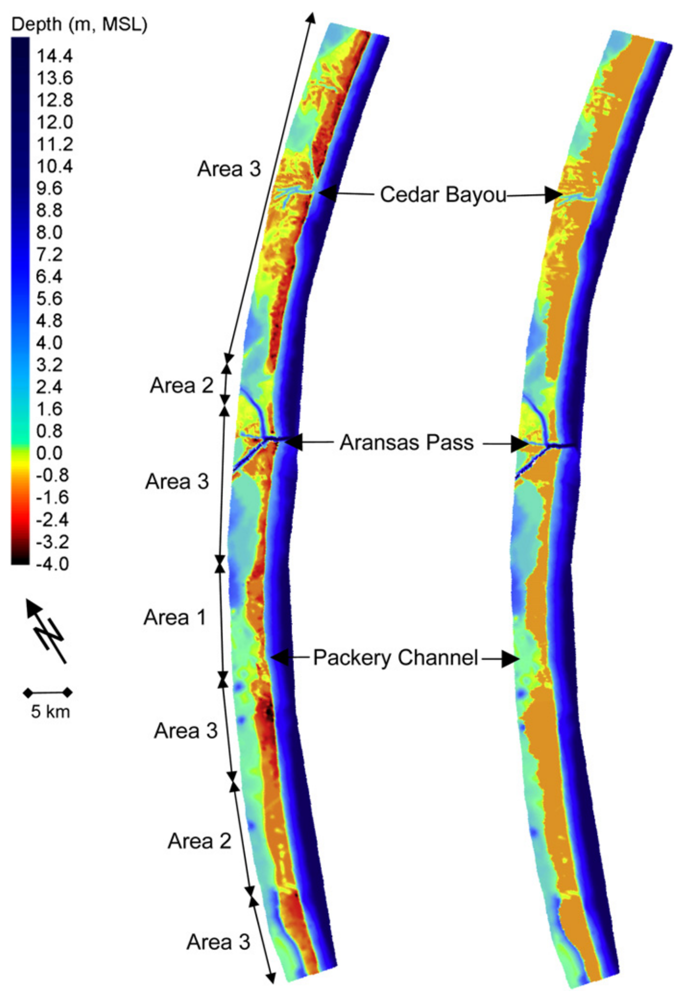

Fig. 2. Padre, Mustang, and San Jose Island topography in the vicinity of Corpus Christi. Left pane shows present-day (2000s) topography while right pane shows a possible future degraded condition, where the entire barrier island system has an elevation no higher than 1 m with respect to MSL during the time period of interest. Areas 1, 2, and 3 indicate morphological reach designation for idealized XBEACH simulations.

oftentimes generating overwash and breach areas which more effectively convey flood waters into Corpus Christi Bay. For example, numerical simulations of hurricane flooding by Hurricane Beulah (1967) indicate widespread barrier island overflow into Corpus Christi Bay [58] occurred during this event. With future SLR and no anthropogenic action, it is expected that this protective barrier island system will degrade, ultimately allowing more storm overflow into Corpus Christi Bay during hurricane surge events.

4. Methods

A combined numerical simulation and geographic information analysis approach was used to evaluate the potential impact of global warming and barrier island degradation on hurricane inundation, damages, and population impacted. The sections below summarize the selection and development of future scenarios with global warming, potential future degraded barrier island conditions, the numerical modeling scheme used to estimate hurricane flood levels, and the geographic information methods used to quantify potential changes in property damages and population impacted. In this analysis, we neglect the impacts of direct wave action, wind, and inland precipitation on damages and consider only those damages directly related to static flooding caused by storm surge induced by wind and barometric pressure, by wave setup, and by SLR. The approach outlined below, with modifications for local conditions, is designed to be applicable for assessing the potential impacts of global warming on tropical cyclone flooding at any worldwide location exposed to coastal storms.

4.1. Future global warming scenarios

To evaluate the combined impact of hurricane intensification, sea level rise, and barrier island degradation on hurricane inundation in the future, climate projections for SST change and eustatic SLR were developed using the climate model MAGICC/SCENGEN [59]. Specifically, two future periods were assessed, the 2030s and the 2080s, by assuming a base year of 1990. For each period, the three abovementioned IPCC carbon-dioxide emission rate scenarios B1, A1B, and A1FI were used, in which three carbon-dioxide doubling sensitivities were considered for each scenario (cool [2.0 °C], average [3.0 °C], and warm [4.5 °C]) [38,58,60]. In total, 27 climate projections were developed using MAGICC/SCENGEN for each period.

Projected rates of SST rise and eustatic SLR ranged from 0.01 °C/year to 0.06 °C/year and 0.24 cm/year to 0.72 cm/year, respectively (Fig. 3). For our analysis, relative SLR in the 2030s and 2080s was taken as the sum of the eustatic rise projected with the climate model plus an estimate of land subsidence. Here, future land subsidence in the Corpus Christi area was assumed to continue at the historical measured rate of 0.29 cm/year. Thus, relative SLR is projected to range from 0.53 cm/year to 1.01 cm/year. Land subsidence makes up 25%–55% of the projected relative SLR at Corpus Christi, depending on climate projection. Under the greatest greenhouse gas emissions scenario considered here, A1FI, the relative SLR rate approximates the minimum of our inferred critical barrier island drowning criteria of 1–2 cm/year (see Section 2.3).

In this paper, we consider potential future hurricanes similar to the historical Hurricane Bret. Of the three major hurricanes impacting Corpus Christi since 1950, Hurricane Bret generated the smallest surge, on the order of 1 m along the open coast. Numerical hurricane flooding simulations for this storm indicate minimal barrier island overwash and breaching occurred during the historical occurrence of this event, as the ocean side flood elevation was very similar to the lowest barrier island elevations [38]. As such, we expect that flood elevations within Corpus Christi Bay will

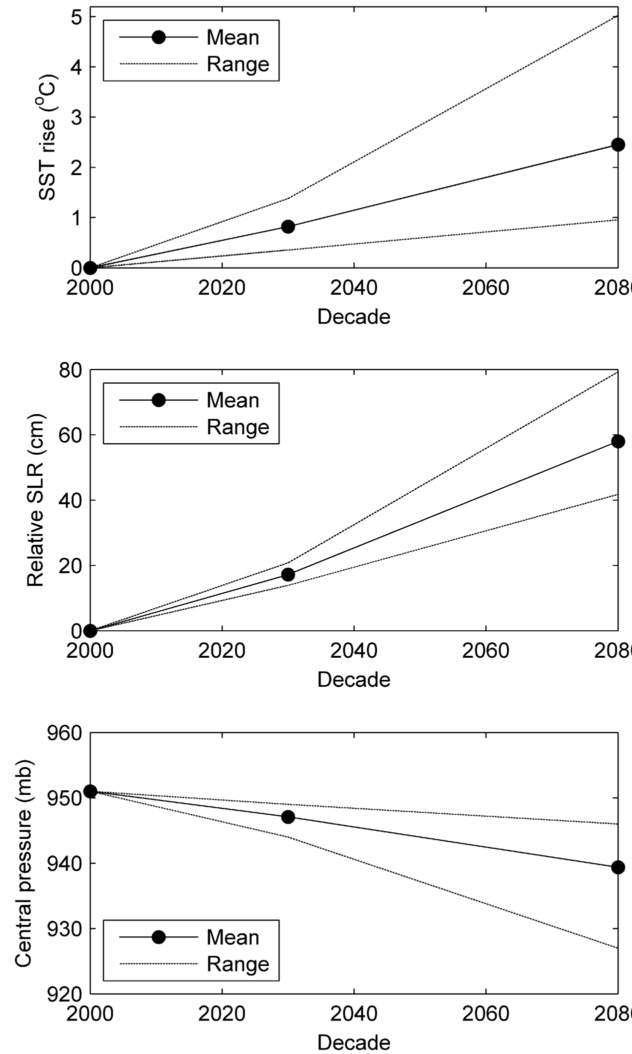

Fig. 3. Projected future sea surface temperature (SST, top pane) rise, relative sea level rise (SLR, center pane), and hurricane intensification for hurricanes like Hurricane Bret (bottom pane). Modified from Mousavi et al. [60].

be sensitive to possible future barrier island degradation. Thus, this storm is highly suitable for evaluating the potential implications of future barrier island degradation on back-bay hurricane flooding. Future hurricanes similar to Hurricane Bret were developed by holding the historical hurricane's track, size, and forward speed

Table 1
Future global warming projections applied to Hurricane Bret for evaluation (modified from Frey et al. [38]).

Future scenario	SST rise (°C)	Landfall central pressure (mb)	Sea level rise (cm)		
			Eustatic SLR	Subsidence	Total relative SLR
Present-day	0	951	0.0	0.0	0.0
A1FI (cool, 2 °C sensitivity) – 2030s	0.36	949	7.6	6.4	14.0
B1 (warm, 4.5 °C sensitivity) – 2030s	1.38	944	14.4	6.4	20.8
A1B (middle, 3 °C sensitivity) – 2080s	2.51	939	36.9	20.9	57.8
A1FI (warm, 4.5 °C sensitivity) – 2080s	5.02	927	58.4	20.9	79.3

constant while varying the hurricane's central pressure. For each climate scenario, the hurricane's central pressure was intensified based on Eq. (1). These projections indicate that this hurricane condition intensifies between 0.1 and 0.3 mb/year (Fig. 3). Table 1 presents the future climate projections selected for detailed hurricane inundation, property damage, and population analysis.

4.2. Future barrier island conditions

The relative SLR projections introduced above suggest that the already low-lying barrier island system fronting Corpus Christi Bay will degrade over time, if no anthropogenic action is taken. However, the relative SLR rates considered here do not indicate that significant barrier island break up and drowning will occur. Our intent in this paper is to evaluate the relative sensitivity of hurricane flooding under future warming scenarios if future degradation of the barrier islands occurs, with respect to no barrier island degradation. Here, we consider one potential degraded barrier island scenario. Our assumptions in creating future barrier island morphology for the modeling herein was to decrease the elevation of the islands to an elevation representative of long-term overwash processes, where no natural or anthropogenic elevation recovery has occurred. As such, the elevations above 1 m along the entire barrier island system were lowered to an elevation of 1 m relative to MSL during the periods of interest (e.g., 2000s, 2030s, or 2080s). Fig. 2 (right pane) shows this degraded barrier island condition. As this figure shows, the majority of the barrier island is represented by a uniform elevation, with the exception being the region just to the north of Aransas Pass, where elevations lower than 1 m above MSL have been maintained. In developing this degraded barrier island scenario, sediment volume removed from the island was deposited into the bay in the form of overwash fans, thereby increasing the width of the low-lying islands. With the above degraded barrier islands scenario, we assume that the amount of sediment deposited in the bay as overwash fans is not eroded away by bayside processes. While the above scenario does not consider all possible future degraded conditions, for example, one in which the barrier island drowns or is further divided by new inlet formation, this scenario can be used to give an indication of the relative role of future barrier island degradation on hurricane flooding. During hurricane simulation, additional barrier island erosion is allowed to occur. Finally, due to the level of degradation considered here, in our analysis we assume that the barrier island is uninhabited in the 2030s and 2080s; therefore, all inundation, damages, and population calculations and results, including those for present-day (2000s), only considering relative impacts to the mainland portion of Corpus Christi (Fig. 1). As such, these calculations are conservative (low).

4.3. Simulation of hurricane flooding

Hurricane inundation was simulated using the finite-element, depth-integrated, hydrodynamic model ADCIRC (ADvanced CIRCulation) [61]. For this investigation, ADCIRC, which solves the shallow-water equations for mass and momentum conservation, was forced with winds, barometric pressure, and wave radiation stress force. Mean sea level within the ADCIRC model was adjusted in order to evaluate future sea level conditions. Hurricane wind and pressure fields were developed with a planetary boundary layer model [62], while wave radiation stress force was developed using the spectral wave model SWAN [63]. Astronomical tidal range at the study location is 40 cm along the open coast to about 10 cm within the bays [46]. Tide level at the time of peak hurricane surge will impact the exact flood elevation and associated inundation and damages. However, since our study objective is to evaluate the relative role of barrier island configuration on bay flooding, we neglect tidal variation in this analysis. All flood levels are based on a mean tide condition. To account for barrier island erosion during hurricane passage, the XBEACH morphological model [64] was employed, and results for dune erosion were used to pre-condition the ADCIRC computational grid. Fig. 4 presents the numerical modeling strategy. Application of the XBEACH model is discussed below, while details of other aspects of the numerical modeling approach are described in Mousavi et al. [60] and Frey [39].

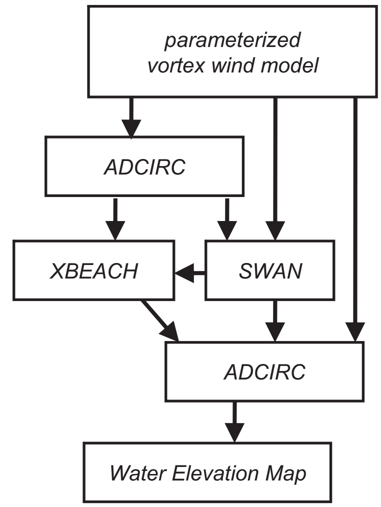

Fig. 4. Schematic of numerical modeling approach for simulating hurricane flooding.

4.4. Simulation of storm-induced barrier island erosion

To account for additional flooding and damages induced by overtopping and breaching of the barrier islands, barrier island lowering and erosion were incorporated into ADCIRC simulations by first estimating storm-induced barrier island erosion, then pre-conditioning the ADCIRC grid prior to flood level simulation. To determine barrier island erosion, the XBEACH morphological model was used [64,65]. XBEACH is a physics-based finite-difference numerical model which simulates morphological change induced by rising water levels and irregular waves; it accounts for erosion due to intermittent dune run up and overtopping by waves as well as erosion due to quasi-steady barrier island inundation. Sediment transport was computed in XBEACH using an advection-diffusion scheme using the Soulsby-van Rijn transport formula [66]. A median grain diameter of 0.217 mm was specified based on beach

Table 2
Present-day (2000s) characteristics of morphological reaches used in XBEACH simulations.

	Area 1		Area 2		Area 3	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Barrier island width (m)	1765	1765	740	3095	1765	3423
Dune height (m, MSL)	2.7	9.0	0.1	1.25	2.6	6.1

sand samples collected in May 2008 [39]. The model includes an avalanching algorithm, which allows for modeling the slumping of sediment when the bottom slope becomes very steep.

To overcome the high computational expense of running a detailed morphological model, a series of idealized simulations with XBEACH were performed to determine dune lowering as a function of initial dune conditions and storm hydrodynamic conditions. Four idealized storm surge and wave conditions were used to span the range of hydrodynamic conditions characterized by the storms in Table 1 [39].

The barrier island system in the vicinity of Corpus Christi was divided into three morphologically-similar areas (see Fig. 2), with some of them were further sub-divided for morphological simulation to better characterize individual areas along the barrier island system. For each area, morphological characteristics including dune height and barrier island width, were determined for existing conditions using the U.S. Geological Survey [67] 10-m Digital Elevation Model (DEM) (Table 2). For the future degraded condition considered here, the maximum barrier island elevation within all XBEACH simulations was specified uniformly as 1.00 m above MSL, as given by the climate scenario considered, everywhere except in the very low area to the north of Aransas Pass. For future degraded conditions, the barrier island width varied from 740 to 3900 m. In total, six idealized topography scenarios were constructed to represent both the present-day (2000s) and future (2030s and 2080s) pre-storm barrier island conditions [39]. For morphological reaches with minimal variation in dune height and barrier island width, the XBEACH grid is uniform in the alongshore direction. For morphological reaches with measurable variation in dune height or width, the grid topography varies alongshore. In these cases, the model topography was organized to allow for a weak location (low dune elevation and/or barrier island width) at the alongshore center of the computational grid to account for the possibility of severe overwash and breaching. The simulated morphological responses indicate regions of erosion that remain above mean sea level (overwash) as well as regions of significant erosion to elevations to below mean sea level (breaching).

Changes in dune elevation were extracted profile-wise from each XBEACH simulation, and barrier island elevations in the ADCIRC grid were lowered. The amount of dune lowering applied to the ADCIRC grid was determined by weighted averaging between the actual hydrodynamic conditions (surge and wave) and the idealized hydrodynamic conditions. To conserve sediment mass when lowering the ADCIRC grid elevations, sediment removed from the dunes was translated landward. All final ADCIRC simulations were performed using the respective lowered barrier island grid configuration.

4.5. *Estimation of inundated area, property damages, and population impacted*

For each hurricane-climate scenario analyzed here, inundated area, property damages, and population impacted were quantified within a geographic information system (GIS) framework [38,39]. To form the basis for geospatial calculations, three datasets within the city limits of Corpus Christi were used: (1) a 10-m resolution digital elevation model (DEM) [67], (2) land parcel data which contained property value among other information [68], and (3) U.S. Census Bureau [69] population data for 2000 by census tract. Simulated flood elevations were intersected with the DEM, and inundated area was computed. Damages to the structure on each parcel due to static flood level were estimated by determining the mean flood depth within each land parcel, then by using the property damage versus flood depth relationships reported by the Federal Emergency Management Agency [70] (equivalent to those relationships integrated in the HAZards United States [HAZUS] system). All property damage values are given with respect to 2009 US dollar value. Finally, the spatial distribution of inundated area

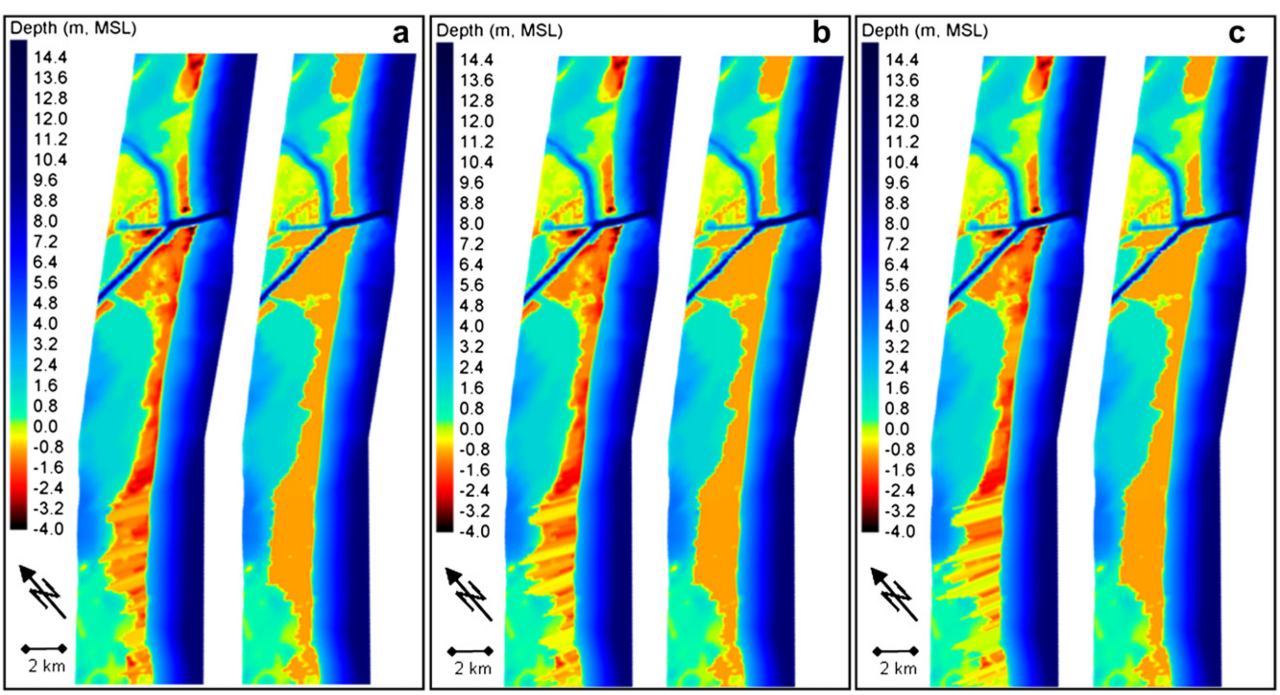

Fig. 5. Estimated storm-induced barrier island erosion on Mustang and Padre Islands: (a) under present-day (2000s) Hurricane Bret conditions when no hurricane intensification or relative SLR is assumed (left pane, MSL datum is MSL_{2000s}); (b) after 1.38 °C of SST rise, representing the 2030s B1 (warm, 4.5 °C sensitivity) scenario (center pane, MSL datum is $MSL_{2030s\text{-}high}$); and (c) after 2.51 °C of SST rise, representing the 2080s A1B (middle, 3 °C sensitivity) scenario (right pane, MSL datum is $MSL_{2080s\text{-}middle}$). In each pane, post-storm topography when no future barrier island degradation is assumed is on left, while post-storm topography when future barrier island degradation is assumed is on right. Area shown extends from Packery Channel to just north of Aransas Pass (see Figs. 1 and 2).

and flood depth were intersected with the population census data to determine the number of people impacted during each hurricane-climate scenario. Here, the population within each census tract was assumed to be evenly distributed throughout the parcel areas of the tracts. In this analysis, population affected reflects only to people living in the flooded areas according to census data but does not include all others affected by loss of jobs, overall slowdown of the economy in the broader area and other social impacts. The above method was executed for the mainland portion of Corpus Christi; as mentioned previously, here we assume that the barrier island would be uninhabited under the future degraded condition considered. Finally, the points of comparison used in the results and discussion are inundated area, property damage, and population impacted on the mainland evaluated for the case in which the barrier island was assumed to retain its present-day (2000s) condition (i.e., no-degradation assumed), where barrier island elevations were assumed to rise correspondingly with future SLR [38,39].

5. Results

5.1. Storm-induced overwash and breaching of Mustang and Padre islands

Under present-day (2000s) conditions, simulated flood elevation on the ocean side of Mustang Island (station 9 on Fig. 1) is 1.0 m, MSL_{2000s}. For the case of no barrier island degradation, post-storm simulation results for the present-day (2000s) hurricane scenario indicate some overwash of Mustang and Padre Islands. Specifically, near Packery Channel, elevations were generally lowered to about 1 m above MSL_{2000s} due to wave-induced erosion, and some narrow channels of slightly lower elevation, about 0.8 m above MSL_{2000s} were predicted (Fig. 5, left pane). For discussion purposes, Fig. 5 (left pane) also shows the predicted post-storm topography under present-day (2000s) conditions when the degraded barrier island condition is specified. Here, predicted storm-induced erosion of the degraded barrier island is negligible.

It is worth noting that with this degraded condition, no alongshore variability is predicted over the large region specified at a uniform 1-m elevation. This is a limitation of the methodology adopted here for estimating dune and barrier island lowering. For the degraded barrier island case, alongshore uniformity has been assumed during the majority of XBEACH simulations, the exception being the region just to the north of Aransas Pass. It is expected that under some real future condition, small perturbations in barrier island elevation would indeed induce channelized overwash areas.

Two additional comparative examples of the predicted storm-induced erosion response are shown in Fig. 5. The center pane shows the predicted response for the 2030s high climate estimate, when SST rise is 1.38 °C (B1 [warm, 4.5 °C sensitivity]), while the right pane shows the predicted response for the 2080s average climate estimate, when SST rise is 2.51 °C (A1B [middle, 3 °C sensitivity]). For the 2030s scenario shown, simulated flood elevation on the ocean side of Mustang Island is 1.2 m, MSL_{2000s}, or 1.0 m with respect to MSL for this 2030s projection ($MSL_{2030s\text{-}high}$). For the case of no barrier island degradation, this flood elevation inundates the lowest-lying sections of the barrier island. Storm morphology estimation indicates overwash of the barrier island in the region north of Packery Channel to elevations on the order of 0.9 m above $MSL_{2030s\text{-}high}$. A shallow breach, with a depth of 0.1 m below $MSL_{2030s\text{-}high}$, is predicted in the region to the north of Aransas Pass. For the case of the degraded barrier island condition, the ocean side flood elevation is on the order of the maximum barrier island elevation of 1.0 m above $MSL_{2030s\text{-}high}$, indicating the entire barrier island system is inundated during the peak of the storm. However, storm erosion predictions

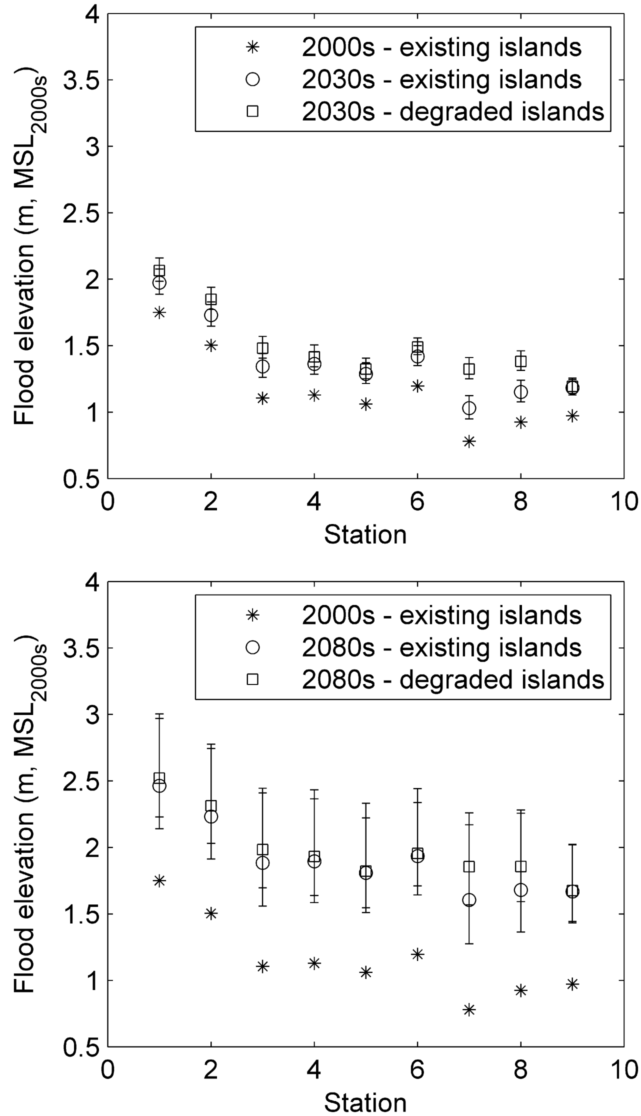

Fig. 6. Flood elevation projections at selected locations (see Fig. 1 for station locations). Symbols indicate mean of all projections while error bars indicate the upper and lower limits of the projections.

show minimal change to the barrier island landscape. These predictions indicate minimal overwash in the narrowest parts of the barrier island, between Packery Channel and Aransas Pass. As with the no-degradation case, predictions for the degraded barrier island case also show the same shallow breach formation in the region to the north of Aransas Pass.

For the 2080s scenario shown, simulated flood elevation on the ocean side of Mustang Island is 1.7 m, MSL_{2000s}, or 1.1 m with respect to MSL for this 2080s projection ($MSL_{2080s\text{-}middle}$). For the no-degradation case, overwash and breaching trends are similar to that for the 2030s scenario. In the 2080s case, somewhat more erosion is predicted to the north of Packery Channel, and the breach to the north of Aransas Pass is deeper, on the order of 0.2 m below $MSL_{2080s\text{-}middle}$, and wider. For the degraded barrier island case, the entire barrier island system is inundated for a short period around the peak of the storm, causing very slight overwash between Packery Channel and Aransas Pass. As with the no-degradation case, the predictions for the degraded barrier island case also indicate the development of a shallow breach to the north of Aransas Pass.

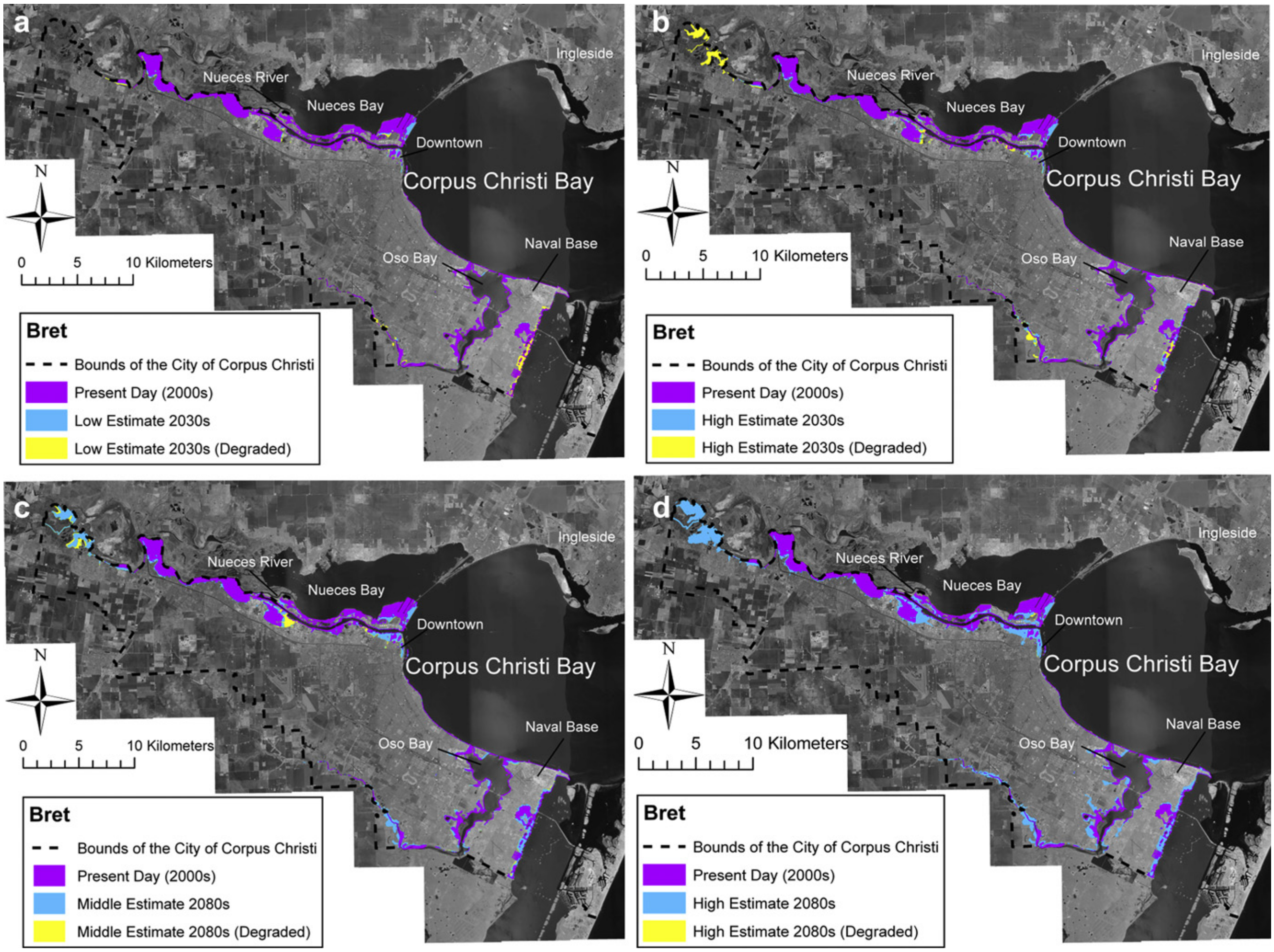

Fig. 7. Projected inundated area maps for mainland Corpus Christi for future storms similar to Hurricane Bret (a) after 0.36 °C of SST rise, representing the 2030s A1FI (cool, 2 °C sensitivity) scenario (top left pane); (b) after 1.38 °C of SST rise, representing the 2030s B1 (warm, 4.5 °C sensitivity) scenario (top right pane); (c) after 2.51 °C of SST rise, representing the 2080s A1B (middle, 3 °C sensitivity) scenario (bottom left pane); and (d) after 5.02 °C of SST rise, representing the 2080s A1FI (warm, 4.5 °C sensitivity) scenario (bottom right pane).

While the predicted morphological response is more dramatic for the case of no barrier island degradation, it will be shown below that the relatively larger volume of water which passes over the uniformly low barrier islands in the degraded case causes flood elevations to rise within Corpus Christi Bay.

5.2. Flood elevations and inundated area on mainland Corpus Christi

Fig. 6 shows the mean and range of flood elevations predicted at selected locations (see Fig. 1), based on the full suite of 27 climate projections per time period for the cases in which no future barrier island is assumed and in which a uniformly degraded barrier island is assumed. By the 2030s, the mean flood elevation prediction, when no barrier island degradation is assumed, is between 0.2 and 0.3 m higher than the present-day (2000s) flood elevation at all locations along the mainland of Corpus Christi. When future barrier island degradation is assumed, the difference between the 2030s mean prediction and the present-day (2000s) flood elevation becomes larger and exhibits more variation along the mainland coastline of Corpus Christi. For example, in Laguna Larga (stations 7 and 8), the difference between the mean predicted 2030s flood elevation and the present-day (2000s) flood elevation is about 0.5 m, and is more than twice the difference predicted for the no-degradation case. In Nueces Bay (stations 1 and 2), the 2030s flood elevation predictions are about 0.1 m higher for the degraded barrier island case with respect to the no-degradation case.

However, in Corpus Christi Bay, between the downtown and Oso Bay (stations 4 and 5), there is little difference between the 2030s projections with and without barrier island degradation. This lack of change in flood elevations can be explained by the relative change in free surface gradient within Corpus Christi [60]. Because Corpus Christi Bay is relatively shallow, with mean depth on the order of 3.5 m, the relative increase in mean depth induced by barrier island overflow during the storm results in relatively less locally generated wind setup and setdown during the degraded barrier island cases. Because of their location, the relative rise in mean flood depth within Corpus Christi Bay during the degraded barrier island condition is balanced by a relative reduction in wind setup [60].

As expected, the relative rise in flood elevation for the 2030s cases when barrier island degradation is assumed, with respect to the no barrier island degradation cases, results in relatively more inundated area in mainland Corpus Christi (Fig. 7, top panes). For the low 2030s estimate (A1FI [cool, 2 °C sensitivity]), additional inundation is predicted along the Laguna Larga shoreline and along Oso Creek and the Nueces River; some additional inundation is also

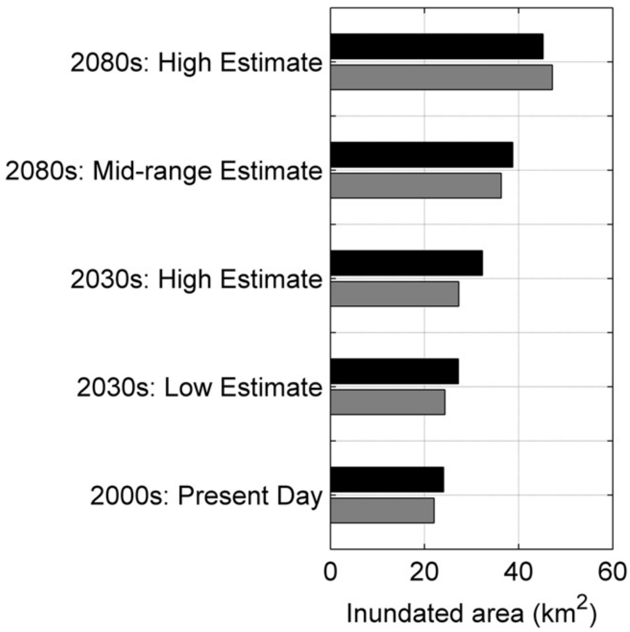

Fig. 8. Projected inundated area on mainland Corpus Christi. Projections when no barrier island degradation is assumed are shown in gray while projections when barrier island degradation is assumed are shown in black. The 2080s: High Estimate shown for the degraded barrier island case is as given by the numerical simulation output and GIS analysis. The difference between this result and that for the no-degradation condition indicates the inherent error in using a uniformly degraded barrier island and is assumed to represent a convergence between the two barrier island conditions.

predicted in the downtown. For the high 2030s estimate (B1 [warm, 4.5 °C sensitivity]), the most significant additional inundation is along the Nueces River. Fig. 8 shows that, for the 2030s projections, the area inundated on mainland Corpus Christi increases between 10% and 20% under degraded barrier island conditions, with respect to no-degradation conditions.

By the 2080s, the mean flood elevation prediction, when no barrier island degradation is assumed, is between 0.8 and 1.1 m higher than the present-day (2000s) flood elevation at all locations along the mainland of Corpus Christi (Fig. 6). When barrier island degradation is assumed, mean flood elevation predictions for the 2080s rise by less than 0.1 m to about 0.3 m with respect to the no-degradation case. The most dramatic difference, about 0.3 m, between the no-degradation and degraded cases is observed in Laguna Larga, immediately behind the barrier island (stations 7 and 8). Predicted inundated area for the middle 2080s scenario (A1B [middle, 3 °C sensitivity]) under the degraded barrier island case is predicted to increase 7% (Fig. 8), with respect to the no-degradation case, primarily along the Nueces River and in the downtown area (Fig. 7, lower left pane).

For the highest 2080s global warming scenario analyzed here (A1FI [warm, 4.5 °C sensitivity]), the simulations indicate slightly more flooding under the no-degradation case than under the degraded case; flood elevation differences are much less than 0.1 m in most locations (Fig. 6, upper limit) while percent change in inundated area is less than 4% (Fig. 7 [lower right pane] and 8). This result is an artifact of the uniformly degraded barrier island assumption, which limits breach formation. As discussed previously, it is expected that natural variability in barrier island elevation would induce breach formation. However, the exact location and extent of these breach formations are not known. Thus, we interpret the results for this 2080s upper limit to indicate the inherent error in the above approach and to represent a convergence between the two barrier island conditions. In other words, for more extreme surge events, the exact barrier island configuration is expected to have minimal impact on bay flooding. In the damage and population impacted discussion below, we assume that results for the degraded barrier island case equal the results for the no-degradation case for this high 2080s global warming estimate.

5.3. Damages to homes and other buildings on mainland Corpus Christi

Property damage estimates for homes and other buildings on mainland Corpus Christi due to static flooding for only selected future climate scenarios are given in Fig. 9. As this figure shows, property damages increase measurably when future barrier island degradation is considered. Property damage projections for the 2030s indicate that under the degraded barrier island case, expected damages increase by more than 50% with respect to the no-degradation case. This corresponds to an overall increase in damages on mainland Corpus Christi between $5 million and $10 million (2009 values) per storm event. Under the no-degradation case, property damage to buildings in the downtown area for the 2030s global warming projections are estimated to be between about $10,000 and $130,000. When future barrier island degradation is considered, damages in the downtown more than double, rising between $25,000 and $300,000 (2009 values) for the 2030s projections. Property damages to homes and buildings in the residential areas outside of the downtown under the no-degradation case are estimated to be between $10 million and $20 million (2009 values) for the 2030s projections, where damages are projected to rise an additional $5 million to $9 million (2009 values) under a degraded barrier island condition.

Projections for the 2080s indicate that property damages under a degraded barrier island case will increase by 25% under a middle-range climate scenario, with respect to damage predictions for the no-degradation case. Under the degraded barrier island case,

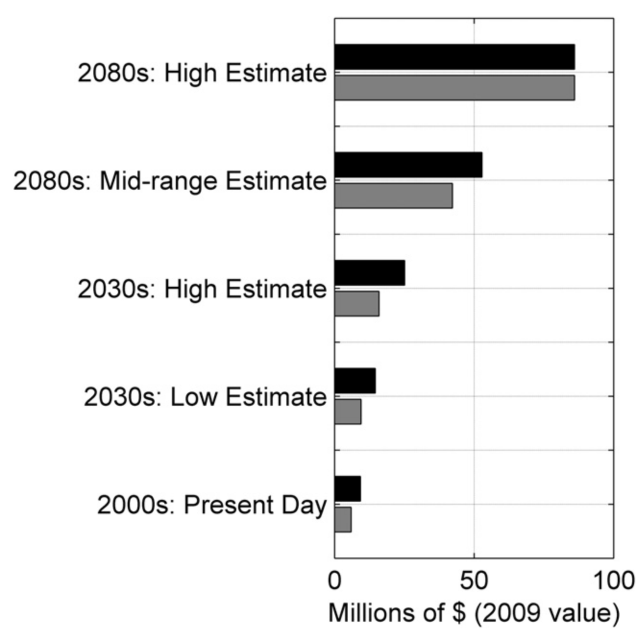

Fig. 9. Projected property damage to homes and other buildings on mainland Corpus Christi. Projections when no barrier island degradation is assumed are shown in gray while projections when barrier island degradation is assumed are shown in black. The 2080s: High Estimate shown for the degraded barrier island case is specified by assuming convergence with the no-degradation condition.

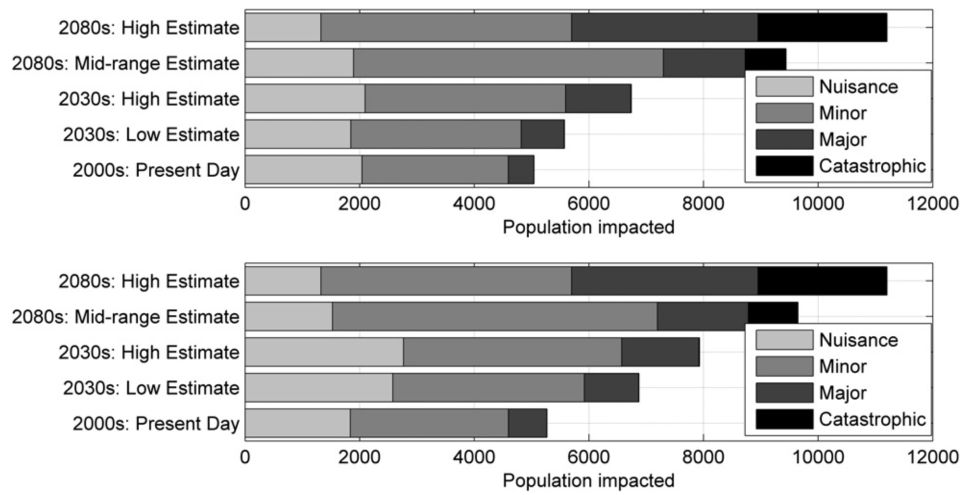

Fig. 10. Projected population impacted on mainland Corpus Christi. Results when no barrier island degradation is assumed are in top pane while results when barrier island degradation is assumed are in bottom pane; populations are segmented by degree of flooding (Nuisance, Minor, Major, or Catastrophic). The 2080s: High Estimate shown for the degraded barrier island case is specified by assuming convergence with the no-degradation condition.

property damages increase over damage values for the no-degraded case by about \$2 million (2009 values) in the downtown and by about \$8 million (2009 values) in other mainland residential areas for this middle-range 2080s projection. However, under higher warming scenarios for the 2080s, additional damages induced by a low barrier island configuration, with respect to no-degradation, are expected to diminish.

5.4. *Population impacted on mainland Corpus Christi*

For the selected climate scenarios in Table 1, projections of population impacted are given in Fig. 10. If a storm like Hurricane Bret were to occur today, it is estimated that about 5000 people on mainland Corpus Christi would be directly impacted by inundation to their property. Projections for the 2030s indicate that an additional 500 to 1700 people (about a 10%–30% rise) would be directly impacted by SLR and hurricane intensification, when no barrier island degradation is assumed. For the case of future barrier island degradation, population impacted rises an additional 1000 to 1300 over the no-degradation estimates, representing a 15–25% increase over the no-degradation case. Projections for the 2080s when no barrier island degradation is assumed indicate that an additional 4400 to 6100 people (about a 90%–120% rise) are directly impacted, with respect to present-day (2000s) conditions. This analysis indicates that potential future barrier island degradation has minimal impact on 2080s projections of total population impacted. Here, differences between the no-degradation and degraded cases give less than a 3% (200 people) increase in population impacted.

To infer the degree to which people are impacted by a given hurricane-climate scenario, changes with initial barrier island conditions, the population data were evaluated based on degree of flooding as defined below:

- Nuisance Flooding: Flooding of the area, but below home or building foundation elevation (<0 m flood depth, with respect to foundation elevation). People in this category are assumed to evacuate, but be able to return home shortly after the hurricane event.
- Minor Flooding: Flooding to depths between 0 and 0.9 m above the foundation elevation. People in this category are assumed to evacuate, but minor property damages will preclude immediate return to their home after the hurricane event.
- Major Flooding: Flooding to depths between 0.9 and 1.5 m above the foundation elevation. People in this category are assumed to evacuate and be displaced from their home, due to major property damage, for some period of time following the hurricane event.
- Catastrophic Flooding: Flooding to depths more than 1.5 m above the foundation elevation. People in this category are assumed to evacuate and experience catastrophic levels of damage to their homes. It is assumed that these people would be either displaced from their home for a significant period of time following the hurricane event or displaced permanently.

Fig. 10 shows that under present-day (2000s) conditions, most people directly impacted by a hurricane like Hurricane Bret experience Nuisance or Minor Flooding. Assuming no barrier island degradation, by the 2030s, relatively more people are impacted by Minor Flooding than by Nuisance Flooding. Inclusion of future barrier island degradation in the 2030s projections, substantially increases (by 30%–40%) the number of people experiencing Nuisance Flooding but has less of an impact on the number of people experiencing Minor Flooding (increasing 8%–12%). The 2030s projections for people experiencing Major Flooding increases by 18%–26% when barrier island degradation is considered, with respect to the no-degradation case. For the middle 2080s projection, while changes in overall population impacted are small, the number of people falling into Minor Flooding or more severe categories rises by 13% when barrier island degradation is considered. For higher 2080s projections, little change is predicted between the no-degradation and degraded barrier island cases.

6. Discussion and conclusions

Based on the above simulations and geospatial analysis, we conclude that potential future barrier island degradation with SLR can have a significant impact on future hurricane flooding, inundation, damages, and population impacted at the coast. However, the results also indicate that the relative sensitivity of bay flooding to exact barrier island geometry diminishes for larger hurricane surge events. Based on the results presented above, we conclude that if future global warming scenarios are realized and barrier islands undergo natural degradation with SLR, flooding by moderate hurricane surge events, such as the Hurricane Bret scenarios considered here, may rise between 20% and 70% by the

2030s, with respect to present-day (2000s) estimates. This rise in flood elevation by the 2030s is projected to increase property damages by 150% to more than 300% and increase population impacted by 230%–290%.

The methodology presented in this paper is transparent to location. It can be readily applied to any location where adequate property and topographic data are available. The surge and wave analysis from the different scenarios presented can be easily transferred to alternate destinations worldwide. Without adequate property data, HAZUS or similar data could be employed. The local sea level projections may also need to be modified based on local relative SLR. The examples of similar analyses by Church et al. [40] for Sydney, Australia, Cooper [35] for the populated coast of New Jersey, and Gornitz et al. [37] for New York City clearly illustrate typical major urban areas that would be impacted by relative SLR and climate change. The methodology is also suitable for application in areas prone to SLR and non-tropical storms such as Europe (e.g., Venice) and the Nile Delta region of Egypt.

Possibly more susceptible to adverse impacts of SLR and climate change are those coastal communities in developing countries. For example, more than 25,000 km^2 of coastal land (from 0 to 3 m MSL) in Central America, Mexico, and the Caribbean are vulnerable to hurricane activity. In India and Bangladesh about 13,000 km^2 of coastal land is subjected to tropical cyclones while about 6000 km^2 is vulnerable on the island of Madagascar. Existing infrastructure, current management strategies, and lack of resources in these regions means that these regions will not likely be able to withstand even small incremental changes in SLR and tropical cyclone climate. Furthermore, population density and projected growth in some of these regions is high. For example, population density in India is projected to increase from a very dense 369 people per km^2 in 2010–465 people per km^2 in 2035, a 20% rise [53]. Population density in Central America is projected to rise about 40% by the 2030s while population in Madagascar is projected to rise by more than 70% by the 2030s [53]. This population growth amplifies the impact of increased flood probability with SLR and climate change in that the relative increase in risk to lives and livelihoods will be higher in areas of higher population growth, with respect to areas with little or declining (e.g., Australia) growths [53]. This suggests the clear importance of the need to consider the broad probabilities of occurrence to bring focus to the risk in these areas where the consequences are very high.

It is not possible, however, to always associate areas prone to hurricane damages to poor and marginalized segments of the coastal populations. Even though that has been observed; for example, in the case of Hurricane Katrina, the devastating impact of hurricane flooding might have been associated more to lack of property insurance or of resources to respond to the event than to the severity of the flood itself. In addition to the direct property damage presented here, flood damage also involves other social and economic impacts, which were not discussed here because they were considered beyond the scope of this paper despite being of critical importance. The analysis presented here also considers only one highly simplified possible future degraded barrier island scenario and considers only damage due to wind- and pressure-generated surge, wave setup, and SLR. If very high rates of SLR are realized over the coming years, such as those that could result if major ice-sheet melting occurs (e.g., [12]) or if groundwater extraction increases with population growth, more severe barrier island degradation scenarios, including inlet and islet formation, could develop. Such severe changes in the barrier island landscape may result in higher flood elevations and associated impacts than those reported here.

Conversely, if adaptive management strategies are adopted through engineering and planning activities such as beach nourishment, these protective barrier islands may be maintained. Other engineering and planning strategies to limit coastal flooding and strengthen the resilience of barrier islands to climate change and relative SLR include:

- Implementing setbacks;
- Using sand fencing and active planting of grasses on barrier island dunes to capture Aeolian sand transport and increase island elevation;
- Using measures to reduce trampling of dunes and vegetation through dune and beach walkovers;
- Eliminating sand and gravel mining of beaches and river systems within the regional littoral system;
- Constructing living vegetated shorelines on the bayside of barrier islands to capture wash over sand within the subaerial island and to build a platform onto which the island can migrate;
- Eliminating subsurface fluid withdrawal;
- Eliminating vessel wakes that erode bay shorelines; and
- Mandating placement of beach-quality sediment that is dredged within the littoral zone, whether trapped behind dams or dredged from navigation channels.

Such engineering and management activities on the barrier islands, when coupled with flood management strategies on the mainland, have the capacity to minimize the potential impacts of global warming on future hurricane flooding.

In conclusion, the results of this study indicate that the potential implications of global warming on hurricane flooding are severe when protective barrier islands are left to degrade naturally. It is thus prudent to consider adaptive management strategies to preserve and restore these island features in populated coastal regions. For example, expenditures for future beach nourishment activities should be measured against the benefit such activities provide in terms of reduced flooding and damages in light of SLR and increased hurricane surge probability. Future research and planning when considering the potential implications of global warming and barrier island degradation should also consider human demographic trends of the coastal population such as degradation of the critical infrastructure including protective ecosystems, as well as additional physical damages induced by wind, direct wave action, and inland precipitation.

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Land parcel data were provided by the City of Corpus Christi with the following disclaimer: "©2009 City of Corpus Christi, Texas. Use at your own risk. This data may contain inaccuracies or errors. The City of Corpus Christi makes no representations or any warranties regarding this data. The City of Corpus Christi disclaims all implied warranties regarding this data."

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