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# Impact assessment of sea-level rise and hazardous storms on coasts and estuaries using integrated processes model

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A R T I C L E I N F O

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A B S T R A C T

The study of this paper focuses on local and regional sea-level rise (SLR) and emphasizes complexities in impact assessment of SLR under combined hydrodynamic and morphodynamic conditions induced by extreme events such as hurricanes and typhoons. In terms of integrated coastal/ocean processes modeling, two case studies are presented: The first one is to predict flooding/inundation and erosion in a small-scale estuary in Taiwan induced by a set of SLR scenarios and local extreme hydrological forcing, which includes waves, tides, river floods, and sediment transport; The second case aims at simulating large-scale hydrodynamic responses (i.e. waves and storm surges) to SLR and a hurricane in a region-scale domain covering the northern Gulf Coast. The model is validated by simulating waves, storm surges and morphological changes by using local hydrological conditions. Prediction results show that the variations of water surface elevations, waves, and morphological changes are generally not linearly proportional to the static SLR; the rates of their variable changes are varying with location and topography/bathymetry. To deal with nonlinear features in unsteady and multiscale hydrodynamic and morphodynamic processes in coasts and oceans, it is essential to adopt this integrated-process modeling approach for coastal hazard management in response to local SLR.

## 1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) reported that the average global mean (or "eustatic") sea level rose at an average rate of 1.8 mm per year from 1961 to 2003 and at an average rate of 3.1 mm per year from 1993 to 2003, and the global mean sea level rise (SLR) by 2100 could be as much as 60 cm (IPCC, 2007). A continued global mean SLR has been referred by various studies (Walton Jr., 2007; Williams et al., 2008; Feldman, 2008; Gill et al., 2008; Batten et al., 2008). It has been reported that the sea level is not only rising, but also accelerating (Douglas, 1997). Recently, Sallenger et al. (2012) identified the evidence of acceleration in SLR at tide stations along the northeast Atlantic coastal region. Boon (2012) also found a similar trend of SLR acceleration in the 20th century and the first 11 years of the 21st century in the U.S. East Coasts and the Canadian Atlantic Coasts.

Williams et al. (2008) have mentioned that there are at least two primary factors contributing to the present rate of global mean sea level rise: thermal expansion of ocean surface waters, and the melting of glaciers as well as their runoff to the oceans. They also pointed out that vertical movements of coastal land surface, due to tectonics, isostatic adjustment of the crust, compaction of sediments, etc., can contribute significantly to the local (or relative) sea level change. Measuring SLR is a complicated process due to varying land subsidence rates (Gibeaut, 2007), as well as the regional climatic and oceanographic variability. In addition to traditional tide gauge observations, more accurate elevation data can be measured from altimetric satellites, such as TOPEX/Poseidon, by eliminating uncertainty of subsidence in some tide gauges (e.g. Douglas and Peltier, 2002; Lee et al., 2009).

Global mean SLR does not translate into a uniform rise in local sea level in coasts and estuaries around the world. Considerable variation often exists between global and local changes over a range of temporal and spatial scales. For example, based on available tide gauge data collected by the National Oceanic and Atmospheric Administration (NOAA) on the mid-Atlantic coast, Cooper et al. (2005) obtained an approximate relative sea-level rise trend of 3.53 mm/yr during the 20th century, which is almost double the global-mean value of sea-level rise. In general, the local sea-level change can be determined by the sum of global mean sea-level rise, regional sea-level change due to meteo-

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oceanographic factors (i.e. atmospheric pressure, storm surge, wave set-up, and ocean circulations), and vertical land movement (Nicholls, 2003).

The continued rise of the local sea level poses many problems along the developed coastal regions. Local SLR can cause permanent inundation and displacement of coastal lowlands, increased flood and storm damage, increased erosion, and saltwater intrusion (Nicholls, 2003). After the sea level rises, extreme events at coasts such as high tides, tropical storms, typhoons, and hurricanes may increase the occurrence and magnitude of flooding and inundation, shoreline erosions, local scouring, and barrier island breaching (e.g. Cooper et al., 2005). SLR may also increase the susceptibility of coastal populations and ecosystems due to drastic changes of coastal zones. Nicholls and Lowe (2004) estimated that this continuous trend of SLR may lead to retreat of millions of people, severe damage to coastal infrastructure and property, and a considerable loss of coastal ecosystems by the end of the 21st Century.

SLR will modify current hydrodynamic and morphodynamic features at coasts and estuaries, due to increasing of wave setup, tidal prisms and currents, and shoreline changes (e.g. Douglas, 1997). The variation of this effect depends on bathymetry, tide ranges, as well as properties of wave and wind. Due to nature of multi-scale and unsteadiness in coastal hydrodynamic and morphodynamic processes, this effect can be predicted by using integrated coastal/ocean processes-based models. The modeling processes and parameters have to be properly based on flow conditions since the modeled conditions represent projected future scenarios beyond the calibrated conditions (ASCE Task Committee on Sea Level Rise and Its Effects on Bays and Estuaries, 1992). Validated computational processes-integrated models can be applied to assess the SLR impacts on a local/regional scale coast. For the purpose of coastal flood management and infrastructure planning, it is essential to take into account SLR under dynamic storm/hurricane conditions for assessing temporal and spatial variation of SLR impact on coasts and estuaries (Ding, 2011).

The study of SLR-related impacts has been performed in previous studies. Based on the selected long-term tide gauges on the East Coast of the United States, it has been found that along the Atlantic coast of the U.S., over the last century, relative sea-level rise rates have ranged between 1.8 mm/yr to as much as 4.4 mm/yr (US-CCSP, 2008). The highest rates ($4.42 \pm 0.16$ mm/yr) have been observed in the mid-Atlantic region between northern New Jersey and southern Virginia. Based on the regional SLR, US-CCSP (2008) proposed three projected SLR scenarios (0.3, 0.5, and 1.0 m of SLR by 2100) to evaluate several aspects of SLR impacts for the mid-Atlantic US coast using a range of elevation data sets which have large variations in vertical resolution and horizontal accuracy. Cooper et al. (2005) also applied digital elevation models (DEM) to study the impact of projected sea level rise to the New Jersey coast. They used two relative sea level rise projections, 0.61 m (2 ft) and 1.22 m (4 ft) to study what areas could be chronically inundated. By comparing with the U.S. Federal Emergency Management Agency (FEMA) tidal surge frequency for 5, 10, 20, 30, 50, and 100-year flood water levels for Atlantic City, New Jersey, they found that sea-level rise will allow current flood levels to be exceeded and low-lying lands to be flooded with increasing frequency. In the case of 0.61 m of SLR, the current 30-year storm will produce a flood water elevation of 2.96 m, which exceeds the current 100-year FEMA flood level (2.90 m at Atlantic City). After a 1.22 m of SLR, the current 5-year storm will cause water levels above the current 100-year flood level. In other words, provided that other factors being equal, New Jersey's current 100-year flood levels could become the 30-year flood level after a 0.61 m sea-level rise and the 5-year flood level after a 1.22 m rise. Bromirski et al. (2012) concluded that if relative mean sea level along the California coast reaches global mean sea level rise projections, extreme flooding events expected to occur once in about 100 years under stationary relative mean sea levels will occur annually.

Local SLR has been detected by analyzing long-term tide records. For example, the so-called permanent service for mean sea level database (PSMSL, 2012) provides a global data bank for long-term sea level change information from tide gauges and bottom pressure recorders. NOAA also provides long-term tide records and sea level trends at tide gauges in the coasts of the Pacific and Atlantic Oceans (NOAA, 2012). In the northern Gulf coasts, for instance, at Grand Isle, Louisiana and Dauphin Island, Alabama, which are located in the study area, the sea level trend observed by NOAA are 9.24 mm/yr and 2.98 mm/yr respectively (NOAA, 2012). The projection shows that local SLR at the two stations could be 92 cm and 30 cm, respectively, in 100 years.

The impacts of sea-level rise can be assessed in different purposes and ranges of spatial scales. In a global or regional scale, some case studies are driven by policy making (e.g. Nicholls et al., 1999; Nicholls, 2004; Schleupner, 2007); some are more science-orientated to examine the methodologies that can transfer scientific knowledge into decision making tools (e.g. Cooper et al., 2005; Capobianco et al., 1999). Local/regional assessment of impacts of sea-level rise usually is required for coastal hazard management in coastal zones (e.g. USACE, 2011), for which the variation of waves, tides, and geomorphology has to be included. For example, to assess the changes and variability of coastal flooding potential in California over 2000–2099, Bromirski et al. (2012) employed the WAVEWATCH III (WW3) wave model (Tolman, 1999) and ocean wave projections derived from global climate model (GCM) output fields. They found that wave activity provides the primary driving force for coastal flooding. Their assessment results also indicated that the incidence extreme wave heights in deep waters would not increase also with SLR. However, the primary SLR impacts on coastal hydrodynamics such as waves and currents, as well as morphological changes due to sediment transport and increased storm waves have not been fully studied. It should be noted that the reliability of the sea-level rise assessment results strongly depend on the accuracy of the coupled physical process models. Reliable and high accuracy of integrated models relies on rigorous model validations for all the submodels for waves, currents, sediment transport, and morphological changes.

As for assessment methodologies, the contour-line projection approaches and downscaling techniques (e.g. Wilby et al., 2002) to assess sea-level rise can only give an average estimation (most likely underestimation) of the impacts. Further accurate numerical simulations are needed to include the nonlinear variations of other physical factors of coastal/ocean processes such as storm surge, wave, tide, etc. along with sea-level rise.

Therefore, the paper presents applications of an integrated coastal/ocean process model, CCHE2D-Coast (e.g. Ding et al., 2006; Ding and Wang, 2008a), to assess the SLR impact on flooding/inundation and morphological changes under the hydrological conditions of storms at two different scales of coasts. The first one is a small-scale estuary in Taiwan, for which a set of sea-level rise scenarios and local extreme hydrological forcing including waves, tides, river floods, and sediment transport are taken into account. The second one is to predict hydrodynamic responses (i.e. waves and storm surges) to SLR and hurricane in a region-scale domain covering the Mississippi and Louisiana coast. This study does not estimate SLR; instead, it uses different hypothetical local SLR scenarios, which are broadly based on recent SLR forecasting studies, to predict variations of coastal dynamics such as water elevations, waves, and morphological changes. Before applying to simulate SLR impact, CCHE2D-Coast has been