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The dynamic effects of sea level rise on low-gradient coastal landscapes: A review

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Special Section:

Integrated field analysis & modeling of the coastal dynamics of sea level rise in the northern Gulf of Mexico

Key Points:

- The dynamic effects of sea level rise (SLR) are interrelated
- SLR research efforts are moving beyond the "bathtub" approach
- Synergetic studies integrating dynamic systems under SLR are needed

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Abstract Coastal responses to sea level rise (SLR) include inundation of wetlands, increased shoreline erosion, and increased flooding during storm events. Hydrodynamic parameters such as tidal ranges, tidal prisms, tidal asymmetries, increased flooding depths and inundation extents during storm events respond nonadditively to SLR. Coastal morphology continually adapts toward equilibrium as sea levels rise, inducing changes in the landscape. Marshes may struggle to keep pace with SLR and rely on sediment accumulation and the availability of suitable uplands for migration. Whether hydrodynamic, morphologic, or ecologic, the impacts of SLR are interrelated. To plan for changes under future sea levels, coastal managers need information and data regarding the potential effects of SLR to make informed decisions for managing human and natural communities. This review examines previous studies that have accounted for the dynamic, nonlinear responses of hydrodynamics, coastal morphology, and marsh ecology to SLR by implementing more complex approaches rather than the simplistic "bathtub" approach. These studies provide an improved understanding of the dynamic effects of SLR on coastal environments and contribute to an overall paradigm shift in how coastal scientists and engineers approach modeling the effects of SLR, transitioning away from implementing the "bathtub" approach. However, it is recommended that future studies implement a synergetic approach that integrates the dynamic interactions between physical and ecological environments to better predict the impacts of SLR on coastal systems.

1. Introduction

This review examines the dynamic effects of sea level rise (SLR) on low-gradient coastal landscapes, primarily in the context of hydrodynamics, coastal morphology, and marsh ecology. The highlighted processes were selected due to their interdependence and integrated feedback mechanisms. In addition, changes in these processes under SLR can ultimately lead to alterations of natural and built communities. Coastal dynamics are not limited to those discussed herein; many other ecological habitats and organisms may experience dynamic alterations in response to rising seas. However, the purpose of this review is to provide a basis for establishing many of the prominent dynamic effects associated with SLR, as well as identifying future research needs. Sections 2, 3, and 4, parallel one another with discussions of hydrodynamics, coastal morphology, and marsh ecology, respectively. Sections 2.1, 3.1, and 4.1 review the physical processes and interactions of these systems to establish a basis for assessing their integrated, dynamic responses to SLR (Sections 2.2, 3.2, and 4.2). Sections 2.3, 3.3, and 4.3 discuss physics and process-based models and methodologies that have been developed to project the response of these processes to SLR, as well as findings from recent modeling and observational studies. Moving beyond the "bathtub" model and employing more complex approaches aids in understanding the dynamic responses of these processes under SLR. Although these studies provide insight to potential future conditions, an integrated approach is necessary to fully understand the response of coastal systems to SLR; Section 5 contrasts the previous sections by describing synergetic studies that consider multiple dynamics in coastal systems. Section 6 summarizes additional considerations for coastal dynamics, as well as potential socioeconomic and management implications. The review concludes with a summary of future research needs.

1.1. Background

Direct observations from long-term tide gauges and global satellite altimetry show that sea level is rising. Analyses of tide gauge records indicate a global mean SLR between 1.6 and 1.8 mm/yr over the 20th century [*Church and White*, 2006, 2011; *Jevrejeva et al*., 2006, 2008]. High-precision satellite altimetry suggests a recent acceleration with rates as high as 3.4 mm/yr between 1993 and 2009 [*Hay et al*., 2015; *Nerem et al*., 2010]. Unlike infrequent large magnitude storms that can reshape the coast within hours, the impacts attributed solely to SLR are typically slow, repetitive, and cumulative [*Fitzgerald et al*., 2008]. Immediate effects include submergence, increased flooding, and saltwater intrusion into surface water, whereas long-term effects will increase shoreline erosion and induce saltwater intrusion into groundwater as the coast adjusts. In addition, coastal wetlands will struggle to keep pace with SLR if sediment supplies are not sufficient [*Nicholls and Cazenave*, 2010]. The effects of SLR have significant socioeconomic consequences for the vast number of coastal communities worldwide. In 2003, it was estimated that 1.2 billion people (23% of the world's population) lived within 100 km of a shoreline and 100 m in elevation of sea level [*Small and Nicholls*, 2003]. Beaches are a key element of the travel and tourism industry, which is becoming increasingly prevalent in global economies [*Houston*, 2013]. In addition to human communities, coastal areas contain ecologically and economically significant estuaries. Coastal wetlands and marshes provide food, shelter, and nursery areas for commercially harvested fish and shellfish. Wetlands also help protect coastal communities by mitigating the impacts of storm surge and erosion [*NOAA*, 2011]. Increased shoreline erosion under accelerated SLR poses a serious threat to economies worldwide. As populations increase, coastal areas are also susceptible to additional stresses due to land-use and hydrological changes [*Nicholls et al*., 2007].

Projecting future SLR is complex due to uncertainty in modeling the various contributory processes, including thermal expansion of ocean water, land ice loss, and changes in land water storage [*Church and White*, 2006; *Jevrejeva et al*., 2006]. Although historic sea level trends provide valuable information for preparing for future changes, they are insufficient for assessing risk under future uncertainties [*Parris et al*., 2012]. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report projects a global mean SLR between 52 and 98 cm by the year 2100 under the highest emissions scenario, and 28–61 cm under the lowest emissions scenario [*Church et al*., 2013]. Alternatively, scenarios of future global mean SLR are a common way to consider multiple future conditions and develop response options, given the range of uncertainty [*Parris et al*., 2012]. To plan for changes under future sea levels at a local scale, it is necessary to have local projections of SLR that accommodate various risk tolerances and cover a range of timescales relevant for planning purposes [*Kopp et al*., 2014].

Additionally, coastal managers need scientific data regarding the potential impacts of SLR to make informed decisions for managing human and natural communities. Therefore, developing integrated, multidisciplinary studies that incorporate the various factors that impact coastal systems at local scales should be given high priority, as they will benefit coastal scientists and stakeholders [*Cazenave and Le Cozannet*, 2013]. However, the complexities associated with coastal systems make determining the future impacts of SLR a difficult process. SLR induces nonlinear changes in hydrodynamics, which influences sediment transport and ecological processes. Although coastal systems are known to be dynamic, many studies have employed a simplistic static or "bathtub" approach when modeling the effects of SLR. More recent efforts have begun to consider the dynamic effects associated with SLR (e.g., the nonlinear response of hydrodynamics under SLR), but little research has considered the integrated feedback mechanisms and co-evolution of multiple interdependent systems (e.g., the nonlinear responses and interactions of hydrodynamics, morphology and ecology under SLR) (Figures 1 and 2).

2. Coastal Hydrodynamics

2.1. Background

Hydrodynamics influences processes in estuaries such as inundation, circulation patterns, and sediment transport. In estuaries, tidal range (the maximum vertical difference between the high and subsequent low tide during a spring tidal cycle) is a significant parameter in determining the strength of tidal currents and their ability to transport and redistribute sediment [*Stevens*, 2010]. Coastal systems and estuaries can be classified based on tidal ranges. Macrotidal coasts exceed 5 m (e.g., the Bay of Fundy), low-macrotidal coasts are between 3.5 and 5.0 m (e.g., the German Bight in the North Sea), high-mesotidal are between 2.0 and 3.5 m (e.g., the Georgia and South Carolina coasts), low-mesotidal are between 1.0 and 2.0 m (e.g., the New

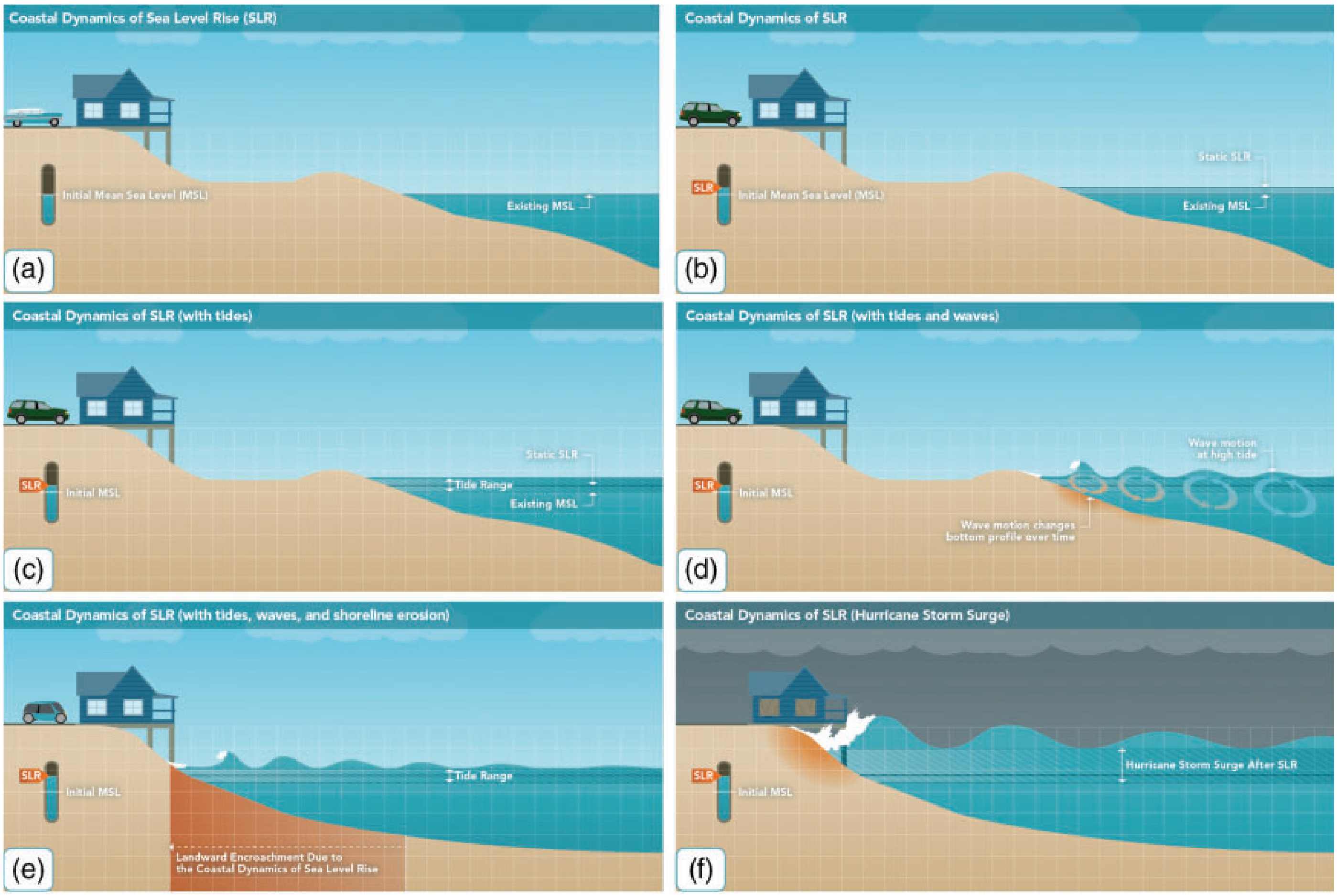

Figure 1. Coastal dynamics of sea level rise along sandy shorelines: (a) existing mean sea level, (b) a static rise on sea level simply elevates existing mean sea level by the amount of SLR, resulting in inundation of the coast, (c) a dynamic rise in sea level accounts for the nonlinear response of the tides, (d) higher water levels allow wave energy to act higher on the beach profile, resulting in erosion, (e) the eroded beach profile results in further inundation under SLR, (f) rising seas have the potential to exacerbate coastal flooding during storm events.

Jersey coast), and microtidal are less than 1 m (e.g., the Florida Gulf coast) [*Hayes*, 1979]. For coasts that experience minimal tides, *Tagliapietra et al*. [2009] proposed the nanotidal class for ranges less than 0.5 m (e.g., the Mediterranean Sea). When the tide outside of an estuary rises and becomes higher than the water within the estuary, the water surface gradient drives water into the estuary; similarly, when the tide outside of the estuary is falling and becomes lower than the water surface within the estuary, the water surface gradient drives water out of the estuary [*Masselink et al*., 2011]. The total volume of water entering the bay on the flooding tide is referred to as the tidal prism [*Dean and Dalrymple*, 2002]. Tidal prisms influence estuarine flushing, mixing, and residence time [*Sheldon and Alber*, 2006].

Tidal asymmetry occurs when the offshore tide becomes distorted as it propagates into shallow estuaries. Generally, tidal asymmetry can be characterized by the duration of the flood/ebb tide and the corresponding velocity; if the duration of the flood tide is longer, leading to a strong peak ebb velocity, then the system will be ebb dominant. Likewise, if the duration of the ebb tide is longer, leading to a stronger peak flood velocity, then the system is flood dominant. A flood-dominant system typically has a net sediment transport shoreward (into the estuary), whereas an ebb-dominant system typically has a net sediment transport seaward (out of the estuary) [*Aubrey and Speer*, 1985]. A distinction can be made between vertical (i.e., water level) and horizontal (i.e., flow velocity) asymmetries. A vertical asymmetry is generated if the period of the flood tide is unequal to ebb, whereas a horizontal asymmetry occurs if a residual transport is generated. This may occur if a difference in the magnitude between maximum ebb and flood velocities exists. Horizontal asymmetry may lead to a residual transport of bed and suspended sediment loads; if the maximum flood

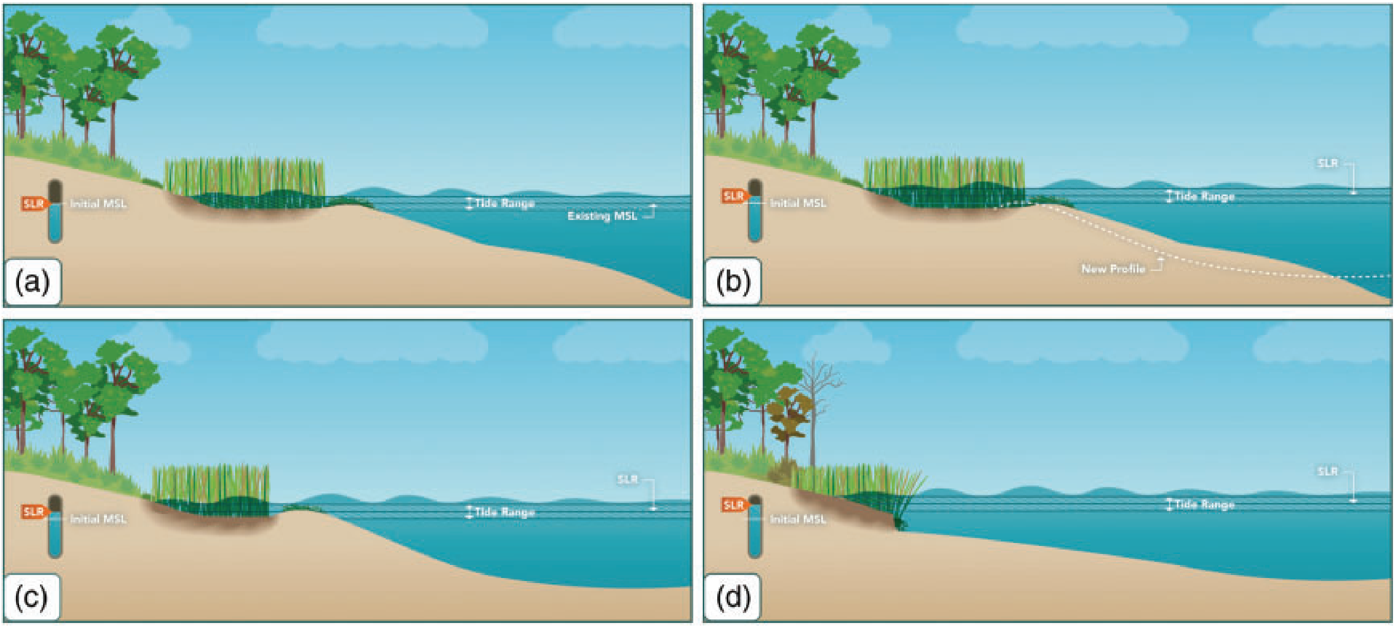

Figure 2. Coastal dynamics of sea level rise along estuarine shorelines: (a) existing mean sea level and tidal range govern biomass productivity in salt marsh systems, (b) higher water levels under SLR may erode the estuarine profile, (c) as sea level rises, the marsh attempts to migrate landward, (d) under higher rates of SLR, the marsh may drown if uplands are not available for landward migration; higher water levels allow waves to erode the marsh boundary.

velocity exceeds the ebb velocity, a residual transport in the flood direction is likely to result. Another type of asymmetry that exists is the difference in the duration of slack water, which affects residual transport of fine suspended sediment. If the duration of slack water before the ebb tide exceeds the duration of slack water before the flood tide, a residual sediment transport in the flood direction is likely [*Wang et al*., 1999].

In semidiurnal regions, oceanic tides generate higher frequency overtides as they enter the estuary's shallow waters [*Aubrey and Speer*, 1985]. These overtides result from the nonlinear physical processes associated with friction and continuity [*Speer and Aubrey*, 1985]. The overtides grow nonlinearly as they propagate through the estuary, which causes the sinusoidal form of the tides to become distorted [*Friedrichs and Aubrey*, 1988; *Blanton et al*., 2002]. Therefore, asymmetry can be characterized by the M2 (principal lunar semidiurnal) constituent and its overtides M4 and M6 [*Blanton et al*., 2002]. *Speer and Aubrey* [1985] developed relationships to classify whether an estuary is flood or ebb dominant by determining the relative M2-M4 phase, equal to twice the M2 phase minus the M4 phase (2M2 − M4). *Blanton et al*. [2002] adapted this concept to include the M6 overtide, yielding a relative phase calculated as 3M2 − M6. The magnitude of asymmetry may also vary throughout the estuary, and can be measured using the ratio of the amplitudes of M4 to M2 (the M4/M2 ratio) [*Aubrey and Speer*, 1985].

Although tidal asymmetry is not unique to semidiurnal systems, studies in diurnal regions are less common. Unlike semidiurnal regions, shallow water modifications are not required to generate asymmetry in diurnal regions. Flow asymmetry in diurnal regions is attributed to the interaction of the O1 (principal lunar diurnal), K1 (lunar-solar diurnal) and M2 tidal constituents; phase-angle relationships between these constituents create a cyclic asymmetry with maximum spring tide velocities persistently in the same direction [*Hoitink et al*., 2003]. The phase-angle relationship varies spatially and therefore the magnitude and direction of the tidal asymmetry may also vary [*van Maren et al*., 2004]. Bathymetry may also have indirect effects on tidal asymmetry, resulting from flow acceleration or divergent propagation of the semidiurnal and diurnal tidal waves [*Pugh*, 1987; *Jewell et al*., 2012]. Fluctuations in flood or ebb dominance may occur throughout the annual cycle, as opposed to fixed asymmetry seen in semidiurnal regions [*Ranasinghe and Pattiaratchi*, 2000; *van Maren et al*., 2004; *O'Callaghan et al*., 2010; *Jewell et al*., 2012]. Tidal asymmetry is equally important in comparison with residual flow (long-term averaged flow) for sediment transport; fine sediment is likely dominated by residual flow, whereas coarser sediment may be more influenced by tidal asymmetry [*van Maren et al*., 2004].

Waves also have significant influences on suspended sediment concentrations (SSCs) in estuaries, especially at times near low tide [*Green and Coco*, 2014]; wave suspended sediments have been found to exceed tidal suspended sediments by a factor of 3 to 5 [*Sanford*, 1994]. Similarly, wave energy during storm events can cause macrotidal estuaries to become wave dominant, which may increase SSCs by an order of magnitude [*Christie et al*., 1999]. In mesotidal estuaries, resuspension of sediments can be completely controlled by episodic waves [*Green et al*., 1997]. In microtidal estuaries, SSCs may decrease as waves subside [*Ralston and Stacey*, 2007]. In some estuaries, tidal current strength (flood and ebb dominance) is not the sole force influencing net sediment transport; wave action has the potential to alter ebb and flood dominance in channels [*Green et al*., 1997].

2.2. Hydrodynamic Response to SLR

SLR can influence tidal hydrodynamics through increased tidal ranges, tidal prisms, surge heights, and inundation of present day shorelines [*National Research Council*, 1987] (Figure 1). In addition, it has the potential to change circulation and sediment transport patterns, which may result in changes to habitats and their organisms [*Nichols*, 1989]. Increased tidal ranges have the potential to increase tidal current velocities; if the increase is significant, additional shorelines may undergo erosion [*Stevens*, 2010]. The magnitude of change in a bay's tidal prism under SLR is dependent on the morphology of the bay's shorelines. Bays surrounded by Pleistocene uplands typically have steep slopes which mitigate the extent-driven impacts of SLR. Shallow bays surrounded with wetlands broaden under SLR due to their gently sloping shoreline; this may be further increased if the marshes drown and transition to open water [*National Research Council*, 1987]. An increase in the tidal prism under SLR is reflected in stronger tidal flows [*Boon and Byrne*, 1981]. In addition, SLR can alter tidal asymmetries [*Speer and Aubrey*, 1985]; understanding tidal asymmetry and its influence on residual sediment transport is necessary to determine whether an estuary will keep pace or drown under SLR [*Wang et al*., 1999]. Changes in tidal propagation (which is strongly influenced by morphology) can influence sediment balance in systems, and may modify the potential of the system to export sediment and consequently alter morphology [*Dias and Picado*, 2011].

Estuaries are especially sensitive to SLR as they undergo different reactions to forcing factors depending on their ecological systems [*Rilo et al*., 2013]. The hydrodynamics of estuaries have important implications for navigation, fisheries, flooding, water quality and the geological evolution of the coastline. If rising seas increase channel depths or alter the volume of water stored in the intertidal zone, tidal asymmetries and resulting sediment transport patterns in estuaries may be fundamentally altered [*Friedrichs et al*., 1990]. Residual transport and circulation are typically dominated by tidal asymmetries and river inflow; understanding changes to residual circulation under SLR is crucial for understanding the impact to a coastal system and its ecosystems [*Valentim et al*., 2013]. In addition, coastal topography will affect how estuaries respond to future accelerated rates of SLR [*Church et al*., 2001].

Rising seas also have the potential to increase coastal flooding caused by storm surges. For a storm of a given magnitude, the surge will be elevated and potentially produce more areas of inundation. In addition, storm surges of a given height are expected to occur more frequently [*Fitzgerald et al*., 2008]. Although there is evidence that tropical cyclones will intensify in the future, SLR is expected to become a dominant driver in increased tropical cyclone flooding [*Woodruff et al*., 2013]. SLR may also cause future changes in wind-wave climates. Wave height is limited by available water depth; therefore deeper water in nearshore environments will cause wave heights to increase [*Smith et al*., 2010]. Inshore wave heights in shallow areas may increase with SLR in some coastal areas, which can affect nearshore sediment transport processes [*Chini et al*., 2010]. As SLR rates increase, extreme flooding from tropical cyclones will also increase. It is expected that resulting storm damage will be the most severe where morphology along populated shorelines heighten storm impacts, as opposed to where tropical cyclone activity is the highest [*Woodruff et al*., 2013].

2.3. Hydrodynamic Modeling of SLR

Many numerical models have been developed to simulate hydrodynamic and transport processes including currents, waves and sediment transport within coastal systems. One-dimensional (1D) hydrodynamic models can be used to model flood flows. Flow in a channel is calculated by average equations over a cross-section, providing an average flow velocity for each section [*Kilanehei et al*., 2011]. These models are computationally efficient and can be used for large hydrologic systems and complex river/channel systems.

However, using a 1D approach is not appropriate for modeling floodplain flows. Two-dimensional (2D) depth-integrated hydrodynamic models have been used for predicting free surface flows, although they can be computationally expensive and less flexible for including complex channel networks [*Lin et al*., 2006]. These models typically simulate flow by integrating governing equations over depth, which results in horizontal velocity and water depth components in each element [*Kilanehei et al*., 2011]. Because these models are depth-integrated, they are unable to simulate vertical components of currents or density variations in the water column. Three-dimensional (3D) models are able to simulate horizontal and vertical currents as well as transport of suspended matter. These models can be useful for simulating hydrodynamics as well as morphology.

Wave-current interactions can be captured with one- or two-way coupling of wave and hydrodynamic models. In the one-way coupling approach, wave radiation stresses are computed in the wave model and provided to the hydrodynamic model to be implemented as surface stress; the hydrodynamic model does not feedback any information to the wave model. In a two-way coupling approach, wave radiation stresses are calculated, passed to the hydrodynamic model which calculates currents and water surface elevations, which are fed back to the wave model to calculate the new wave radiation stress. For both approaches, feedback does not occur at every time step.

Integrated coastal/ocean processes models can aid in dynamic assessments of local impacts of SLR to better assess coastal vulnerability and coastal hazard management [*Ding et al*., 2013]. The coastal flooding response under SLR can be either linear or nonlinear. A linear response, or static response, occurs when the existing dynamics are simply elevated by the amount of SLR. For example, if the present flooding extent is located at the 10 m topographic contour, then the future flooding extent under 0.5 m of SLR would be located at the 10.5 m topographic contour. A nonlinear response, or dynamic response, accounts for nonlinear effects in the system; the 0.5 m of SLR may lead to a greater or lesser flooding extent than the 10.5 m topographic contour [*Hagen and Bacopoulos*, 2012]. Two-dimensional and three-dimensional hydrodynamic models have been widely applied to simulate the dynamic responses to SLR scenarios [e.g., *Mousavi et al*., 2011; *Hagen and Bacopoulos*, 2012; *Atkinson et al*., 2013; *Ding et al*., 2013; *Bilskie et al*., 2014; *Passeri et al*., 2015]. However, there is neither a vetted framework for incorporating SLR into hydrodynamics nor critical reviews comparing various methodologies and outcomes.

Hydrodynamic assessments of SLR have shown changes in tidal parameters including constituents, tidal range, tidal prisms, flow velocities, residual currents, and tidal datums. *French* [2008] used a 2D model to simulate hydrodynamics in a mesotidal, barrier-enclosed estuary in England under SLR. Tidal hydrodynamics were simulated under a rise of 0.30 m with present day bathymetric conditions. Tidal prisms increased by 28% in the estuary, which significantly increased peak flood tidal flows and slightly increased peak ebb flows. The M2 tidal constituent amplitude decreased by approximately 5%, whereas the M4 amplitude was reduced by 20%–40%. Overall, SLR significantly reduced the ebb dominance of the estuary [*French*, 2008]. SLR has also been shown to reduce residual circulation. Under 0.42 m of SLR in a mesotidal estuary in Portugal, residual circulation was reduced by almost 30% under normal river discharge conditions, and 10% under maximum discharge conditions [*Valentim et al*., 2013]. Inundation extent may also be altered under SLR, although quantification may vary depending on whether a static or dynamic approach is taken. Using a 2D model to simulate astronomic tides under various SLR scenarios in the Florida Panhandle, U.S., *Hagen and Bacopoulos* [2012] found that a static approach underestimated the amount of the inundated floodplain area by a ratio as low as 2:3 in comparison with the dynamic approach. The authors concluded that SLR should be assessed using a dynamic approach to capture future dynamic interactions that may otherwise be missed with a static approach [*Hagen and Bacopoulos*, 2012]. Hindcast studies can also be beneficial for studying the effects of SLR on hydrodynamics. *Leorri et al*. [2011] employed a 3D hydrodynamic model to simulate water levels and currents in response to SLR over the Holecene period in the mesotidal Delaware Bay, U.S. The sea level was lowered corresponding to 4000 years ago although bathymetry was not altered from present day conditions. Lowering the water level changed the geometry of the bay from a funnel-shape to an elongated wide type, which in turn altered the hydrodynamic behavior. The tidal range increased in the shallower section of the bay near the mouth, and decreased upstream. The reduction in the elevation of high tide and mean tide was nonlinearly related to the amount of sea level fall. In addition, tidal currents became asymmetrical with longer ebb durations [*Leorri et al*., 2011].

In addition to tidal hydrodynamics, SLR has the potential to alter storm surge dynamics with increased flooding and wave heights. Using a 2D hydrodynamic model coupled with a wave model, *Smith et al*. [2010] simulated hypothetical hurricanes that produced 100 year water levels in Southeast Louisiana, U.S., under future SLR scenarios. The authors found that the response of the surge to SLR was nonlinear, and that the long return period water levels could modestly increase above the SLR, whereas shorter return period water levels could significantly increase. In addition, wave heights significantly increased in previously shallow areas as a result of the larger depths [*Smith et al*., 2010]. Similarly, *Mousavi et al*. [2011] demonstrated the nonlinear effects of storm surge along the coast of Texas, U.S., under SLR scenarios, with some areas experiencing reductions in peak surge, and others experiencing increases in peak surge. The effects of SLR on storm surge vary depending on the geographic region and storm scenario. *Atkinson et al*. [2013] used a coupled wave and hydrodynamic model to simulate storms along the coast of Texas, U.S., with similar meteorological characteristics but various landfall locations to examine how coastal features influenced storm surge under SLR. Topography controlled increased flooding, although regions were not equally at risk. In addition, SLR increased wave heights in the nearshore and inland areas [*Atkinson et al*., 2013]. It is also important to note that implementing a dynamic approach when quantifying storm surge flooding under SLR may result in the same depth of floodplain inundation as a static approach; however, the spatial distribution of flooding may differ [*Hagen and Bacopoulos*, 2012].

3. Coastal Morphology

3.1. Background

Coasts are dynamic systems that are continuously transforming over different temporal and spatial scales as a result of geomorphological and oceanographical changes [*Cowell et al*., 2003a, 2003b]. Shorelines assume a specific maintained state that can often be distinguished by a characteristic morphology. The state is sustained by negative feedbacks, but may be altered as a result of short-term perturbations, the system exceeding an inherent threshold, or a change in boundary conditions (e.g., sea level). Shorelines can adopt different types of equilibrium. If the processes are balanced, the shoreline will remain constant in a static equilibrium. If the boundary conditions do not change and the average state of the shoreline is unchanged over time, a steady-state equilibrium occurs. If the boundary conditions change and the landscape continuously evolves to adjust to the new conditions, a dynamic equilibrium occurs [*Woodroffe*, 2003, 2007].

Coastal environments can be generally characterized as wave dominated, tide dominated, or mixed (a balance between wave and tide forces), depending on the predominate force for sediment transport. Microtidal coasts are often wave dominant. Low-mesotidal coasts have mixed wave and tidal energy but are more wave dominant. High-mesotidal coasts also have mixed wave and tidal energy, but are more tide dominant. Low macrotidal and macrotidal coasts are tidal dominant [*Hayes*, 1979]. Coastal morphology is often influenced by tidal range, except along coastlines with high wave energy and high tidal range (e.g., the Bay of Fundy), as well as low wave energy and low tidal range (e.g., the Gulf of Mexico). In high energy regions, high wave energy controls coastal morphology rather than tidal range. In low energy regions, there is a delicate balance between wave and tidal processes that allow tide-dominant, wave-dominant, or mixed energy morphology to develop with little variation in wave and tidal parameters; a low energy region may transition from wave-dominant to mixed energy or tide dominant with a small increase in tidal range [*Davis and Hayes*, 1984]. Additionally, because morphological response times in low energy regions are long, morphology is often dominated by high energy processes such as storms [*Masselink et al*., 2011].

Storm surge has a significant impact on morphology in locations that are sheltered from waves and tides (e.g., near the heads of estuaries and landward sides of barrier islands), as well as low energy regions, especially when surge levels exceed tidal ranges. Surge allows wave processes to operate on the upper foreshore of beaches, which are typically only affected by aeolian processes [*Jackson et al*., 2002]. Storm inundation processes are nonlinear; inundation is gradual until a threshold is reached, followed by rapid inundation due to local topography [*Zhang*, 2011]. Barrier islands are especially susceptible to impacts from storms, depending not only on the magnitude of the storm, but also characteristics such as surge, waves, wave runup, and the geometry of the island. Barrier island impact from tropical and extra-tropical storms are typically characterized by the following four regimes: (1) the swash regime, (2) the collision regime, (3) the overwash regime, and (4) the inundation regime. In the swash regime, runup is confined to the foreshore, which typically erodes during the storm but recovers post storm; therefore, there is no net change. The collision regime occurs when wave runup exceeds the base of the foredune ridge and impacts the dune with net erosion. In the overwash regime, wave runup overtops the berm or foredune ridge. This causes net landward transport which contributes to the net migration of the barrier island landward. In the inundation regime, storm surge completely and continuously submerges the island, which initiates net landward sediment transport [*Sallenger*, 2000]. However, these regimes do not consider the influence of storm surge ebb flows, which can transport sediment seaward across the shoreface, resulting in net losses. Although this phenomenon has been studied less, it has been well documented as a dominant erosive force during hurricanes including Hugo (1989) [*Hall et al*., 1990], Andrew (1992) [*Davis*, 1995], and Ike (2008) [*Goff et al*., 2010] along the U.S. coasts. Although storms have the ability to reshape beach profiles from equilibrium conditions over a relatively short period of time [*Walton and Dean*, 2007], shorelines and nearshore bathymetry tend to recover to the pre-storm equilibrium conditions [*Leadon*, 1999; *Wang et al*., 2006].

3.2. Coastal Morphologic Response to SLR

The most simplistic approach to assess the physical response of shorelines to SLR is to consider inundation under a static rise (or fall) in sea level, often referred to as the “drowned valley concept” [*Leatherman*, 1990]. Under this approach, the shoreline migrates landward according to the slope of the coast as the SLRs. The shore becomes submerged, but otherwise unaltered [*Leatherman*, 1990]. Areas with mild slopes will experience more inundation for a given rise in sea level than areas with steep slopes [*Zhang et al*., 2004]. This concept is suitable for regions with rocky or armored shorelines, or even where the wave climate is subdued [*Leatherman*, 1990]. Along sandy shorelines and coastal marshes, shoreline retreat has a more dynamic effect than just inundation, including permanent or long-term erosion of sand from beaches as a result of complex, feedback-dependent processes that occur within the littoral zone, as well as migration and loss of marshes [*Fitzgerald et al*., 2008] (Figures 1 and 2). Unlike inundation, erosion is a physical process in which sand is removed from the shoreface and deposited elsewhere, typically offshore. Long-term, gradual shoreline recession is believed to be mainly a result of low energy processes such as SLR, as well as variations in sediment supplies [*Zhang et al*., 2002]. The relatively moderate era of SLR that shorelines have experienced in the recent past has concluded, and shorelines are beginning to adjust to new boundary conditions [*Woodruff et al*., 2013]. As SLR continues to accelerate, long-term erosion rates are also expected to increase [*Zhang et al*., 2004], which may have significant consequences for barrier islands and coastal embayments.

Barrier islands are often considered to be either transgressive (consistently migrating landward) or regressive (consistently building seaward), depending on the rate of SLR and sand supply along a particular coast [*Curray*, 1964]. A low sand supply and/or high SLR rate will cause barriers to migrate landward. Likewise, a high sand supply and/or low SLR rate will allow for seaward migration. Tidal prisms control the cross-sectional area of inlets and ebb-tidal delta volumes. Increases in bay tidal prisms as a result of SLR can increase the dimensions of tidal inlets. This allows for sand to be transferred from the adjacent barriers, which increases the volume of sand contained in the ebb-tidal deltas. Ultimately, this may cause barrier segmentation and landward migration [*Hayes and Fitzgerald*, 2013]. Barriers may experience one of three responses to high rates of SLR: erosion, translation, or overstepping. Barrier erosion occurs when the shoreface geometry is maintained but decreases over time as the entire profile migrates landward with SLR. Barrier translation or “roll over” entails the entire barrier migrating landward without loss of material as a result of erosion from the shoreface being deposited behind the barrier as washover fans. Overstepping occurs when SLR is too high and the barrier cannot respond, resulting in drowning. Determining the response of barriers to SLR depends on the SLR rate, the gradient of the underlying substrate, longshore transport, and sedimentation in back-bays [*Masselink et al*., 2011].

Shoreline changes under SLR are not limited to beaches; SLR can be a major factor in estuarine shoreline changes resulting in the loss of intertidal areas, erosion of shorelines and increased flooding of low-lying areas [*Rossington*, 2008]. Estuarine shorelines are often comprised of both sandy and marsh shorelines that interact with physical processes including waves, winds, tides, and currents, which dictate erosion, transport, and deposition processes [*Riggs and Ames*, 2003]. Estuarine shoreline response to SLR depends upon the amount of energy acting on the shoreline [*Stevens*, 2010]; if the energy is high enough, the shoreline will erode, whereas if the energy is low, the shoreline will be inundated [*Department of Environmental and Heritage Protection*, 2013]. The eroded material becomes part of the estuary's sediment budget and is deposited along other shorelines within the basin [*Stevens*, 2010]. Inundated marsh shorelines in estuaries experience an increase in wave energy, which may erode the marsh platform and accelerate marsh loss [*Fitzgerald et al*., 2008].

Under some circumstances, changes in wave climates may cause shoreline recession to be an order of magnitude greater than recession due to SLR alone [*Cowell and Thom*, 1994]. Changes in littoral transport budgets as well as changes in storm intensity and recurrence intervals will influence wave climates and alter episodic erosion and nearshore recovery [*Cowell and Kench*, 2001]. For example, shifts in hurricane-generated wave climates since the 1970s have already begun to reshape large-scale, coastal cuspate features in North Carolina, U.S., by making them more asymmetrical [*Moore et al*., 2013]. SLR will likely contribute to changes in wave directions as a result of changes in water depths influencing nearshore wave refraction patterns [*Cowell and Kench*, 2001].

3.3. Coastal Morphologic Modeling of SLR

Projecting long-term morphology is difficult due to the stochastic nature of the processes as well as a lack of understanding in the dynamic interactions and feedback that cause changes [*Sampath et al*., 2011]. As a result, coastal scientists do not have a reliable universal model to accurately predict the impacts of SLR along a variety of coastlines [*Fitzgerald et al*., 2008]. Observations of beach profiles led to the characterization of the equilibrium beach profile concept, which assumes that the beach profile maintains an average, constant shape (aside from periods of storm-induced changes) as the profile moves parallel to itself seasonally [*Bruun*, 1954]. Assuming conditions, other than sea level, remain unchanged, the active beach profile extending from the shoreline to a seaward boundary denoted as the depth of closure will translate upward and landward to keep pace with rising seas, while maintaining shape (equilibrium) [*Bruun*, 1962]. This concept, known as the Bruun Rule, can be used to predict shoreline recession (R) under a rise in mean sea level, given as

$$R = S\frac{L^*}{b + h^*} \tag{1}$$

where S is the rise in mean sea level, b is the elevation of the berm, h^* is the depth of closure, and L^* is the width of the active beach profile [*Bruun*, 1962]. The depth of closure delineates the nearshore (landward of the closure depth to the shoreline) from the offshore (seaward of the closure depth) and represents the threshold where bed sediments are no longer significantly transported by waves. Therefore, it is assumed that all sediment erosion, transportation, and deposition occurs landward of the closure depth [*Fitzgerald et al*., 2008]. The Bruun Rule is considered a coarse, first-approximation approach, as it is a theoretical model and does not take into account the effects of longshore transport, coastal inlets or structures, or aeolian transport [*DECCW*, 2010]. The legitimacy of the assumptions behind the Bruun Rule such as the existence of an equilibrium profile, and/or uniform alongshore transport have been questioned [*Thieler et al*., 2000; *Cooper and Pilkey*, 2004], and numerous studies that have applied the Bruun Rule have come to conflicting conclusions about its validity [*Schwartz*, 1967, 1987; *Rosen*, 1978; *Hands*, 1983; *List et al*., 1997; *Leatherman et al*., 2000; *Zhang et al*., 2004]. However, the underlying concept remains a central assumption in many coastal response models [*Hanson*, 1989; *Dean*, 1991; *Patterson*, 2009; *Ranasinghe et al*., 2012]. In addition, various models have modified the Bruun Rule to incorporate factors such as barrier translation [*Dean and Maurmeyer*, 1983], landward transport [*Rosati et al*., 2013], the dune sediment budget [*Davidson-Arnott*, 2005], and variations in rainfall/runoff [*Ranasinghe et al*., 2012].

Statistical methods such as extrapolation of historical trends have also been applied to predict future shoreline positions [*Fenster et al*., 1993; *Crowell et al*., 1997; *Crowell and Leatherman*, 1999; *Galgano and Douglas*, 2000]. This involves determining the location of new shorelines based on trends established from historical shoreline positions. Various methods have been used to compute shoreline change rates including linear regression, end point, and minimum description length criterion [*Crowell et al*., 1997]. The advantage of using historical trend analysis is that it takes into account the variability in shoreline response based on local coastal processes, sedimentary environments and coastline exposures, under the assumption that shorelines in the future will respond in a similar way as in the past (with a secondary assumption that SLR is the prominent function and all other parameters remain relatively constant) [*Leatherman*, 1990]. *Passeri et al*. [2014] compared erosion rates predicted by the Bruun Rule with historic shoreline erosion rates provided by the USGS Coastal Vulnerability Index (CVI) [*Thieler and Hammar-Klose*, 1999, 2000] and the USGS National Assessment of Shoreline Change [*Morton et al*., 2004; *Morton and Miller*, 2005] along the U.S. South Atlantic

Bight and Northern Gulf of Mexico coasts. The authors found that erosion rates predicted by the Bruun Rule matched long-term erosion rates in parts of northeast Florida (e.g., Melbourne) and concluded the Bruun Rule could be used at these locations to predict future recession, under the assumption that historic erosion is completely attributed to the forces related to SLR. The CVI shoreline change rates were typically much larger than those provided by the National Assessment of Shoreline Change; therefore, the authors advise that care should be taken when extrapolating historical shoreline change rates to predict future shoreline positions [*Passeri et al*., 2014].

More recently, researchers have implemented probabilistic approaches to manage uncertainty associated with long-term shoreline predictions [*Cowell and Zeng*, 2003; *Cowell et al*., 2006]. Statistical approaches using Bayesian networks have been applied to project long-term shoreline changes under SLR [*Hapke and Plant*, 2010; *Gutierrez et al*., 2011; *Yates and Le Cozannet*, 2012]. The Bayesian network, based on the application of Bayes' theorem, is used to define relationships between driving forces, geological constraints, and coastal responses to make probabilistic predictions of shoreline changes under future SLR scenarios [*Gutierrez et al*., 2011]. Considering observations of local rates of relative sea level rise (RSLR), wave height, tidal range, geomorphic classification, coastal slope, and shoreline change rates, *Gutierrez et al*. [2011] developed a Bayesian network to predict long-term shoreline changes. The Bayesian network was used to make probabilistic predictions of shoreline changes along the U.S. Atlantic coast under different SLR scenarios. Results indicated the probability of shoreline retreat increased with higher SLR rates. The accuracy of the model was assessed with a hindcast evaluation, in which the network correctly predicted 71% of the cases [*Gutierrez et al*., 2011]. Following this methodology, *Yates and Le Cozannet* [2012] created a Bayesian network to make statistical predictions of shoreline evolution along European coastlines. The output was compared with historic shoreline evolution trends and was found to accurately reproduce more than 65% of the trends. The authors concluded that the development of Bayesian networks is a useful tool for estimating future coastal evolution under changes in wave regimes or SLR [*Yates and Le Cozannet*, 2012]. Bayesian networks have also been applied to project retreat along coastal cliffs, which are typically more complex due to the need to model both sandy beaches in conjunction with the coastal cliff system. Hindcast evaluation accurately predicted 70%–90% of the modeled transects, indicating that the approach could be used to predict cliff erosion on time scales ranging from days (storm events) to centuries (SLR) [*Hapke and Plant*, 2010].

As changes in coastal morphology occur at time scales that are an order to two orders of magnitude greater than hydrodynamic time scales [*Stive et al*., 1990], conventional morphodynamic simulations using numerical models have been inefficient and lengthy [*Dissanayake et al*., 2012]. However, in more recent years, progress in process-based models has allowed the simulation of multiscale hydrodynamics and morphology to be feasible. These simulations can be accomplished using numerical modeling in which the wave field, current field, and bathymetric changes are computed sequentially under the specified boundary conditions and sea level changes. The following are practical numerical models for simulating hydrodynamic and morphodynamic processes in coasts and estuaries: (1) 1D longshore coastline models that describe longshore sediment transport and shoreline evolution using the sand budget approach (2) 2D cross-shore profile models that predict variations in coastal profiles but do not consider longshore transport (3) 2D horizontal coastal/estuarine/oceanic process models that simulate hydrologic and morphologic variations with a wide range of spatial scales but no considerations of variations in waves and currents (4) 3D models that take into account vertical and horizontal variations in waves and currents, but are generally restricted to predicting changes on small scales and in short durations [*Ding*, 2012].

Behavior-oriented models based on empirical rules and analysis can be more effective for simulating long-term shoreline evolution in comparison with numerical models, which are unable to account for variability in wave and current conditions on longer timescales. In the 1990s, large-scale morphological-behavior models were developed to simulate future changes in coastal morphology under SLR and variations in sediment supply. Many of these models are centered on the equilibrium profile translation principle, but incorporate additional drivers to predict shoreline evolution. However, validation of these models is difficult and can only be accomplished through inverse modeling, in which the model is calibrated with stratigraphic data and sea level history for specific areas and shoreline translation is recreated on geological time scales.

Early behavior-oriented models include The Shoreface-Translation Model [*Cowell et al*., 1995], and those of *Stive and De Vriend* [1995] and *Niedoroda et al*. [1995]. The coast-basin interaction model ASMITA (Aggregated Scale Morphological Interaction between a Tidal basin and the Adjacent coast) was developed to describe the morphological interactions between tidal basins and the adjacent coast at various spatial and temporal scales in response to external forcing factors. This behavior-oriented model is based on the assumption that a tidal basin can reach an equilibrium volume relative to mean sea level, at which point the accommodation space is equal to zero. A morphological equilibrium can be obtained for each element in the tidal system (e.g., ebb-tidal delta, intertidal flats, etc.) depending on its hydrodynamic and morphometric conditions [*Stive et al*., 1998]. *Van Goor et al*. [2003] employed this model to examine whether the geomorphology of tidal inlets in the Dutch Wadden Sea could maintain equilibrium under rising sea levels. The authors found that if the rate of sediment import matched the rate of SLR, a new state of dynamic equilibrium was achieved, whereas if the import rate was less than SLR, the morphological state would deviate from equilibrium and the system would eventually drown. GEOMBEST (Geomorphic Model of Barrier, Estuarine, and Shoreface Translations) was developed to simulate the evolution of coastal morphology under changes in sea level and variations in sediment volume. The model is able to simulate the effects of geological framework on shoreline migration by defining the substrate with stratigraphic units characterized by erodibility and sediment composition. Unlike the Bruun Rule, changes in morphology are controlled by disequilibrium stress caused by changes in sea level, which vertically displace the equilibrium profile. This may result in net loss or gain of sediment volume as the profile tries to attain equilibrium. Applying GEOMBEST to simulate coastal stratigraphy in Washington, U.S. and North Carolina, U.S. indicated that the model could be used as a quantitative tool for coastal evolution assessments on geological time scales [*Stolper et al*., 2005]. Following the approach of *Storms et al*. [2002], Barrier Island Translation was developed to simulate the evolution of a sand barrier using simplified equations and taking into consideration the effects of various processes such as wind waves, storm surge, and sea level oscillations. The model is based on the assumptions of conservation of mass and conservation of the equilibrium profile. It is capable of simulating the processes of sediment redistribution by waves in the shoreface, sediment diffusion by waves in the inner shelf, overwash during storms, and lagoonal deposition in the back-barrier. The model used to simulate the dynamics and evolution of a barrier island in Sand Key, Florida U.S. during the last 8000 years. Results indicated that the rate of overwash and lagoonal deposition was crucial for the survival for the barrier island under the historic sea level changes [*Masetti et al*., 2008]. *Sampath et al*. [2011] used a simplified behavior-oriented model to predict long-term morphological evolution in the Guadiana estuary, Portugal in response to SLR based on historic sedimentation rates and tidal inundation frequency. The model calculated the increased tidal inundation frequency under SLR using an empirical formula based on tidal range, determined from historic tide gauge data. However, the model did not take into account potential changes to tidal ranges or inundation areas under SLR. *Ranasinghe et al*. [2012] developed a physically based, scale-aggregate model to estimate changes in coastlines due to SLR and variations in rainfall-runoff in Vietnam. Results indicated changes can be very significant along shorelines adjacent to small inlet-basin systems; these areas cannot be neglected in coastal management and planning decisions.

4. Marsh Ecology

4.1. Background

Tidal marshes are dynamic systems governed by tidal inundation, hydroperiod, sediment supply, and biological dynamics [*Stralberg et al*., 2011]. Areas with limited tidal prisms create smaller inlet/marsh systems with shallow channels [*Friedrichs and Madsen*, 1992], which dictate tidal propagation and asymmetry [*Townend et al*., 2011]. Vegetation on the marsh platform is crucial for damping the flow of water and waves. Energy is reduced exponentially with distance from tidal creek edges due to a decrease in flow speed [*Leonard and Luther*, 1995]. Flow damping allows particles to settle within the marsh, limits erosion on the marsh surface and can increase accretion [*Townend et al*., 2011]; this interconnection works as a hydrologic system [*Leonard and Luther*, 1995]. In addition, dissipation of wave energy protects nearby shorelines from erosion [*Möller et al*., 1999]. Moreover, transported and deposited sediments near rivers and creeks play a key role in sustaining marsh habitats in river deltas [*Martin et al*., 2002].

The governing parameters for biomass productivity in salt marshes are the elevation of the marsh table, mean low water (MLW), and mean high water (MHW), which determine the relative depth of the salt marsh

[*Morris et al*., 2002]. The elevation of the marsh table progresses through sedimentation and accretion; deposition is controlled by tidal inundation and direct deposition of organic matter from root growth. The capturing of particles during inundation periods is dictated by flow velocities; at high tidal flows greater than 0.4 m/s, particle capture can account for over 70% of the sediment delivered to the marsh [*Mudd et al*., 2010]. In addition, hydroperiod is an influencing factor on vertical marsh accretion. Hydroperiod depends on tidal range, which also dictates sediment transport potential [*Reed*, 1990]. In general, an increased hydroperiod will increase the accretion rate of inorganic sediments until the accreted platform eventually decreases the hydroperiod. For organic sediments, an increased hydroperiod induces stress on the vegetation, which lowers the production of organic matter, decreases accretion, and increases the hydroperiod as a positive feedback [*Friedrichs and Perry*, 2001]. In conjunction with hydroperiod, an optimal level between mean sea level and mean high water exists where plant productivity is at a maximum [*McKee and Patrick*., 1988].

Processes that increase sediment concentration in tidal creeks adjacent to marshes can also increase the marsh accretion rate. These processes include local suspension of sediments through increased tidal velocity, wind waves, proximity to estuarine turbidity, and an increase in background concentration due to offshore erosion [*Friedrichs and Perry*, 2001]. Distance from creeks is also crucial, as areas near the banks of the creeks tend to accrete faster than inner marsh [*Townend et al*., 2011]. Tidal asymmetries affect sediment transport in marsh tidal creeks, which can also dictate marsh sediment supply. Flood-dominant tides in salt marsh creeks move sediment landward whereas ebb-dominant tides tend to move sediment seaward. Flood-dominant currents increase the SSC at the creek/marsh boundary, which supplies more marine sediment to the marsh. This causes accretion on the platform until the decreased inundation frequency reduces net deposition. Similarly, ebb-dominant currents reduce the supply of the sediment to the marsh. An additional parameter that influences net sediment transport in tidal creeks is the difference in the rate of current change near high water slack compared to low water slack. If high water slack duration is longer than that of low water slack, more sediment will fall out of suspension after the flood tide relative to the ebb tide; this enhances landward sediment transport and increases the sediment supply to the marsh [*Friedrichs and Perry*, 2001]. Sediment movement onto the marsh can also occur regardless of tidal asymmetry, due to settling lag [*Postma*, 1967] as well as higher sediment concentrations moving landward during flood tides in comparison to those moving seaward during ebb tides [*Krone*, 1987].

As marsh vegetation considerably dampens the flow across the marsh, waves typically do not cause long-term erosion of the marsh platform [*Townend et al*., 2011]. Although particle erosion may occur if stress is exerted on the marsh platform by hydrodynamic forces [*Francalanci et al*., 2013], eroded areas are typically restored with regular tidal inundation [*Pethick*, 1992]. However, waves can influence edge erosion, bank failure, and retreat. Wave impact may undermine the residual cohesion in the marsh platform due to normal and shear stresses occurring on the soil that connects the platform to the bank [*Pethick*, 1992]. The integrated influences of tidal range, waves, and storms provide insight to distinctions in marsh morphology and response. Unlike mesotidal and macrotidal estuarine marshes which depend on recurrent tidal action for sediment distribution [*Stumpf*, 1983; *French and Spencer*, 1993], marshes in microtidal estuaries depend upon storms for sediment supply and respond with rapid vertical accretion and horizontal expansion [*Townend et al*., 2011]. For example, in Louisiana, U.S., Hurricane Andrew increased vertical accretion and surface elevation on the order of what typically occurs over semi-annual and annual time scales; the storm generated between 2 and 6 cm more vertical accretion than the accumulation in the marsh during the year before and the year after the storm [*Cahoon et al*., 1995]. Erosion during storm events occurs as the marsh adjusts to maximize cross-shore dissipation of wave energy and increase resiliency [*Townend et al*., 2011].

4.2. Marsh Response to SLR

Marsh response to increased rates of SLR depends on factors such as sediment supply, vegetation productivity, rates of subsidence or uplift, changes in storm frequency and intensity and availability of inland areas for migration [*Stralberg et al*., 2011]. Under a given sediment supply, a marsh can prograde or erode as a function of SLR [*Mariotti and Fagherazzi*, 2010]. For a marsh to maintain its present form and withstand SLR, sedimentation must keep pace with the rate of rise. A slight increase in sea level may advance biomass production and increase the amount of settling on the marsh surface [*Reed*, 1990; *Nyman et al*., 2006]. However, if the rate of SLR exceeds the rate of accretion, the marsh will drown [*Reed*, 1990]. SLR may cause marshes to migrate landward at a rate almost equal to the seaward erosion; this can be especially detrimental if the marsh is backed by seawalls or bulkheads [*Friedrichs and Perry*, 2001]. A low rate of SLR can reduce depths on adjacent tidal flats, increasing wave dissipation and sediment deposition; this leads to the marsh boundary prograding. However, a high rate of SLR deepens the tidal flats and allows higher waves to erode the marsh boundary (Figure 2). If the rate of SLR is too fast, the entire marsh will drown and transform into a tidal flat [*Mariotti and Fagherazzi*, 2010]. The marsh hydroperiod is expected to increase with SLR, which can allow for either more deposition on the marsh platform (therefore increasing productivity) or more erosion and drowning of vegetation [*Friedrichs and Perry*, 2001]. Coastal morphology can also influence the response of salt marsh systems to SLR. Deposition from nearby eroded shorelines can be a sufficient sediment source for marshes; *Phillips* [1986] estimated that shoreline erosion along the Delaware Bay, U.S., supplies 4.5 times the amount of sediment required to maintain the elevation of the adjacent marsh platforms.

Microtidal marsh systems are more sensitive to SLR and changes in SSCs because they cannot readily adjust their mean platform elevation with respect to the tidal elevation. A relatively small increase in sea level or a decrease in accretion can cause a microtidal marsh to become submerged. If there is ample accretion, the marshes will advance seaward more quickly than marsh systems in higher tidal ranges. This is because less vertical growth is required to reduce the duration and frequency of the submersion time, which allows available sediment to be deposited landward. Mesotidal and macrotidal marshes may be able to keep pace with accelerating SLR because of enhanced sediment concentrations and flood dominance as tidal range increases [*Friedrichs and Perry*, 2001]. However, even if a marsh has exhibited the ability to keep pace with SLR in the recent past and near future, a critical rate of SLR exists at which the marsh will eventually drown out [*Morris et al*., 2002]. If suitable uplands are not available, marshes will be unable to migrate landward under SLR as they have historically, which will result in loss [*Stralberg et al*., 2011]. It is also important to note that other factors such as changes in large-scale processes or anthropogenic interventions may have as much of an influence on marsh systems as SLR [*French and Burningham*, 2003].

4.3. Marsh Modeling of SLR

Various models have been developed to simulate marsh processes, including empirical and physical models of marsh sedimentation, coupled vegetation and marsh sedimentation models, marsh boundary evolution, coupled vegetation and sedimentary process models and below ground organic production (for detailed model reviews, see *Fagherazzi et al*. [2012]). However, developing models that combine realistic local processes of sediment feedback in marshes with larger estuarine-scale spatial dynamics is challenging [*Stralberg et al*., 2011]. Determining the effects of accelerated SLR is also difficult because isolating SLR as a driver is not feasible in natural wetlands [*Kirwin and Temmerman*, 2009].

Numerical models can provide insight to the effects of SLR on marsh productivity because they are able to separate SLR as a driver of change [*Fagherazzi et al*., 2012]. Many modeling approaches have been developed (see *Kirwin and Temmerman* [2009] and references therein), a few of which are highlighted herein. *Morris et al*. [2002] developed a theoretical model used to predict marsh biomass productivity under changes in sea level. The model is able to capture the interactions between accretion and biomass productivity through a feedback process; the net rate of change in elevation of the marsh platform is equivalent to the net rate of accretion, which depends on biomass productivity. As the sea level rises, the marsh constantly adjusts toward a new equilibrium [*Morris et al*., 2002]. *Kirwan and Murray* [2007] expanded the model to include the coupling effects between vegetation-influenced evolution of the channel network and accretion on the marsh platform. *Schile et al*. [2014] applied the *Morris et al*. [2002] Marsh Equilibrium Model to four marshes in San Francisco Bay, U.S., with varying SLR and suspended sediment scenarios to quantify potential changes in marsh distributions. At high SLR and low sediment concentrations, the marshes were dominated with mudflats. Areas with adjacent uplands were able to gain new marsh habitats under the highest rate of SLR, stressing the significance of these areas in conservation planning. The study also indicated that marshes can sustain vegetated elevations with rising sea level to a certain point, but accretion alone is not enough to support the marsh habitat. *Temmerman et al*. [2003] developed a zero-dimensional physically based model to simulate tidal marsh accumulation rates under changes in SLR and SSCs with the ability to quantify the combined effect of SLR and SSC on accumulation rates. The model was applied to the Scheldt estuary in Belgium to evaluate historical growth; results signified the importance of considering temporal variations in SSC in the marsh rather than a constant SCC, which led to an underestimation in growth. *Rybczyk and*

Cahoon [2002] developed a cohort modeling approach to simulate sediment dynamics (accretion, decomposition, compaction and belowground productivity) and sediment height to determine marsh elevation. Biomass productivity was calculated using a coupled productivity and sediment dynamic model, while changes in decomposition, root distribution, sediment compaction, peat characteristics, and marsh surface elevation were incorporated. An application of the model to two marshes in Louisiana, U.S. revealed that the model was most sensitive to changes in the rates of deep subsidence. Under the current rate of SLR, the marsh surface elevation at both sites would fall below mean sea level over the next 100 years. *Stralberg et al*. [2011] developed a hybrid modeling approach that involved a process-based model of accumulation, which included feedback mechanisms between elevation and sediment inputs to simulate accretion dynamics under climate change scenarios. However, the model lacked a hydrodynamic component to allow for spatial sediment transport. The model was applied to San Francisco Bay, U.S., and although it provided insight into marsh responses to SLR, the authors concluded that a high-resolution, process-based model coupled with a broad-scale spatial model incorporating hydrodynamics would be ideal. Numerical simulations using a 1D marsh evolution model by *Mariotti and Fagherazzi* [2010] illustrated that low rates of SLR increase wave dissipation and sediment deposition, whereas high rates cause wave-driven erosion and recession of the marsh shoreline. The authors suggest that as edge erosion increases, salt marshes will be wedged between increasing sea levels seaward, and increasing urbanization landward.

Ecosystem-based landscape models have also been developed to forecast effects of SLR on marsh systems. This goal of this modeling approach is to simulate the dynamic and spatial behaviors of systems, taking into account important landscape variables such as ecosystem type, water flows, sedimentation, subsidence, salinity, productivity, nutrients, and elevation [*Sklar et al*., 1985]. These models are beneficial because they can be applied with high resolution to large domains. Interactions of organisms (such as plants) with the surrounding environment are considered with either direct or indirect calculations. A direct calculation model allows for feedback mechanisms by calculating hydrodynamics and biological processes simultaneously. An indirect calculation model computes hydrodynamics first, and then uses model outputs to simulate biological processes. The benefit of these models is that they are often easy to implement and require less computational time than direct calculation models [*Fagherazzi et al*., 2012]. *Costanza et al*. [1990] developed the Coastal Ecological Landscape Spatial Simulation (CELSS) model which incorporated forcing factors such as subsidence, SLR, river discharge and climate variability to determine marsh productivity at 1 km resolution. Hydrodynamics were approximated using a mass balance approach, which the authors recognized were not accurate for short-term simulations. The model was applied to the Atchafalaya marsh in Louisiana, U.S., to determine marsh productivity under various SLR scenarios. Results indicated net gains in land under a rate of SLR equal to twice the eustatic rate, whereas higher rates drowned the marsh out. The authors concluded that healthy marshes with adequate sediment inputs can act as a buffer against moderate rates of SLR. Using the CELSS framework, *Reyes et al*. [2000] developed The Barataria-Terrebonne ecological landscape spatial simulation model to predict future trends in marsh productivity under SLR, river discharge changes and climate variability in the Mississippi Delta, U.S. Hydrodynamic calculations were improved by incorporating a 2D vertically integrated hydrodynamic module. This allowed biomass productivity to be simulated with a daily time step at a resolution of 1 km^2. Other direct calculation models include those of *Martin et al*. [2002] and *Reyes et al*. [2004a]. Based on *Reyes et al*. [2000], *Reyes et al*. [2004b] compared projected marsh losses under SLR for the Atchafalaya delta and the Barataria Basin in Louisiana. Under a SLR rate double that of the current, fresh and brackish marsh loss was between 30% and 50% for the two marshes. However, in a scenario with increased river discharge, losses were reduced as a result of additional nutrient and sediment input to the marshes.

One of the most well-known indirect calculation models is SLAMM (Sea Level Affecting Marshes Model), a spatial model that simulates dominant processes associated with wetland conversion to simulate the effects of SLR on productivity. The model considers the effects of SLR on inundation, erosion, overwash, salinity, and soil saturation. Although the model is capable of simulating broad-scale spatial patterns it is unable to accurately model elevation and sediment dynamic feedbacks or crucial local processes [*Craft et al*., 2009]. Using field and laboratory measurements in conjunction with SLAMM modeling, *Craft et al*. [2009] found that tidal marshes at lower and upper salinity ranges will be most affected with accelerated SLR, unless vertical accretion can allow marshes to migrate inland or keep pace with SLR.

5. Synergetic Studies of SLR

Recently, more studies have aimed to incorporate multiple coastal processes to achieve a more holistic evaluation of the effects of SLR on coastal environments. Incorporating changes in land use/land cover (LULC) and coastal morphology in conjunction with SLR into hydrodynamic modeling allows for an improved understanding of the coastal response under future scenarios. For example, *Bilskie et al*. [2014] investigated the interaction between changes in LULC, topography, and coastal flooding under past (1960), and present (2005) sea levels and shoreline positions, as well as under projections of future LULC and sea levels (2050) along the Mississippi and Alabama coast. To examine the nonlinear interaction and sensitivity of storm surge to the changes in landscape and sea level, the authors developed the Normalized Nonlinearity (NNL) Index:

$$\mathrm{NNL} = \frac{\eta_2 - \eta_1 - \lambda}{\lambda} = \frac{\eta_2 - \eta_1}{\lambda} - 1 \tag{2}$$

where η_2 and η_1 are the maximum generated surges for the lower and higher sea levels, given an amount of SLR. Historic changes in the nearshore topography both amplified and reduced storm surge depending on location. Projections of future urbanization amplified maximum storm surge by 70% more than the applied SLR scenario. The authors recommend considering future landscape changes including LULC and coastal morphology, in addition to altering the sea level for a more comprehensive assessment of future flood inundation. Furthermore, *Passeri et al*. [2015] tested the sensitivity of a hydrodynamic model to projected shoreline changes and SLR along the Florida Panhandle. The projected shoreline changes had variable influences on tidal and storm surge hydrodynamics, including minimal changes in tidal prisms, increased barrier island overtopping during storm events, and increased volumes of storm surge in back-bays. It was concluded that the sensitivity of individual areas to projected shoreline changes should be assessed for a better evaluation of the effects of SLR on the coastal environment.

The effects of landscape changes and SLR on coastal flooding have also been examined in a tidally influenced river in Malaysia to observe modifications in the hydrodynamic behavior. Overall, SLR was found to increase the river's peak stage level, and either increase or decrease peak velocities, depending on location. The results were compared with flooding scenarios that included runoff under past and present land cover conditions. Urbanization and increased runoff were found to have a greater impact on the hydrodynamics in the river than SLR alone [*Sathiamurthy*, 2013]. Consideration of future landscape scenarios is also beneficial when evaluating future project proposals under SLR. *Cobell et al*. [2013] simulated hypothetic hurricanes to analyze storm surge and wind waves under current and future conditions in Louisiana, where future conditions implemented SLR, changes in landscape elevations due to subsidence and accretion, bottom roughness changes due to vegetation changes, and proposed hurricane protection projects such as levees and landscape restorations. All future scenarios that did not consider protection showed increased inland inundation, and increased significant wave heights in areas with higher water depths. Levees protected areas landward of the structure, but increased surge in areas seaward. Restored landscapes provided wave attenuation but had minimal effects on surge reduction. Accretion and increased vegetation due to sediment diversions dampened waves and surge and protected inland areas.

Marsh and hydrodynamic processes have also been integrated to simulate the dynamics within each process and observe changes in marsh productivity under SLR. *Hagen et al*. [2013] investigated the impacts of SLR on a salt marsh system in the St. Johns River using a 2D hydrodynamic model coupled with a zero-dimensional marsh model. Changes in the governing parameters of biomass productivity (MHW and MLW) under conservative (0.15 m) and modest (0.30 m) SLR scenarios were observed. The hydrodynamic simulations showed that MHW and MLW responded nonlinearly, elevating by amounts unequal to the amount of SLR; MLW was elevated by less than the SLR, and MHW was elevated by more than the SLR, especially within the tidal creeks. The variability in MHW and MLW significantly affected the distribution of biomass productivity over the marsh. Without accretion, biomass productivity decreased, whereas with accretion, the marsh was able to maintain its productivity. Improving on this methodology, (Alizad et al., A coupled two-dimensional hydrodynamic marsh model with biological feedback, submitted to *Journal of Limnology and Oceanography*, 2015, hereinafter referred to as Alizad et al., submitted manuscript, 2015) enhanced the coupled model to incorporate inorganic and organic marsh platform accretion, as well as changes in biomass density through biological feedback mechanisms. Nonlinear SLR scenarios are captured using a "coupling time step", which incrementally advances and updates the solution. The model was applied to the same salt marsh system in the St. Johns River to simulate biomass productivity under low (0.11 m) and high (0.48 m) SLR scenarios for the year 2050. On average, biomass density increased by 54% under the low SLR scenario, but declined by 21% under the high SLR scenario (Alizad et al., submitted manuscript, 2014].

Including coastal processes that modify morphology for delineating future inundation under SLR is difficult due to the lack of reliable models that predict erosion and accretion in response to SLR [*Zhang*, 2011]. *Ding* [2012] used an integrated model to simulate hydrodynamic and morphologic responses to SLR scenarios during a storm event in the Tochien Estuary, Taiwan. Results indicated changes in erosion/deposition in areas due to SLR, and the model was considered to be effective for simulating nonlinear and unsteady hydrodynamic and morphodynamic processes in coastal areas under SLR scenarios. Using a 2D hydrodynamic model coupled with a morphological scale factor to update bed morphology, *Dissanayake et al*. [2012] simulated the effects of SLR over a 110 year period in a large inlet/basin system. Applying a morphological scale factor instead of a conventional morphodynamic model allowed for dynamic simulations of morphology and hydrodynamics to be accomplished at a reasonable computational cost. Model results indicated that the existing flood dominance of the system increases as SLR rates increase, which causes the ebb-tidal delta to erode and the basin to accrete. Erosion and accretion rates were positively correlated with the rate of SLR, and under the highest scenario the tidal flats eventually drowned out.

6. Additional Considerations

6.1. Additional Coastal Dynamics

Although not a main focus of this review, hydrologic changes and saltwater intrusion into groundwater should also be considered in future synergetic studies, as they contribute to changes in coastal landscapes and ecosystems. Increased rainfall intensity and temporal shifts of extreme rainfall events under climate change have the potential to increase flooding, and sediment and nutrient loading into estuaries, especially under SLR [*Gordon et al*., 1992; *Wang et al*., 2013]. Runoff has the potential to increase sediment loading in river systems depending on the rainfall intensity, slope, soil, and LULC; increased sediment loading aids in salt marsh survival under SLR [*Defersha and Melesse*, 2012]. Therefore, there is a need for integrated models that not only capture the dynamic effects of SLR on biomass productivity, but also include runoff impacts on sediment deposition in marsh systems.

Changes in precipitation patterns across the coastal watershed may modify the magnitude of aquifer discharge to the sea, inducing saltwater intrusion, which can be exacerbated under SLR. Saltwater intrusion, or the infringement of coastal saltwater into fresh groundwater in the coastal aquifer regime, may penetrate landward as the SLRs. The magnitude and rate of migration is a function of local hydrogeologic variables such as aquifer thickness, rate of recharge, hydraulic conductivity, groundwater discharge rate to the estuary, as well as anthropogenic actions such as over pumping and increase in paved areas from urbanization [*Werner and Simmons*, 2009; *Chang et al*., 2011]. The landward migration of the saltwater fringe may impact the coastal ecosystem via nearshore and/or large-scale submarine discharge patterns and nutrient loading levels [*Li et al*., 1999; *Robinson et al*., 2007; *Chang et al*., 2011]. Despite qualitative claims that saltwater intrusion may be exacerbated under SLR, quantitative studies are limited and are typically focused on site-specific observations or numerical studies, making it difficult to draw general conclusions [*Werner and Simmons*, 2009]. Similarly, few studies have examined the combined effects of climate change and anthropologic impacts on saltwater intrusion [*Chang et al*., 2011].

In addition, the dynamic effects of SLR discussed herein should be considered in biologic assessments of SLR (e.g., oysters, sea turtles, shorebirds, and beach mice). Until recently, biological assessments have mostly focused on the effects of rising temperatures, precipitation changes, and extreme weather events rather than the effects of SLR. The impacts of SLR have the potential to be one of the greatest causes of global species extinctions and ecosystem disruption in the upcoming decades and centuries [*Noss*, 2011]. Anthropogenic and climate change stressors often interact synergistically; therefore, integrated assessments of processes that threaten coastal species are needed for conservation efforts [*Reece* *et al*., 2013]. Biological assessments should also implement a synergetic approach, considering alterations in hydrodynamic patterns, sediment transport, morphology, marsh migration/loss, and hydrologic changes.

6.2. Socioeconomic Considerations

Future socioeconomic change is potentially equally as significant as future climate change when evaluating impacts and mitigation strategies [*Brown et al*., 2011]. Future socioeconomic conditions are a fundamental driver in influencing changes in coastal systems with and without climate change. Although SLR-driven impacts to coastal wetlands could potentially be significant, human-induced direct and indirect effects may be much larger based on existing trends [*Nicholls*, 2004]. If future SLR does not occur, the number of people flooded per year would still change depending on socioeconomic changes such as growing populations and the desire to live in coastal areas [*Nicholls and Tol*, 2006]. Human-induced changes including coastal defenses, wetland destruction, ports and harbors, reduced sediment supply to dams, drainage and groundwater withdrawal have convoluted the effects of climate-induced SLR during the 20th century. However, these effects are so extensive that they necessitate more systematic studies to better establish mitigation and adaptation strategies [*Nicholls and Cazenave*, 2010].

Socioeconomic impacts of SLR can be characterized as follows: (1) direct loss of economic, ecological, cultural and subsistence values as a result of loss of lands, infrastructure and habitats, (2) increased flood risk to people, land, infrastructure and the previously discussed values, and (3) impacts related to water management, salinity, and biological activities [*Klein and Nicholls*, 1999]. Until recently, socioeconomic assessments have mostly focused on economic effects considering SLR alone without other climate changing variables [*IPCC*, 2007]. Assessments are now considering the combined effects of climate change variables and SLR, including changes in precipitation, temperature and extreme events (e.g., *Houser et al*. [2014]). Numerous studies dating back to the early 1990s have examined the socioeconomic cost of SLR [*Turner et al*., 1995; *Yohe et al*., 1996; *Yohe and Schlesinger*, 1998; *West et al*., 2001; *Nicholls and Tol*, 2006; *Hallegatte et al*., 2011; *Hallegatte et al*., 2013; *Hinkel et al*., 2014]. Early studies evaluated economic loss in terms of property value that was susceptible to SLR as well as estimates of protection costs [*IPCC*, 2001]. Recent studies have expanded analyses to include impacts to coastal businesses, coastal erosion, loss of wetland value, consumer surplus losses, etc. [*Wei and Chatterjee*, 2013]. As sea levels rise in the 21st century and socioeconomic development increases within coastal floodplains, flood damages are also expected to escalate. Without adaptation, it is estimated that 0.2%–4.6% of the global population will experience flooding annually in 2100 with a SLR of 25–123 cm; global gross domestic product is expected to have a 0.3%–9.3% annual loss [*Hinkel et al*., 2014]. Considering future socioeconomic changes alone, average global flood losses are projected to increase to $52 billion per year by 2050, compared to $6 billion per year estimated in 2005. If coastal flood defenses keep flooding probability constant, subsidence and SLR will still increase global flood losses to $60–$63 billion per year in 2050 [*Hallegatte et al*., 2013]. More studies estimating future damages and adaptation costs are essential for designing strategies to mitigate and adapt to increased coastal flooding [*Hinkel et al*., 2014].

6.3. Managing Future Risk

Regional and local managers are responsible for planning and responding to threats such as SLR [*Gilmer et al*., 2011]. Planning for changes under future sea levels may require a more active role from managers to protect estuaries and natural systems [*Nicholls et al*., 1995]. Many coastal communities are not equipped for increases in extreme flooding frequency. Although large uncertainties in cyclone climatology, SLR and morphology make planning difficult for coastal planners and policy makers, the high probability of increased flooding justifies preparations. Changes in sediment supply, and subsidence induced by groundwater, oil and gas extraction should also be considered, especially along barrier coasts and deltaic systems [*Woodruff et al*., 2013].

There are two potential responses to SLR: mitigation and adaptation. Mitigation is a global-scale activity whereas adaptation is subglobal (local to national scale); therefore SLR assessments need to operate on multiple scales. In coastal areas, the goal of mitigation is to reduce the risk of passing irreversible thresholds regarding major ice sheet breakdown, and limit the rate of SLR to be adaptable at reasonable economic and social costs. Adaptation involves strategies responding to both mean and extreme rises in sea level [*Church et al*., 2010]. Adaptation can be accomplished with protection, accommodation, or planned retreat;

choosing a viable option is both a technical and sociopolitical decision depending on which avenue is desirable, affordable, and sustainable in the long term. Due to the uncertainties regarding the impacts of SLR, an improved understanding of the various adaptation strategies is necessary, as adaption is one of the most influential elements discerning between impacts actually occurring rather than potentially occurring [*Nicholls and Cazenave*, 2010]. It has been proposed that the most reasonable response to SLR involves a combination of adaptation strategies to handle the inevitable rise and mitigation strategies to restrict the long-term rise to a manageable level [*Nicholls et al*., 2007].

Quantification of the dynamic effects of SLR on inundation extents as well as social, economic, and ecologic impacts will aid in creating comprehensive policies to reduce the risks associated with future SLR [*Zhang*, 2011]. There is a need for more integrated responses and management strategies that consider a balance between protecting socioeconomic activity and ecology in the coastal zone under rising seas [*Nicholls and Klein*, 2005; *Church et al*., 2010]. Assessments of SLR impacts and responses within a coastal management context will address all the potential drivers of change within the coastal zone [*Church et al*., 2010].

7. Conclusions

This review has examined the dynamic effects associated with SLR through various studies in the context of hydrodynamics, coastal morphology, and marsh ecology. Hydrodynamic response to SLR is dynamic, with nonlinear changes in parameters such as tidal ranges, tidal prisms, tidal asymmetries, increased flooding depths and inundation extents during storm events. Coastal morphology strives to achieve equilibrium as sea levels rise, which may significantly reshape the coastal landscape. Marsh productivity is a function of tidal inundation and elevation; sediment accumulation and migration are vital aspects in marsh survival under future SLR. The studies discussed herein employ more complex approaches rather than the "bathtub" approach to account for the dynamic responses of the coastal system. Although these studies provide an improved understanding of the effects of SLR on coastal environments, synergetic studies that integrate multiple system dynamics allow for more comprehensive evaluations. These present and future dynamic, integrated studies can contribute to an overall paradigm shift in how coastal scientists and engineers approach SLR modeling, transitioning away from the "bathtub" approach.

Based on the above review, a number of current research needs are summarized:

1. A critical review comparing various hydrodynamic models used to simulate SLR and an established framework for incorporating SLR into hydrodynamic models. This will provide a more uniform methodology that can be applied to various models to produce better evaluations of the effects of SLR on hydrodynamics.
2. A more quantitative understanding of shoreline response to SLR. Long-term monitoring of shorelines and more efficient morphological models will improve understanding of shoreline dynamics and give insight to how higher seas may reshape the coast. Furthermore, as barrier islands are particularly vulnerable to SLR, a fifth tropical cyclone impact regime, namely "Recession" should be considered because of its unique effects on short-term morphology and postevent hydrodynamics.
3. More economic-cost evaluations considering the various dynamics of SLR. Presently, most studies only focus on the effects of SLR inundation without incorporating future changes to the landscape (such as shoreline erosion), which may alter projected costs.
4. Additional studies incorporating the impacts of human-induced changes such as coastal defenses, wetland destruction, ports and harbors, reduced sediment supply to dams, drainage and groundwater fluid withdrawal. Understanding how these changes might affect coastal systems during normal and extreme conditions will aid in management decision making and adaptation planning.
5. A better understanding of feedback processes between the physical and ecological environment under SLR. Little work has examined the interactions and feedbacks between coastal systems under SLR and climate change (e.g., hydrodynamics, marsh ecology, coastal morphology, hydrologic changes, and saltwater intrusion into groundwater). To make more informed decisions on adaptation planning, a holistic understanding of these synergetic processes is needed.
6. Integration of socioeconomic implications into the overall synergistic process. At present, the vast majority of socioeconomic evaluations are performed after the physical- and process-based

assessments are completed. Incorporating this human element will ultimately influence future management and planning activities.

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