Future Impacts of Sea Level Rise on Coastal Wetland Ecosystems: An Overview

Luke Maier

Research Assistant, Nicholas School of the Environment, Duke University
Research Intern, Marine Policy Institute, Mote Marine Laboratory

Abstract: Climate-driven sea level rise (SLR) will affect wetland flora and fauna in various—mostly negative—ways. While ample reviews and case studies examine the geomorphic and species-specific *impacts* of SLR on wetlands, to date, there seems to be no cohesive overview of how SLR will drive *adaptive responses* among coastal wetland species. By examining the research on relatively well-studied species, this technical overview for coastal planners aims to distill themes in how wetland flora and fauna will be impacted by and respond to future SLR. Wetland vegetation will likely respond by vertically or horizontally tracking niche optimums (mainly elevation and salinity), though some flora populations (especially coastal trees) will be less mobile and more likely to substantially decline by 2100. Wetland vertebrates and macrofauna will be more physically able to retreat or shift ranges to cope with SLR. However, compounding influences from habitat loss will contribute to declines in these fauna populations, especially on islands. Current research offers few conclusions about the responses of invertebrates and microfauna. Overall, SLR-induced changes in coastal wetlands will lower biodiversity and productivity in these ecologically and economically significant ecosystems.

Introduction

Coastal wetlands have ubiquitously influenced human and natural history (Maltby and Barker 2009). Future climate-related sea level rise (SLR) will change shoreline boundaries (IPCC 2013), groundwater salinity, saturation level, tidal flat coverage, and other coastal conditions that will affect wetland-dependent species (for overview, see Blankespoor and others 2012; Nicholls and others 2007). For thousands of years, sea levels have fluctuated (Donoghue 2011), generally rising since the last ice age ended 18,000 years ago. Climate change models predict that the earth will warm between 1.1-6.4 degrees Celsius by 2100 (NRC 2011; IPCC 2013), and the warming trend will likely last several hundred years (Canadell and others 2007; Eby and others 2009; Gleckler and others 2012; Mikolajewicz and others 2007). This will cause ocean water to expand and land-ice to melt and increase the global volume of ocean water. Although projections of future SLR vary (see Figure 1 in Appendix), the most comprehensive research available (IPCC 2013) predicts future global warming will induce a global average of .26-.97 m of SLR by 2100 (See Figure 1). The level of rise (Mitrovica and others 2009) and types and severity of resultant impacts (IPCC 2013; NRC 2011, p. 169) will vary among coastal regions and ecosystems.

Future SLR particularly threatens coastal wetlands (hereafter, 'wetlands'), because, by definition, these ecosystems occupy low-lying, semi-saturated areas between median low-tide line and maximum king-tide line (Blankespoor and others 2012; EPA n.d.). Even small changes in sea level can induce significant changes in wetlands' soil saturation balance, aquatic extent, and salinity levels (McKee and others 2012). Depending on future human development, SLR will likely destroy between 20-70% of the world's wetland habitats by 2080 (Nicholls 2004). This destruction would

dramatically diminish wetland ecoservices to coastal communities such as natural shoreline protection and biomass deposition (Craft and others 2008).

Coastal wetland flora and fauna species (hereafter, 'wetland species') will respond to SLR in various ways. Overall, SLR rates will outpace evolutionary adaptation capacity of most plants (Colautti and others 2010; Kirwan and others 2010) and animal species (e.g., see discussion in Pearlstine and others 2010). However, some studies have observed evolution could be the adaptation response of some amphibians (Kearner and others 2012), brackish water fish (Purcell and others 2008), and decadal-generative herbaceous plants (Davis and others 2005). Noting most wetland species cannot adapt to future SLR by evolving, how will they adapt?

Researchers have studied this question through empirical case studies (e.g., see Geselbracht and others 2011, Donnelly and Bertness 2001, Williams and others 1999) or predictive modeling (e.g., see Nicholls 2004, Menon and others 2010, Purcell and others 2008, Baker and others 2006). Most case studies have examined the effect of SLR on a particular keystone species or exemplary species, whose responses to SLR affect or resemble the responses of other species. Additionally, several scientific literatures on the effects of SLR on wetlands exist (Blankespoor and others 2012; FitzGerald and others 2008; Park and others 1989). This paper aims to overview this body of research for coastal policymaking and planning initiatives by distilling broad themes in the types of changes SLR will induce in wetland species populations. Although SLR impacts vary regionally and local-level adaptation is needed most (Gregg and others 2011), understanding general trends in SLR impacts can serve as a starting point for coastal communities to assess their local impacts and adaptation needs (Lausche and Maier forthcoming 2013) . The next two sections present, organize, and compare research on the impacts of SLR on 1) wetland flora and 2) wetland fauna. Each section focuses on *a*) how SLR will change conditions that affect wetland species' population success and *b*) how species will respond to these changes. The conclusion compares the research on flora and fauna and identifies relevant topics needing research.
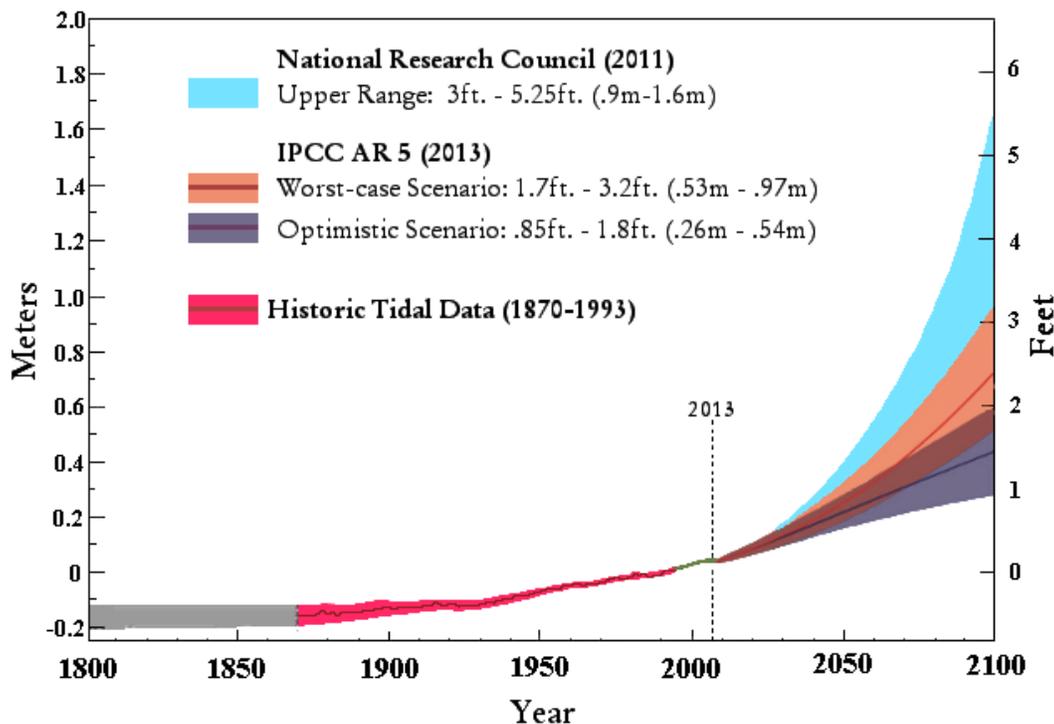

Figure 1: Future SLR Projections of the NRC and IPCC. Source: Lausche and Maier (forthcoming 2013) adapted from IPCC 2013 and others.

Flora

Vegetation constitutes the foundation of most wetland habitat structures (EPA n.d.) and food chains (Valiela and others 2004). As the EPA's *Wetlands: A World in Our Backyard* describes, trees, mangroves, and scrubs provide sediment stability for smaller vegetation, and they provide niches for many fauna species. Generally, mangroves and salt marshes occupy, respectively the seaward and inland margins of wetlands (EPA n.d.). Trees can be distributed randomly or in non-marginal, usually late-succession flats such as swamps. Fluvial discharge or precipitation runoff give wetlands most of their freshwater, and sea-water intrusion determines flora's salinity optimums (which affects nutrient and water uptake). SLR will cause optimum saline conditions to shift inland. In addition, most wetland flora species have elevation optimums, which is the depth at which the plants balance root saturation and foliage aeration. Elevation optimums will also shift inland unless sedimentation enables vertical migration.

Wetland flora species will likely track these optima via vertical or horizontal range shifts or extinction. The type of response a species expresses will largely rely on availability of migration corridors—physical routes through which species can shift habitats over time.

Horizontal Migration

Access to new ranges and tracking of salinity and elevation optimums will likely cause both the seaward and landward margins of flora's ranges to shift inland. SLR already caused horizontal migration in wetlands in areas such as the Ten Thousand Island Region, FL, (Krauss and others 2011) and northern coasts of Australia (Rogers and others 2012). Gilman and others (2007) found some relatively mobile flora species (mangroves) migrated inland 12-37 times faster than SLR rates, which suggests other SLR-altered factors (such as storm surge strength) can compound migration driven by optimum tracking. Moreover, Krauss and others (2011) and Rogers and others (2012) similarly observed mangroves' landward margins migrated inland faster than their seaward margins did (though both moved inland), resulting in overall range expansion and net horizontal migration. Both studies concluded that SLR-induced saltwater intrusion could enable saltwater-preferring vegetation to expand ranges inland in relatively flat areas.

Horizontal migration and inland range expansions of seaward species correlate to population decline in high ground vegetation. There are two drivers of this. First, introduction of seaward populations to previously high ground areas increases competition for nutrients and habitat space. This driver especially threatens endangered species (Levy 2004). For example, empirical studies on Florida's Sugarloaf Key demonstrated SLR-induced intrusions of mangroves caused population decline of high ground endemic pines (Ross and others 2008). Second, SLR raises salinity of high ground areas, which can exogenously decrease their resident populations. For example, based on 2500 years of macrofossil data, Donnelly and Bertness (2001) found that SLR brought increasingly saline conditions (both perennial and flooding-related) to high ground areas, which independently caused high ground vegetation population to decline. This, they conclude, opened new habitat space for cordgrasses. If unchanged, current rates of rise would allow seaward species to continue to replace high ground species (Donnelly and Bertness 2001). However, if SLR accelerate, then both cordgrasses and high ground species will drown.

The inland shift of cordgrasses provides an important example of the broader vulnerabilities SLR poses to high ground species and ecosystem productivity in wetlands. Overall floral biodiversity (Waide and others 1999) and high ground species in particular (Walker and others 1981) contribute significantly to biomass production. Pioneer wetland vegetation such as cordgrasses contribute relatively little to biomass production (Donnelly and Bertness 2001), and thus replacement of high ground species with less productive pioneer species will likely lower overall biomass production.

Vertical Migration

Some wetland flora species will respond to SLR by migrating *vertically*. Vertical migration entails topographically heightening the mean elevation of a population without geographically shifting ranges. Generally, this is possible if sedimentation or peat formation elevates the floor of a range's water or saturation columns at a rate commensurate with the SLR rate. Sedimentation is moderated by several feedback loops which are affected by abundance of water-suspended microbes (which deposit detrital material), clastic deposition, and hydrologic factors such as current speed (Morris and others 2002). Case studies on sedimentation and vertical adaptability of Caribbean mangroves found that globally typical sedimentation rates (as present in the Caribbean) do not allow laterally immobile mangrove populations to tolerate present rates of rise (McKee and others 2007). Studies on the Mississippi Delta Plain (which currently experiences a relative SLR rate similar to future global average rates) corroborate this. Day and others (2007) found elevation declines in this region
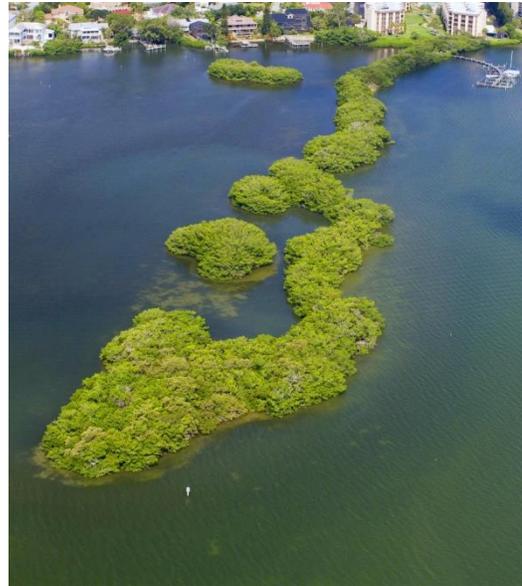

Figure 2: Florida Mangroves being inundated in King Tide event commensurate with level of rise experienced by 2050. Photo Credit: Sarasota Bay Estuary Program's King Tide Photo Competition Archive.

caused wetland populations to fall, which exacerbated Hurricane Katrina's storm surge and damage to human coastal communities.

Two major feedback loops mediate vertical adaptability and vegetation abundance. First, microbes rely on oxygen released by the roots of wetland plants (Cronk and Fennessy 2001). Decreases in vegetation abundance can cause suspended elevation-contributing microbe populations to decrease, which suggests SLR-induced decreases in vegetation abundance can accelerate loss of elevation. Confirming this, Morris and others (2002) experimentally found that salt marshes in elevations *above* the optimal elevation for primary productivity will be able to cope with SLR up to 3x current rates. This is because SLR in these areas will move optimal elevation for primary productivity closer to these marshes' oxygen output (the plant roots), which has no limiting effect on microbe abundance. However, Morris and others (2002) note that evidence suggests that by the end of the century, SLR will exceed the maximum tolerable rate, causing microbe ranges to move farther away from their oxygen source. This would leading to the drowning illustrated in Figure 2.

Second, rotting vegetation directly contributes to peat formation. McKee and others (2007) experimentally found mangroves critically contribute to coastal peat formation—a basal determinant of capacity for upward elevation shifts—in coastal ecosystems by providing root structures to catch sediment and decomposed mangrove materials. This finding suggests losses of mangroves or similar structural wetland vegetation can accelerate decreases in elevation adaptability.

In addition, Craft and others (2008) suggest that some degree of vertical migration capacity is necessary for vegetation to migrate horizontally. Overall, researchers believe a preponderance of variables influence and loop feedback to vertical adaptation capacity (for review, see McKee and others 2012). More research will need to be done to increase understanding of the viability of vertical adaptation as a response to SLR.

Population Collapse

Some wetland vegetation types, especially coastal forests, have little ability to migrate horizontally or vertically. Populations can have low migration potential if they have confined ranges (such as the mangroves in Figure 2) or slow reproductive cycles. In the northern Gulf of Mexico, marsh area declined on both seaward and inland margins due to SLR and anthropogenic land-use change, respectively (Shirley and Battaglia 2006). Some vegetation populations with theoretically high migration potential, such as mangrove forests in Thailand's superdelta, failed to migrate without explanation (Saito and others 2007), suggesting all explanatory variables for flora migration capacity have not been described. Other than these two studies, most research on wetland species with low migration capacity centers on coastal trees.

Williams and others (1999) found SLR-related flooding severely hindered coastal forest replacement in microtidal wetlands in western Florida. They traced the hindrance to increases in groundwater salinity, which killed or stunted young saplings. Williams and others (1999) also found increases in tidal flat area (interstitial area between mean high and low tide lines) correlated to SLR, which increased day-to-day variability in salt exposure and soil saturation. Saha and others (2011) empirically found this variability in groundwater salinity affected abundance of rare coastal trees from 1999-2009 in Florida. Following up their 1999 study, Williams and others (2003) found that SLR will affect coastal forest persistence even before other climate change impacts, such as increased storm severity and rainfall variability. However, in contrast, (Saha and others 2011) find drought effects will predate inundation effects on at least some tree species (particularly hammocks). Moreover, Desantis and others (2007) found droughts interactively exacerbate impacts on coastal forests.

Modeling forecasts that 1m SLR will destroy the vast majority (83% in Florida's case) of coastal forests in shallow-slop wetlands, and expanded tidal flats in low-slope topographies can cause migration of *inland* forests due to ground water salination and crowding out resulting from coastal vegetation's inland intrusions (Geselbracht and others 2011). Supporting the forecasts of Saha and others (2011), Geselbracht and others (2011) found that SLR damaged tree species richness in all of their Floridian studies areas. Because coastal forests tend to be populated by late succession species, losses in forest species richness can damage overall ecosystem productivity (Geselbracht and others 2011). However, some research indicates peat-formation provided by high-density mangroves can help forests and other slow-migrating species adapt (Kumara and others 2010).

Fauna

Because Nature abhors voids, fauna are distributed throughout wetland habitats. The literature on SLR-induced impacts on wetland fauna populations is not as developed as that on wetland flora; it focuses on macrofauna and vertebrates, and thus research related to these populations will be the focus here. Case studies on specific species, particularly endangered species, predominate extant literature (e.g., see Baker and others 2006, LaFever and others 2007, and Schmidt and others 2012). Emerging patters in findings suggest SLR will pose two main threats to wetland faunal species: increasing frequency of episodic flooding and accelerating perennial inundation. These drivers can act independently or exogenously.

Worsening Episodic Flooding

Worsening episodic flooding will likely affect wetland fauna by causing catastrophic erosion events and flood areas important to reproduction. Catastrophic erosion events particularly threaten to alter terrestrial migration routes (like seen in Figure 3) and destroy low-lying areas important to species for habitation and reproduction. For example, episodic floods can destroy low- lying nests built by saltmarsh sparrows (Bayard and Elphick 2011) and dune nests built by turtles (Fish and others 2005; Fuentes and others 2010). In addition to episodic habitat disturbance, perennial in-

undation from SLR will result in faunal habitat loss through coastal erosion, vegetation loss, and changing salinity conditions. Habitat loss will occur among aquatic, low-lying, and avian wetland fauna (Nicholls and others 2007).

Modeling predicts estuarine or deltaic wetland fish will lose freshwater or brackish water habitat due to heightening salinity; this could induce marine-favoring selection within species (Purcell and others 2008). In some areas (especially deltas), SLR can introduce ponds in the middle of marshes (Shirley and Battaglia 2006).

Perennial Saturation and Erosion

Moreover, SLR brings about perennial saturation and erosion. Because SLR could dramatically increase perennial habitat saturation and expand tidal flat coverage, low-lying species—such as marsh rabbits (LaFever and others 2007)—will likely experience acute habitat loss. As a portending example, 20th century SLR already destroyed 48% of the Florida marsh rabbit's habitat (Schmidt and others 2012). SLR-induced habitat destruction even threatens non-low-lying mobile species, especially those that live on islands and cannot swim such as Florida's Key deer (Maschinski and others 2011).

Though paradigmatic occupants of the sky, coastal bird species will also experience SLR-related habitat loss. Hughes (2004) found that SLR will negatively affect breeding, nesting, and hunting grounds in wetland bird species, which lowers carrying capacity. Hughes (2004) notes that although habitat loss will inflict significant damage, losses of carrying capacity among coastal birds will primarily result from losses of food resources. Though not wetland species, dune-reliant birds experience similar habitat losses. In the case of Florida's endangered Snowy Plovers, which build their seashell-lined nests on dune sandlines, SLR-induced reductions in carrying capacity will exceed rates of habitat land loss due to compounding effects of decreasing food resources (Aiello-Lammens and others 2011). Moreover, losses of wetlands can also affect migratory birds that use wetlands as seasonal resting grounds (Galbraith and others 2002).

Island fauna will be most vulnerable to terrestrial habitat loss, because island habitats often offer limited or non-existent inter- or intra-island retreat options (Wetzel and others 2013). Shoreline modeling of the Northwestern Hawaiian Islands (notable for their flat topography) predicts habitat losses will vary significantly from location to location, but overall terrestrial habitat loss will be dramatic (Baker and others 2006). Habitat losses among island species will cause much of the biodiversity loss associated with SRL (Menon and others 2010). Despite the overall habitat losses associated with SLR, there is limited evidence that some species populations (such as mangrove-dwelling mice) could benefit from SLR-induced range expansions among vegetation such as mangroves (Traill and others 2011).
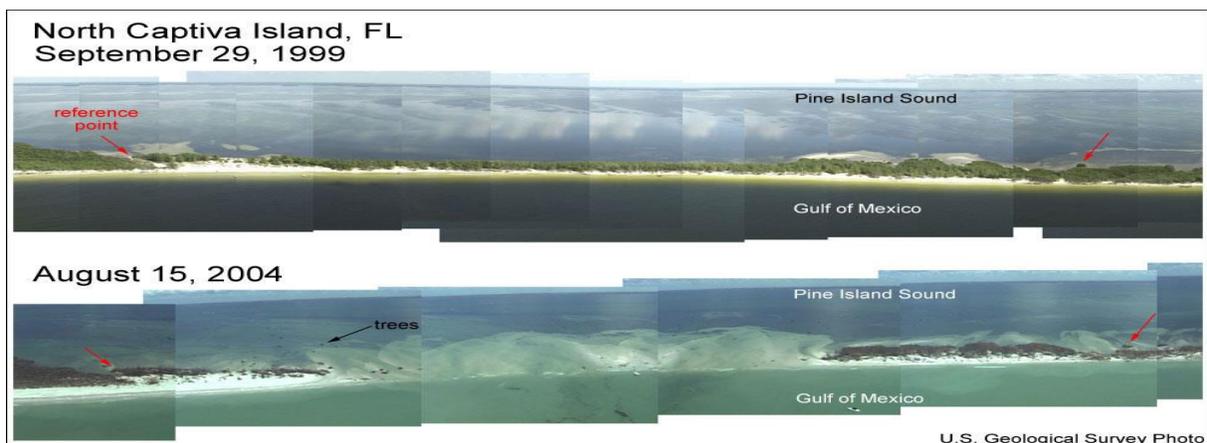

Figure 3: Disconnecting of North Captiva barrier island caused by Hurricane Charley in August 2004. Photo credit: USGS.

While research on the probable adaptation responses of wetland fauna is limited, wetland fauna could cope with SLR-associated habitat loss by shifting ranges inland or shifting habitats altogether where possible. However, future erosion of key island features (such as that seen in Figure 3) could destroy key habitat connectivity and possible migration corridors.

Conclusion

SLR will induce manly negative changes in coastal wetland species. Wetland flora and macrofauna will both experience shifts or losses of habitat; biodiversity in wetlands will diminish. For vegetation, changing salinity and elevation optimums constitute the main risks and drivers of adaptation. Relatively mobile flora such as mangroves or saltmarsh grasses will adapt by migrating vertically and/or horizontally, but some flora will be unable to adaptively migrate due to slow reproductive cycles or physical habitat constraints. Like flora, wetland fauna will also face habitat losses, and non-resident fauna (such as migratory birds and sea turtles) could also be affected by loss of wetland area. Because vegetation (such as mangrove forests) provide keystone ecosystem functions (such as habitat structure and primary production), population declines in vegetation will exacerbate stresses on wetland fauna populations. The research on fauna's future adaptation needs and responses is scarce and vertebrae-centric, but, like flora, fauna will probably need opportunities to retreat or shift habitats to avoid population decline. Wetland species with low migration capacity (especially coastal trees and island species) will likely experience significant population decline.

Extant research is insightful, but the literature has notable gaps. Research on the feedback loops affecting SLR-induced impacts and adaptation is thus far inconclusive and deserves further efforts, as does the literature on the impact of SLR on invertebrates and intertidal fauna. Moreover, few research outputs relate or compare SLR impacts on wetlands to intra- and inter-ecosystem linkages and other effects of climate change, such as changes in atmospheric carbon dioxide and increased surface temperatures.

SLR and its threats to coastal wetland species resulted from past human decisions. Future human actions can affect the resilience of coastal wetlands to SLR and other climate threats. The vitality of coastal wetlands will strongly influence the future economies, cultures, and lifestyles of coastal societies (Craft and others 2008; Maltby and Barker 2009). Understanding SLR impacts on wetlands, realizing wetlands' benefits to coastal communities, and using long-term decision-making must provide the bulwark to defending the valuable nexus between coastal societies and the world's coastal wetland species.
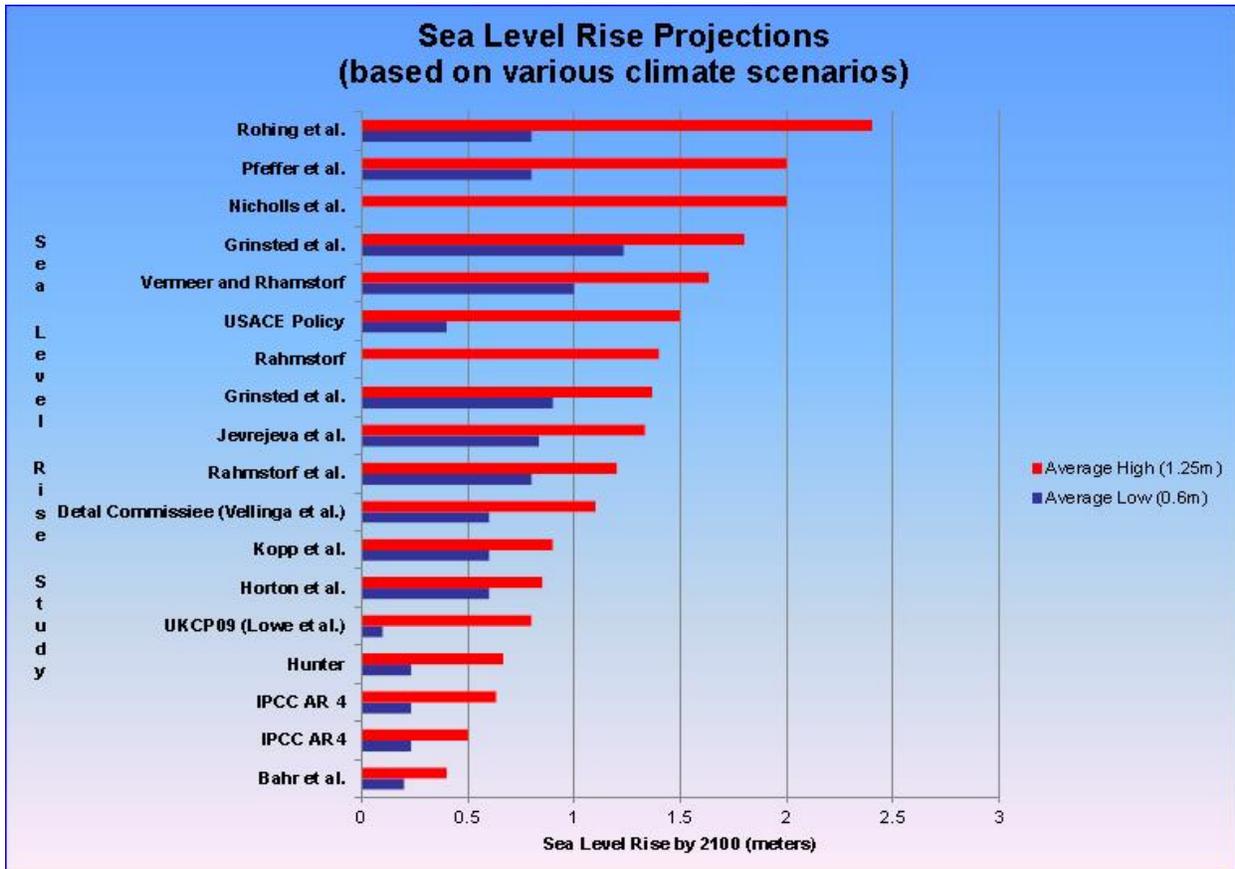
Appendix:

Figure 4: Various projections of future SLR. Source: Maucy, Doug. 2012. "Mapping and Visualizing Sea Level Rise and Coastal Flooding Impacts." Webinar Presentation. NOAA Coastal Services Center.

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