AGU PUBLICATIONS

Earth's Future

RESEARCH ARTICLE

10.1002/2016EF000384

Suspended sediment projections in Apalachicola Bay in response to altered river flow and sediment loads under climate change and sea level rise

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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:

- Sediments loads under SLR are obtained by downscaled global climate modeling.
- TSS variations are investigated by coupled hydrodynamic and sediment transport modeling.
- Simulations indicate that SLR yields a substantial decrease in TSS in two oyster reefs.

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Citation:
Huang, W., S. C. Hagen, D. Wang, P. A. Hovenga, F. Teng, and J. F. Weishampel (2016), Suspended sediment projections in Apalachicola Bay in response to altered river flow and sediment loads under climate change and sea level rise, *Earth's Future*, *4*, 428–439, doi:10.1002/2016EF000384.

Received 28 MAY 2016
Accepted 28 SEP 2016
Accepted article online 3 OCT 2016
Published online 25 OCT 2016

Abstract Suspended sediments, or total suspended solids (TSS), are an important factor for oyster habitat. While high concentrations of suspended sediments can cause a reduction of oyster density, some level of suspended sediment is required to supply oysters with necessary nutrients. In this study, characteristics of TSS variations in response to sea level rise (SLR) at two oyster reefs in Apalachicola Bay are investigated by coupled estuarine hydrodynamic and sediment transport modeling. A storm event in 1993 and a year-long period in 2010 under recent sea level conditions are selected as the baseline conditions. Scenarios of river flow and sediment loads under SLR and climate change are obtained by downscaled global climate modeling. Compared to the baseline conditions, simulations of TSS indicate that predicted SLR yields a substantial decrease in TSS near the two oyster reefs. However, TSS levels differed at the two study locations. TSS changes by SLR revealed minimal impact on oyster habitat at the Dry Bar site (to the west of the mouth of the Apalachicola River) but are projected to have a significant impact at the Cat Point site (to the east of the Apalachicola River). At Cat Point, because SLR causes the increase of salt water intrusion from the Gulf through a large tidal inlet (East Pass), maximum sediment concentration is near zero for 0.2-m SLR and equal to zero for 0.5- and 1.2-m SLR. Therefore, SLR may result in a substantial loss of nutrients from suspended sediment in the oyster reef at Cat Point.

1. Introduction

Apalachicola Bay is a highly productive estuarine system that supported an economically important recreational and, up until recently, commercial fishery. Apalachicola Bay oysters historically comprised about 90% of Florida's annual oyster landings and 10% of the catch nationwide [*Wilber*, 1992; *Livingston et al.*, 2000]. This oyster fishery is an icon of Florida, and many jobs are dependent on the oyster industry. Oysters are sensitive to changes in the salinity and other environmental parameters. The growth, reproduction, and survival of oysters are influenced by multiple factors, including water circulation, salinity, temperature, food availability, sedimentation, benthic substrate, predation, disease, and pollution [*Livingston et al.*, 2000; *Wang et al.*, 2008]. Cat Point and Dry Bar are the two most productive oyster beds in Apalachicola Bay [*Wilber*, 1992; *Livingston et al.*, 2000].

1.1. Eastern Oyster—Indicator for Estuarine Ecosystem Health

The eastern oyster, *Crassostrea virginica*, has been widely used as the key indicator for ecological health evaluations in estuaries in the northern Gulf of Mexico and Florida waters [*Livingston et al.*, 2000; *Powell et al.*, 2003]. Examples include *Christensen et al.* [1998] and *Livingston et al.* [2000] for Apalachicola Bay and *Powell et al.* [2003] for Galveston Bay in Texas. Individual oysters filter water, removing phytoplankton, particulate organic carbon, sediments, pollutants, and microorganisms from the water column [*Newell and Langdon*, 1996]. This filtration results in greater light penetration in water, promoting the growth of submerged aquatic vegetation. Although oysters assimilate most of the organic matter that they filter, they deposit the remainder on the bottom, providing food for benthic organisms. Furthermore, the oyster's ability to form large reef structures qualifies it as a keystone species [*Coen et al.*, 1999]. The oysters' complex, three-dimensional reef habitat attracts numerous species of invertebrates and fish [*Meyer*, 1994]. To date, many species have been identified as depending, either directly or indirectly, on oyster reefs [*Tolley et al.*, 2006]. Many of these organisms are prey items for commercially important fish species [*McMichael and Peters*, 1989]. Effects of sea level rise (SLR) on estuarine salinity have been conducted by many researchers [*Hong and Shen*, 2012; *Rice et al.*, 2012; *Liu and Liu*, 2014; *Yang et al.*, 2015]. *Huang et al.* [2015] conducted the study of SLR effects on salinity in Apalachicola Bay. This study presents the continuing research of SLR effects on suspended sediment transport and the resulting influences on oysters in the Apalachicola estuary.

1.2. Suspended Sediment—Important Factor for Oyster Reef Habitat

Sediment increases in the water column caused by high energy tides can smother oyster larvae, as well as disturb the filter feeding process of oysters, affecting their growth and development [*Chew*, 2002]. Higher levels of suspended sediments could reduce the pumping rate in oysters. Excessive sedimentation may also reduce oyster recruitment as oyster settlement is higher on shells with less siltation. Contaminants and nutrients carried by excessive sediment is an important stressor on oyster habitat. *Volety and Encomio*'s [2006] study indicated that sedimentation and resuspension is an important factor for restoring oyster reef habitat in the Charlotte Harbor estuary, Florida. The oyster population modeling study for Apalachicola Bay by *Wang et al.* [2008] indicates that sediment concentration affects oyster growth. *Wilber and Clarke* [2001] integrated findings from biological and engineering studies to assess the effects of increased concentrations of suspended sediment caused by human activities, such as navigation dredging, on estuarine fish and shellfish. Much of the available data come from bioassays that measured acute responses and required high concentrations of suspended sediments to induce the measured response, usually mortality. The review by *Cake* [1983] shows that insufficient currents permit adverse sedimentation that may bury oysters, and normal accumulation of riverborne sediments in the Matagorda Bay, Texas destroyed 2430–2835 ha (6000–7000 acres) of oyster reefs between 1926 and 1962. Sediment transport can affect coastal morphology, which may influence the formation of the oyster reefs [*Twichell et al.*, 2006, 2010; *Biria et al*., 2015] (Figure 1).

Gonda-King et al. [2010] examined the effect of sedimentation, a significant anthropogenic impact in the Chesapeake, on the growth of juvenile *Crassostrea virginica*. Increased volume of storm water runoff at higher flow from a watershed can cause excessive erosion and sediment loads to the estuary. In general, global climate change can also affect the sediment loads to the estuary because of extreme rainfalls. Research based on oysters in Virginia by *Thomsen and McGlathery* [2006] showed that species abundance

Figure 1. Oyster reefs, Dry Bar and Cat Point, in Apalachicola Bay, Florida.

was impaired by stressful, high-sediment conditions. High-sediment loads can trigger oysters to close and stop filtering. Suspended sediment loads composed of a large proportion of inorganic matter may be detrimental to the growth of *C. virginica* by overwhelming the oyster and preventing growth [*Coco et al.*, 2006]. Oyster spat (immature bivalve) and larvae are more sensitive to suspended sediments than adults [*Davis and Hidu*, 1969; *Saoud and Rouse*, 2000; *Soletchnik et al.*, 2007]. Substrate degradation caused by boring sponges and sedimentation may reduce the availability of clean substrate (generally oyster shell) for oyster settlement. Oysters filter and assimilate organic matter from the water column and deposit the remaining portions on bottom sediments. High and persistent levels of sediment may cause permanent changes in oyster reef community structure [*Cairns*, 1990], which includes diversity, density, biomass, growth, and rates of reproduction and mortality as well as altering local food webs. In addition to sedimentation, oyster reef communities are negatively impacted by excess nutrients in sediments from watershed runoff, which promotes algae growth and increases turbidity. Resulting algal blooms not only deplete oxygen available for organisms such as oysters and fish but also limit needed sunlight for other vegetative species surrounding the growing oyster reefs [*Cheney et al.*, 2001].

Some studies also suggest that intermediate rates of sedimentation and the possibility of a combination of water-quality factors yield the highest growth rates. Some sediment is likely necessary for spat growth, but excessive levels may inhibit growth. Sediment loads have been shown to carry nutrients that stimulate the growth of phytoplankton as foods for oysters [*Fritz et al.*, 1984; *Crain*, 2001; *Rasmussen et al.*, 2008; *Blomberg et al.*, 2015]. *Coco et al.* [2006] observed that extremely low levels of sedimentation eliminate growth in the pinnid bivalve *Atrina zelandica* in much the same way as high rates of sedimentation, possibly due to the low level of nutrients associated with the low level of sediments. The highest growth and the highest mortality rates are seen at sites with intermediate rates of sedimentation.

1.3. Watershed Runoff and Sediment Loading: Major Source for Estuarine Sediment

Runoff from industrial or agricultural sources often seeps into and is absorbed by sediments. Finer sediments, however, tend to have higher pollutant concentrations because they are not as porous as coarser sediments, so they retain pollutants longer. Oysters exposed to polluted sediments can experience a deterioration of function, leading to health issues. Heavy metals that seep into the sediment may cause stress that reduces an oyster's ability to resist diseases and parasites, causing mortality of embryos and larvae and reducing larvae and spat growth as well as spat settling. *Corbett et al.* [2006] conducted a study of sediment loading effects on oysters in the Caloosahatchee Estuary, which receives periodic freshwater releases from Lake Okeechobee. These releases are regulated by the opening and closing of weirs upstream, where lands are subject to agricultural practices and pesticide and heavy metal usage. Pesticides and heavy metals are bound to the organic matter around sediment particles and are carried downstream with massive freshwater releases. Due to their filter feeding nature, clams and oysters are exposed to high-sediment concentrations and/or contaminant loads associated with the sediments. Future climate change and SLR may cause changes in rainfall runoff and sediment loading from the Apalachicola River watershed and hydrodynamics within Apalachicola Bay [*Chen et al.*, 2014; *Bilskie et al.*, 2016; *Hovenga et al.*, 2016], which could affect oyster ecology in the bay.

In this study, the effects of sediment loads from Apalachicola watershed on suspended sediment concentration in two oyster reefs (Figure 1), Cat Point and Dry Bar, under different SLR scenarios are characterized by numerical simulations. River flow and sediment loads for corresponding SLR conditions are derived from a downscaled climate and watershed hydrological modeling study by *Chen et al.* [2014] and *Hovenga et al.* [2016]. A storm event in 1993 and a year-long period in 2010 under existing sea level conditions are selected as the baseline conditions. By changing only SLR conditions and keeping the same model parameters, estuarine hydrodynamic and sediment transport modeling simulations are conducted to characterize the changes of sediment concentration in oyster reefs by comparing results from SLR scenarios to those under the baseline conditions.

2. Sediment Loading and Flow Under SLR Scenarios

Projected daily streamflow and sediment load used for this study were provided by *Chen et al.* [2014] and *Hovenga et al.* [2016], in which the Soil Water Assessment Tool was used to model hydrological processes within the Apalachicola River region under future conditions. Future conditions incorporated both climate and land-use-land-cover (LULC) change for 2100 that corresponded to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) scenarios A2, A1B, and B1. The SRES scenarios represent equipotential future carbon emissions that are driven by social, environmental, technological, demographic, and economic factors [*Intergovernmental Panel on Climate Change*, 2000]. Climate change was modeled using stochastically downscaled temperature and rainfall data from three general circulation models (HADCM3, IPCM4, and MPEH5) used in the IPCC Fourth Assessment Report (AR4) [*Intergovernmental Panel on Climate Change*, 2007; *Semenov and Stratonovitch*, 2010]. LULC change data were provided by the *United State Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center* [2014]. SLR scenarios by *National Oceanic and Atmospheric Administration* [2012] were used for this study.

The streamflow and sediment loading inputs used in this study were simulated at the mouth of the river, prior to being discharged into Apalachicola Bay. The annual averages and Cumulative Distribution Function (CDF) of the 2100 discharges were utilized to select the datasets used in the future SLR assessments. Among the SRES scenarios, a significant distinction was not observed. The A1B scenario was ultimately chosen due to its middle ground for future carbon emission; CO_2 emissions (gigatonnes carbon) for A2, A1B, and B1 scenarios for the region are 6.91, 2.25, and 0.99, respectively [*IPCC*, 2000]. The A1B narrative storyline describes a world with rapid economic growth, population that increases until the mid-century and then declines by 2100, and growth of efficient technology with balance between supply sources [*IPCC*, 2000]. Between the general circulation model outputs, HADCM3 was selected due to its mean and standard deviation falling between those of IPCM4 and MPEH5. In general, future monthly streamflow was predicted to have higher high flows and lower low flows, and future sediment loading followed a similar pattern [*Hovenga et al.*, 2016].

Grain-size data for suspended sediment in Apalachicola River are not available. Therefore, for the assessment of SLR effects, grain size was selected from the literature. *Walling et al.* [2000] reported that more than 95% of the suspended sediment load was <0.063 mm (i.e., silt- and clay-sized material) in their study from two rivers in UK. The study by *Blanchard et al.* [2011] indicates that more than 90% of the measured suspended sediment was composed of fine-grained particles less than 0.063 mm in their study of two rivers in the United States, which is quite similar to the finding for UK rivers by Walling et al.. Therefore, a grain size under 0.063 mm can be approximately considered for suspended sediment transported from general rivers to estuaries because larger or heavier grains are mostly deposited in riverbeds as bed loads. *Twichell et al.* [2010] conducted a study of geological evolution and sediment grain distribution in Apalachicola Bay by collecting and analyzing bathymetric data, side-scan-sonar imagery, high-resolution seismic profiles, and sediment cores. Results indicate that bed materials in the bay consist of muddy sand and mud with different grain sizes across the bay. The majority area of the bay floor is covered by mud delivered by the Apalachicola River. In general, mean grain sizes of mud in the majority areas of the bay (including oyster reefs) are approximately between 4 phi (0.063 mm) and 6 phi (0.035 mm), with the averaged mean grain size about 0.05 mm. Considering that delta deposits in the estuary are the results of sediment transport from the river, the approximate averaged grain size in the bay [*Twichell et al.*, 2010], $d50 = 0.05$ mm, was selected as the baseline reference sediment condition for all SLR scenario simulations. Considering that the objective of this study is to characterize rather than to quantify the SLR effects on total suspended solids (TSS) under SLR scenarios, the selected constant of suspended sediment grain size for all simulation scenarios will provide a reasonable baseline condition to characterize the SLR impacts. Based on the chart given in *HEC-18* [2012], the corresponding falling velocity for sediment grain size of $d50 = 0.05$ mm is $w = 0.003$ m/s.

3. Description of Hydrodynamic and Sediment Transport Model

3.1. Hydrodynamic Model

The Princeton Ocean Model [POM, *Blumberg and Mellor*, 1987] was used for the application to Apalachicola Bay estuary. The model is a semi-implicit, finite-difference model that can be used to determine the temporal and spatial changes of surface elevation, salinity, temperature, and velocity in response to wind, tide, buoyancy, and Coriolis forces. The model solves a coupled system of differential, prognostic equations describing conservation of mass, momentum, heat, and salinity. The model incorporates a second-order turbulence closure submodel that provides eddy viscosity and diffusivity for the vertical mixing. This model has a track of successful applications in estuaries. The model is capable of simulating time-dependent hydrodynamics in estuaries under wind, river flow, and tidal forcing conditions. Details of model descriptions can be found in *Blumberg and Mellor* [1987].

The POM model has been previously calibrated and verified for tidal circulation and salinity in Apalachicola Bay [*Huang et al.*, 2002, 2014, 2015]. The model employs the curvilinear, orthogonal, horizontal grid system, with a minimum grid width of 100 m and a maximum grid size of approximately 900 m. In the vertical direction, five sigma layers were employed. In *Huang et al.* [2002], the model was calibrated for the period of June and verified for the period of July, using a dataset for 1993. Salinity conditions at the open boundary inlets to the Gulf of Mexico employ free flux in ebb flow and an approximately constant 34 ppt salinity (approximate average salinity in coastal ocean and the Gulf of Mexico) of during the flood tide. Results indicated satisfactory model predictions for surface elevation and salinity. Using a dataset located in the Apalachicola River mouth, *Huang* [2010] improved the turbulence submodel in the POM model for more accurate descriptions of the 3D stratifications near the river mouth. *Huang et al.* [2015] further validated the hydrodynamic model performance using the dataset for the period of June, 2006, confirming the satisfactory performance of the hydrodynamic model. The hydrodynamic model was applied to investigate SLR effects on salinity variation in the bay by *Huang et al.* [2015]. Results show the increasing westerly salinity intrusion from East Pass as the increase of SLR The oyster reef at Cat Point is found to be more sensitive to the SLR because it is located in the eastern part of the Bay as the result of salinity from East Pass.

3.2. Sediment Transport Model

The sediment module in the Environmental Fluid Dynamic Code (EFDC) by *Hamrick* [1996] has been popularly used in many estuarine model applications [*Hamrick*, 1996; *Ji et al.*, 2002; *Lin and Kuo*, 2003; *Yang and Hamrick*, 2003; *Liu and Huang*, 2009]. Considering that the POM and EFDC models employed similar numerical methods (e.g., mode splitting method for external model and internal mode), the sediment transport module in the EFDC model was used to build the sediment transport module coupled with the POM hydrodynamic model in our study. Water column transport is based on the same advection–diffusion scheme used for salinity and temperature. The sediment transport model is coupled with the hydrodynamic model with the same resolution. While details of sediment transport model have been described in *Hamrick* [1996], the sediment transport equation is given below:

$$\frac{\partial HC}{\partial t} + \frac{\partial HuC}{\partial x} + \frac{\partial HvC}{\partial y} + \frac{\partial (wC) - \partial \left(w_s C\right)}{\partial \sigma} = \frac{\partial}{\partial x}\left(A_H H \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H H \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial \sigma}\left(\frac{A_V}{H}\frac{\partial C}{\partial \sigma}\right) + Q_s + J_o \tag{1}$$

where is suspended sediment concentration in g/L; u, v, w are velocity in x, y, and z direction in m/s unit, respectively; w_s is settling velocity in m/s; A_H is the horizontal diffusivity determined by the Smagoringsky scheme in m^2/s; A_V is the vertical eddy diffusivity estimated by the Mellor-Yamada level 2.5 turbulence closure scheme in m^2/s; Q_s represents external sources and sinks; and J_o is net sediment flux (deposition flux + resuspension flux) from the bed water column, dependent on the bottom flow stress and sediment critical stress as described in *Hamrick* [1996] and *Liu and Huang* [2009]. Referring to *Ji et al.* [2002], critical stress for deposition was set to 0.03 N/m^2, and the critical stress for resuspension was 0.04 N/m^2 in this study.

When the terms of sources/sinks and net sediment flux, as well as falling velocity, are equal to zero, the sediment transport equation (Equation 1) reduces to the same equation of salinity and temperature with different boundary conditions. Because observed data for suspended sediment grain size for watershed loading and TSS concentration in the bay are not available for sediment model calibration, the sediment module was evaluated by simulating a conservative water-quality constituent with zero falling under the same boundary condition as salinity. Horizontal and vertical mixing coefficients are the same as those used in the calibrated hydrodynamic and salinity transport model. Results indicate that the sediment transport model can produce the same results as the salinity transport model under the same boundary condition without sediment source/sink and bottom flux. Therefore, the sediment transport module can provide reasonable predictions of TSS sediment transport in the bay if appropriate sediment properties are selected. Field observation studies by *Walling et al.* [2000] and *Blanchard et al.* [2011] show that general suspended sediment grain size in rivers is less than 0.062 mm (i.e., silt- and clay-sized material). Referring to the study of sediment grain distribution in Apalachicola Bay by *Twichell et al.* [2010] as described above, it is reasonable for us to select the approximately averaged grain of $d50 = 0.05$ mm for all scenario simulations to characterize the SLR impacts. Based on the HEC-18, the falling velocity corresponding to $d50 = 0.05$ mm is $w = 0.003$ m/s.

4. Characteristics of Suspended Sediment in Responses to Sea Level Rise

By comparing to the baseline conditions with the same model parameters, hydrodynamic and sediment transport modeling simulations were conducted to characterize the magnitude of suspended sediment changes in response to different SLR scenarios. Considering that the time series of suspended sediment data were not available, and the sediment module method was tested in many applications [e.g., *Hamrick*, 1996; *Ji et al.*, 2002; *Lin and Kuo*, 2003; *Yang and Hamrick*, 2003; *Liu and Huang*, 2009], only limit validations for the sediment transport module were conducted in this study. Under the special condition, if sediment falling velocity was equal to zero without bottom sediment flux, the sediment module equations were reduced to those of the conservative salinity transport module. Therefore, to evaluate the sediment transport module in the special case of a conservative constituent with zero falling velocity, the sediment module was tested by simulating salinity as a conservative water-quality constituent. Results indicate that the sediment transport module reproduced the same results as those from the calibrated salinity transport model [*Huang et al.*, 2015] when the sediment falling velocity was specified to zero with salinity boundary conditions. In addition, the further validation of the sediment transport module in modeling a storm event as given below indicates that the range of TSS from model simulation is very close to those from remote sensing of TSS by *Chen et al.* [2011].

Model scenario simulations were mainly intended to characterize the SLT-induced TSS changes rather than to quantify the actual values of suspended sediment at oyster reefs by comparing SLR scenarios to the baseline condition. Under the same settings of model parameters for all scenarios, different simulations were conducted by changing only the SLR conditions and the corresponding sediment loads as the results of climate changes. To simulate TSS transport in the bay, TSS concentrations in the river boundary were derived from sediment loads and flow and set to zero at all tidal boundaries. Salinity was specified as zero in river boundary and as constant 34 ppt in tidal boundaries.

4.1. Suspended Sediment Responses to a Storm-Induced Sediment Load Event

Hydrodynamic and sediment transport model simulations were conducted for different sea level conditions to assess the salinity and total suspended sediment response to river flow and sediment loading for an extreme event (Figures 2 and 3). By altering only the sea level condition for the different simulations, the results characterize the change of suspended sediment induced by changing sea levels. The simulation period covers 1 February 1991 – 20 March 1991, which includes a 25-year storm event over 24 h [*Chen et al.*, 2014]. The first 10 days were used as model spin-up to provide appropriate initial conditions for model simulations for the remaining period. Base water levels at tidal boundaries are derived from the National Oceanic and Atmospheric Administration (NOAA) tidal station at Apalachicola River by applying the neural network model [*Huang et al.*, 2003]. Tidal boundary conditions under different SLR conditions are derived by adding SLR to the base tidal boundary condition. Winds are specified as zero to serve as a baseline condition for the SLR study and because wind data are not available during the period of 1991. At river inflow boundaries, freshwater input in the Apalachicola River is specified by using USGS observations (Figure 2), salinity is equal to zero, and suspended sediment concentrations are specified by the suspended sediment concentrations derived from sediment loading divided by river flow (Figure 3).

Results of salinity responses at Cat Point and Dry Bar oyster reefs are shown in Figure 2, which depicts salinity variations in response to river inflow under different SLR conditions. At both stations, salinity drops in response to the increase of freshwater during the period of 32 – 45 days for all SLR conditions. In general, salinity increases in response to the increase of SLR. At Cat Point, salinity reaches the constant boundary salinity level when SLR is equal to or greater than 0.5 m, indicating the intrusion of saline gulf water into the Cat Point oyster reef region. At Dry Bar, which is closer in proximity to the Apalachicola River, salinity still varies in response to river flow and tides even when SLR is set to 1.2 m.

Results of TSS concentrations at two oyster reefs are given in Figure 3. At Dry Bar, mean suspended sediment concentration in the pre-storm period of 10 – 25 days is 15.6, 9.8, 4.9, and 3.5 mg/L, and the maximum concentration is 102.6, 79.8, 56.4, 56.4, and 48.0 mg/L under the SLR of 0.0, 0.2, 0.5, and 1.2 m scenarios, respectively. This shows that while SLR causes a substantial decrease of sediment concentration at Dry Bar, a low level of sediment concentration is still present even under the 1.2-m SLR condition. At Cat Point, mean suspended sediment concentration in the pre-storm period of 10 – 25 days is 12.2, 0.1, 0.0,

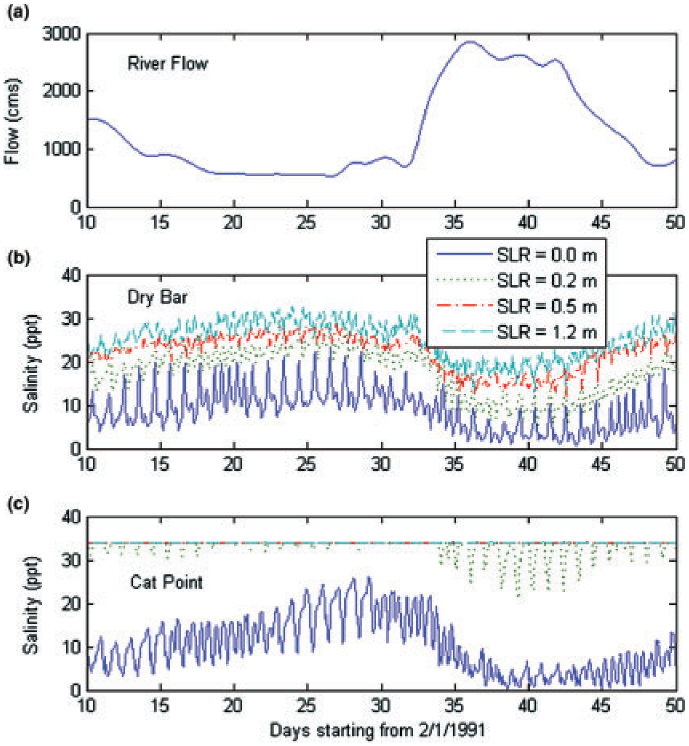

Figure 2. Salinity responses to sea level rise (SLR) scenarios during a storm-induced sediment load event in 1991.

and 0.0 mg/L, and the maximum concentration is 113.7, 2.3, 0.0, and 0.0 mg/L under the SLR of 0.0, 0.2, 0.5, and 1.2 m scenarios, respectively. This indicates that SLR causes a substantial decrease of maximum sediment concentration close to zero at Cat Point. In addition, the mean pre-storm sediment concentration is reduced from 12.2 mg/L to zero under an SLR of 0.5 and 1.2 m conditions, indicating significant impacts.

Chen et al. [2011] used remote sensing to map two snapshots of TSS in Apalachicola Bay for a rainstorm event: one before the storm and another 1 day after the storm. The remote sensing indicates that TSS near Dry Bar approximately ranges between 15 and 17 mg/L before the storm and about 90 mg/L 1 day after the storm. In our model simulation, mean TSS was about 15 mg/L before the storm and about 90–95 mg/L 1 day after the peak storm. Therefore, the range of the TSS variations from the model simulation under the baseline sea level condition is reasonably close to Chen et al.'s remote sensing TSS study.

4.2. Suspended Sediment Responses to Sediment Loading During a Year Period Under Different SLR Scenarios

Model simulations were conducted for the period of a year to examine suspended sediment responses at the two oyster reef locations under different SLR scenarios. River flow and sediment loading for circa 2000 were selected as the baseline conditions. Future river flow and sediment loading conditions correspond to 2100 and were derived from the HADCM3 global climate model. SLR scenarios projected for 2100 were selected from the *NOAA* [2012] report as shown in Table 1. Simulations from December of 1999 were used as the model spin-up period to produce appropriate initial salinity and currents for model simulations. Zero wind speed was used as a baseline wind condition because our focus is to investigate SLR effects, and wind data for 2000 were not available. Tidal boundaries were derived from the neural network model based on the NOAA tidal data observed in Apalachicola River. Under the same tidal and wind conditions, comparisons of model simulations between the SLR scenario and the base sea level condition were used to show the effects of SLR on suspended sediment at two oyster reefs. The TSS concentration from the river was specified by the sediment load divided by the river flow. Zero sediment concentration was specified as a reference at tidal boundaries.

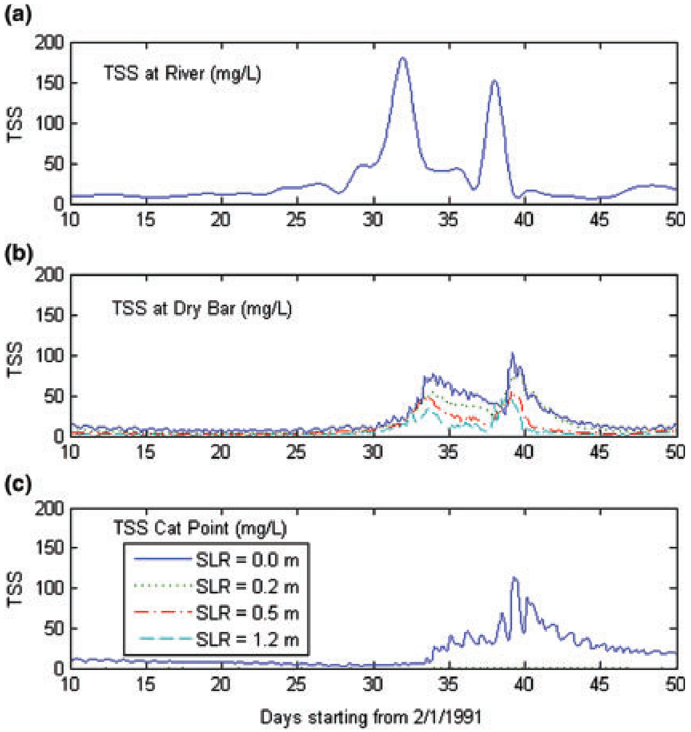

Figure 3. Total suspended solid (TSS) responses to sea level rise (SLR) scenarios during a storm-induced sediment load event in 1991.

Table 1. Sea Level Rise Scenarios and Corresponding River Flow and Sediment Loading

Scenarios*NOAA* [2012]	Existing	Lowest	Intermediate-Low	Intermediate-High
SLR by 2100 (m)	0.0 m	0.2 m	0.5 m	1.2 m
River flow, sediment loading	Baseline 2000	HADCM3	HADCM3	HADCM3

SLR, sea level rise.

4.2.1. Oyster Reef at Dry Bar

Figure 4 shows the time series of river flow and sediment load from the river and the resulting salinity and suspended sediment at Dry Bar. In general, high river flow and sediment loading occur in the spring season, which cause low salinity and high-suspended sediment concentration at Dry Bar. The peak of the suspended sediment concentration corresponds to the peak of river flow and sediment loading from the river. For the peak sediment loading near the end of January, the resulting suspended sediment concentration was about 79.1, 47.8, 32.8, and 29.2 mg/L under SLR scenarios of 0.0, 0.2, 0.5, and 1.2 m, respectively (Table 2). The increase of sea level led to the decrease of suspended sediment concentration at Dry Bar. This is mainly because SLR increases the water volume in the bay, which dilutes sediment loading. Low river flow and load sediment loads result in low sediment concentration. During August to December, river flow is generally low, and sediment loading is also low. As a result, suspended sediment concentration under the baseline condition generally varies from 10 to 20 mg/L, with the mean concentration of 14.7 mg/L. SLR causes some reduction of TSS, but a low level of concentration remains consistent (Table 3). The mean TSS concentrations are 10.4, 9.0, and 7.2 mg/L under SLR scenarios of 0.2, 0.5, and 1.2 m, respectively. This is due mainly to the westward currents induced by SLR [*Huang et al.*, 2015], which push the river discharge with higher TSS to the west of the Dry Bar.

4.2.2. Oyster Reef at Cat Point

At Cat Point, TSS also shows a matching response to river flow and sediment loading (Figure 5). Under the baseline conditions, TSS with two peaks of about 50 mg/L occurs during the end of January–March in response to the peaks of sediment loading from the river, and TSS with very low concentrations below

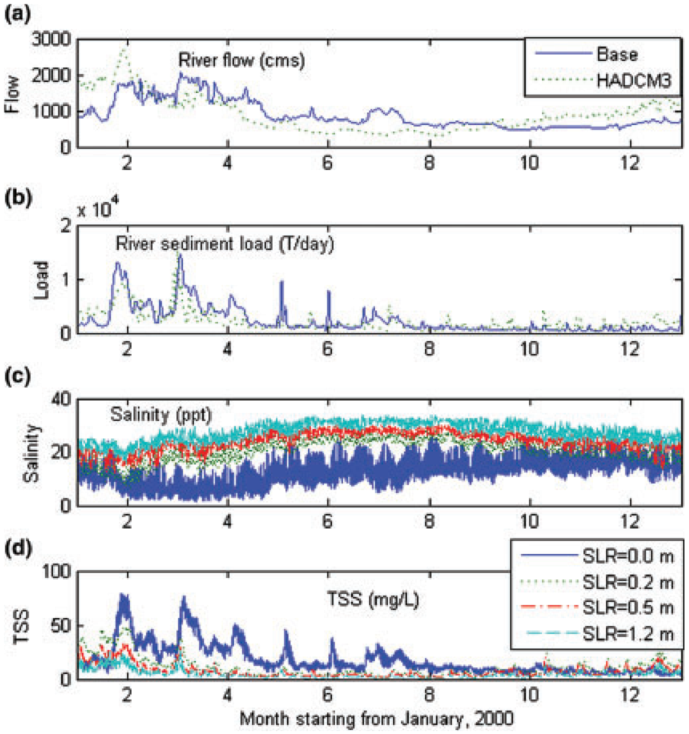

Figure 4. Flow and sediment loading from Apalachicola River and salinity and suspended sediment responses in the oyster reef at Dry Bar under different sea level rise scenarios. TSS, total suspended solid.

Table 2. Maximum Suspended Sediment Concentration (mg/L) in Response to River Sediment Loading at Oyster Reefs Under Different Sea Level Rise Scenarios

	SLR = 0.0	SLR = 0.2 m	SLR = 0.5 m	SLR = 1.2 m
Dry Bar	79.1	47.8	32.8	29.2
Cat Point	57.1	0.4	0.0	0.0

SLR, sea level rise.
Note: Boundary sediment concentrations at tidal inlets are specified as 0. Therefore, zero sediment indicates seawater intrusion from Gulf of Mexico.

Table 3. Mean Low Suspended Sediment Concentration (mg/L) During the Low Sediment Loading Period (August–December) at Oyster Reefs Under Different Sea Level Rise Scenarios

	SLR = 0.0	SLR = 0.2 m	SLR = 0.5 m	SLR = 1.2 m
Dry Bar	14.5	10.4	9.0	7.2
Cat Point	5.8	0.1	0.0	0.0

SLR, sea level rise.
Note: Boundary sediment concentrations at tidal inlets are specified as 0. Therefore, zero sediment indicates seawater intrusion from the Gulf of Mexico.

5 mg/L occurs from August–December, which corresponds to the low sediment loading from the river. Because Cat Point has been a historically productive oyster reef under recent sea level conditions, this low TSS condition under the baseline condition may display the needed TSS with nutrients to this oyster reef site without causing excessive TSS problems. In general, the TSS concentration at Cat Point is lower than that at Dry Bar. Under all SLR scenarios, the TSS concentration at Cat Point is close to zero (Tables 2 and 3) because of the intrusion of gulf water with zero concentration, as defined in this study, in addition to the increase of bay volume from SLR. The intrusion of saline gulf water can be shown by the salinity at Cat

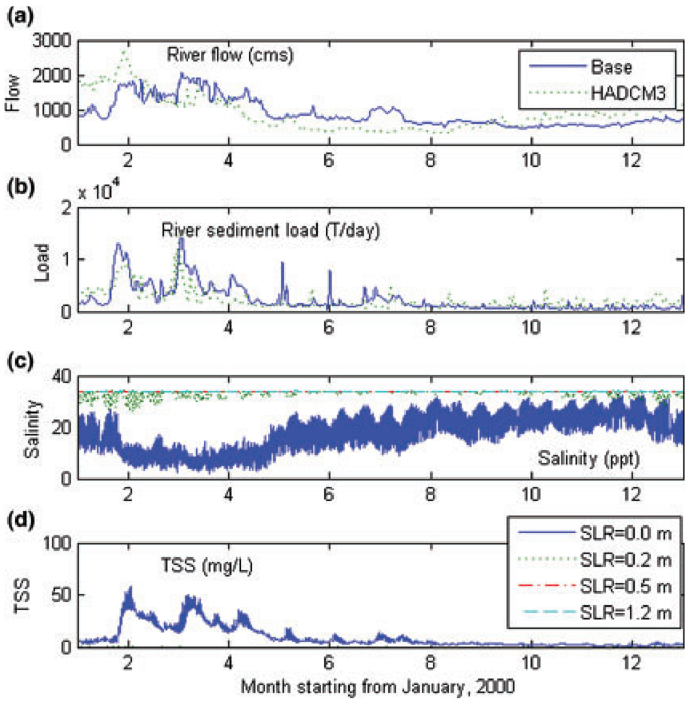

Figure 5. Flow and sediment loading from Apalachicola River and salinity and suspended sediment responses in the oyster reef at Cat Point in the bay under different sea level rise (SLR) scenarios. TSS, total suspended solid.

Point (Figure 4). Under all SLR scenarios, salinity at Cat Point reaches close to a boundary salinity of 34 ppt, indicating that the majority of water is from the gulf. The finding is consistent to some previous studies. In the previous study of SLR effects on salinity in Apalachicola Bay [*Huang et al.*, 2015], westerly salinity intrusion from the Gulf through East Pass has been shown by SLR. Because Cat Point is located in the eastern part of the bay, the westerly seawater intrusion pushes the sediment plume from river discharge away from Cat Point to the western portion of the bay. Previous studies of the geological evolution of oyster reefs in Apalachicola Bay by high-resolution seismic profiles and sediment cores of the bay bedding [*Twichell et al.*, 2010] suggest the westerly migration of oyster reefs in the bay, indicating historical SLR effects on westerly sediment transport since 6400-year BP when sea level was 4–6 m lower than present. Consistent with the study on the SLR-induced westerly sediment transport in the past by *Twichell et al.* [2010], this study predicts the SLR-induced westerly sediment transport under future SLR scenarios as the result of the SLR-induced westerly seawater intrusion from the Gulf through East Pass. SLR-induced westerly saline water intrusion from the Gulf through East Pass results in almost no suspended sediment from the river at Cat Point. This may make it difficult for oysters to obtain enough nutrients from TSS for growth and reproduction at the existing location of Cat Point.

5. Conclusions

Hydrodynamic and sediment transport modeling has been conducted to characterize the effects of SLR and sediment loading scenarios on the suspended sediment concentrations at two oyster reef sites in Apalachicola Bay. Results indicate that, in general, SLR causes the decrease of suspended sediment at oyster reefs. At Dry Bar, the maximum TSS concentration decreases from 79.1 mg/L to 47.8, 32.8, and 29.2 mg/L under SLR scenarios of 0.2, 0.5, and 1.2 m, respectively; the mean low TSS concentration decreases from 14.5 mg/L to 10.4, 9.0, and 7.2 mg/L under SLR scenarios of 0.2, 0.5, and 1.2 m, respectively. At Cat Point, the maximum TSS concentration decreases from 57.1 mg/L to 0.5, 0.0, and 0.0 mg/L under SLR scenarios of 0.2, 0.5, and 1.2 m, respectively; the mean low TSS concentration decreases from 5.8 mg/L to 0.1, 0.0, and 0.0 mg/L under SLR scenarios of 0.2, 0.5, and 1.2 m, respectively.

Although optimal suspended sediment concentration for oyster growth is unknown, many studies [e.g., *Crain*, 2001; *Coco et al.*, 2006; *Rasmussen et al.*, 2008; *Blomberg et al.*, 2015] have shown that high-suspended sediment will cause the decrease of oyster production, while some level of low-suspended sediment is still necessary because suspended sediment carries nutrients from the river that provides food for oyster growth. Based on the results of the numerical simulations, the changes of sediment concentration caused by SLR may not have an impact on oyster habitat at Dry Bar but will have significant effects on Cat Point. At Dry Bar, the peak sediment concentration will decrease, while some level of low sediment concentration still exists during the low sediment loading seasons. At Cat Point, because SLR causes the intrusion of Gulf water from the large tidal inlet at East Pass, sediment maximum concentration is close to zero for 0.2 m SLR and equal to zero for 0.5 and 1.2 m SLR. Therefore, SLR will cause a substantial loss of nutrient from suspended sediment in Cat Point.

This approach based on two sites can be expanded to depict potential future conditions across the entire Apalachicola Bay. Armed with these new spatially explicit data, ecosystem managers/restoration ecologists may be able to evaluate and prepare future sites that represent potentially viable oyster habitats under the new SLR regimes.

Acknowledgments
Flow and sediment loads under existing SLR conditions were obtained from USGS. Projected daily streamflow and sediment load used for this study were provided by *Chen et al.* [2014] and *Hovenga et al.* [2016]. All data for this paper have been properly cited and referred to in the reference list. This research was funded in part under Award No. NA10NOS4780146 from the National Oceanic and Atmospheric Administration (NOAA) Center for Sponsored Coastal Ocean Research (CSCOR). The research was also partially supported by NOAA-ECSC at FAMU and summer research collaboration by Dr. Huang with Tongji University (NSFC grants #91225301 and #51279134). The statements and conclusions are those of the authors and do not necessarily reflect the views of NOAA-CSCOR or their affiliates.

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