Ecological Modelling 327 (2016) 29–43

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

A coupled, two-dimensional hydrodynamic-marsh model with biological feedback

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ARTICLE INFO

Article history:
Received 22 September 2015
Received in revised form 21 January 2016
Accepted 22 January 2016

Keywords:
Salt marsh
Hydrodynamics
Timucuan marsh system
Sea-level rise
Marsh equilibrium model (MEM)
Hydro-MEM model

ABSTRACT

A spatially-explicit model (Hydro-MEM model) that couples astronomic tides and *Spartina alterniflora* dynamics was developed to examine the effects of sea-level rise on salt marsh productivity in northeast Florida. The hydrodynamic component of the model simulates the hydroperiod of the marsh surface driven by astronomic tides and the marsh platform topography, and demonstrates biophysical feedback that non- uniformly modifies marsh platform accretion, plant biomass, and water levels across the estuarine landscape, forming a complex geometry. The marsh platform accretes organic and inorganic matter depending on the sediment load and biomass density which are simulated by the ecological-marsh component (MEM) of the model and are functions of the hydroperiod. Two sea-level rise projections for the year 2050 were simulated: 11 cm (low) and 48 cm (high). Overall biomass density increased under the low sea-level rise scenario by 54% and declined under the high sea-level rise scenario by 21%. The biomass-driven topographic and bottom friction parameter updates were assessed by demonstrating numerical convergence (the state where the difference between biomass densities for two different coupling time steps approaches a small number). The maximum coupling time steps for low and high sea-level rise cases were calculated to be 10 and 5 years, respectively. A comparison of the Hydro-MEM model with a parametric marsh equilibrium model (MEM) indicates improvement in terms of spatial pattern of biomass distribution due to the coupling and dynamic sea-level rise approaches. This integrated Hydro-MEM model provides an innovative method by which to assess the complex spatial dynamics of salt marsh grasses and predict the impacts of possible future sea level conditions.

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1. Introduction

Coastal salt marsh systems provide intertidal habitats for many species (Halpin, 2000; Pennings and Bertness, 2001), many of which (e.g., crabs and fish) have significant commercial importance. Marshes also protect shorelines by dissipating wave energy and increasing friction, processes which subsequently decrease flow energy (Knutson, 1987; Leonard and Luther, 1995; Möller and Spencer, 2002; Shepard et al., 2011). Salt marsh communities are classic examples of systems that are controlled by and in turn influence physical processes (Silliman and Bertness, 2002).

Studying the dynamics of salt marshes, which are characterized by complex inter-relationships between physics and biology (Townend et al., 2011), requires the coupling of seemingly disparate models to capture their sensitivity and feedback processes (Reed, 1990). Furthermore, coastal ecosystems need to be examined using dynamic models, because biophysical feedbacks change topography and bottom friction with time (Jørgensen and Fath, 2011a). Such coupled models allow researchers to examine marsh responses to natural or anthropogenic changes in environmental conditions. The models can be divided into landscape scale and fine scale models based on the scales for projecting vegetation productivity. Ecosystem-based landscape models are designed to lower the computational expense by expanding the resolution to the order of kilometers and simplifying physical processes between ecosystem units (Fagherazzi et al., 2012). These models connect

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http://dx.doi.org/10.1016/j.ecolmodel.2016.01.013
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different drivers including hydrology, hydrodynamics, water nutrients, environmental inputs and integrate them in a large scale model (Clough et al., 2010; Costanza and Ruth, 1998; Costanza et al., 1990; Craft et al., 2008; Fitz et al., 1996; Martin et al., 2002, 2000; Park et al., 1986, 1989; Reyes et al., 2000; Sklar et al., 1985). However, fine scale models with resolutions on the order of meters can provide more realistic results by including different feedback mechanisms. Most relevant to this work is their ability to model the response in marsh productivity to a change in forcing mechanisms (e.g., sea-level rise-SLR) (Allen, 1997; Hagen et al., 2013; Kirwan and Murray, 2007; Marani et al., 2013; Mariotti and Fagherazzi, 2010; Morris et al., 2002; Mudd et al., 2004; Reed, 1995; Schile et al., 2014; Stralberg et al., 2011; Tambroni and Seminara, 2012; Temmerman et al., 2003).

Previous studies have shown that salt marshes possess biological feedbacks that change relative marsh elevation by accreting organic and inorganic material (Baustian et al., 2012; Kirwan and Guntenspergen, 2012; Morris et al., 2002; Patrick and DeLaune, 1990; Reed, 1995; Turner et al., 2000). SLR also will cause salt marshes to transgress, but extant marshes may be unable to accrete at a sufficient rate in response to high SLR (Donnelly and Bertness, 2001; Warren and Niering, 1993) leading to their complete submergence and loss (Nyman et al., 1993).

Salt marsh systems adapt to changing mean sea level through continuous adjustment of the marsh platform elevation toward an equilibrium (Morris et al., 2002). Based on long-term measurements of sediment accretion and marsh productivity, Morris et al. (2002) developed the Marsh Equilibrium Model (MEM) that links sedimentation, biological feedback, and the relevant time scale for SLR. Marsh equilibrium theory holds that a dynamic equilibrium exists, and that marshes are continuously moving in the direction of that equilibrium. MEM uses a polynomial formulation for salt marsh productivity and accounts explicitly for inputs of suspended sediments and implicitly for the in situ input of organic matter to the accreting salt marsh platform. The coupled model presented in this manuscript incorporates biological feedback by including the MEM accretion formulation as well as implementing a friction coefficient effect that varies between subtidal and intertidal states. The resulting model not only has the capability of capturing biophysical feedback that modifies relative elevation, but it also includes the biological feedback on hydrodynamics.

Since the time scale for SLR is on the order of decades to centuries, models that are based on long-term measurements, like MEM, are able to capture a fuller picture of the governing long-term processes than physical models that use temporary physical processes to extrapolate long-term results (Fagherazzi et al., 2012). MEM has been applied to a number of investigations on the interaction of hydrodynamics and salt marsh productivity. Mudd et al. (2004) used MEM coupled with a one-dimensional hydrodynamic component to investigate the effect of SLR on sedimentation and productivity in salt marshes at the North Inlet estuary, South Carolina. MEM has also been used to simulate the effects of vegetation on sedimentation, flow resistance, and channel cross section change (D'Alpaos et al., 2006), as well as in a three-dimensional model of salt marsh accretion and channel network evolution based on a physical model for sediment transport (Kirwan and Murray, 2007). Hagen et al. (2013) coupled a two-dimensional hydrodynamic model with the zero-dimensional biomass production formula of Morris et al. (2002) to capture SLR effects on biomass density and simulated human-enhanced marsh accretion.

Coupling a two-dimensional hydrodynamic model with a point-based parametric marsh model that incorporates biological feedback, such as MEM, has not been previously achieved. Such a model is necessary because results from short-term limited hydrodynamic studies cannot be used for long-term or extreme events in ecological and sedimentary interaction applications. Hence, there is a need for integrated models, which incorporate both hydrodynamic and biological components for long time scales (Thomas et al., 2014). Additionally, models that ignore the spatial variability of the accretion mechanism may not accurately capture the dynamics of a marsh system (Thorne et al., 2014), and it is important to model the distribution at the correct scale for spatial modeling (Jørgensen and Fath, 2011b).

Ecological models that integrate physics and biology provide a means of examining the responses of coastal systems to various possible scenarios of environmental change. D'Alpaos et al. (2007) employed simplified shallow water equations in a coupled model to study SLR effects on marsh productivity and accretion rates. Temmerman et al. (2007) applied a more physically complicated shallow water model to couple it with biological models to examine landscape evolution within a limited domain. These coupled models have shown the necessity of the interconnection between physics and biology; however, the applied physical models were simplified or the study area was small. This paper presents a practical framework with a novel application of MEM that enables researchers to forecast the fate of coastal wetlands and their responses to SLR using a physically more complicated hydrodynamic model and a larger study area. The coupled Hydro-MEM model is based on the model originally presented by Hagen et al. (2013). This model has since been enhanced to include: spatially dependent marsh platform accretion, a bottom friction roughness coefficient (Manning's n) using temporal and spatial variations in habitat state, a "coupling time step" to incrementally advance and update the solution, and changes in biomass density and hydroperiod via biophysical feedbacks. The presented framework can be employed in any estuary or coastal wetland system to assess salt marsh productivity regardless of tidal range by updating an appropriate biomass curve for the dominant salt marsh species in the estuary. In this study, the coupled model was applied to the Timucuan marsh system located in northeast Florida under high and low SLR scenarios. The objectives of this study were to (1) develop a spatially-explicit model by linking a hydrodynamic-physical model and MEM using a coupling time step and (2) assess a salt marsh system long-term response to projected SLR scenarios.

2. Methods

2.1. Study area

The study area is the Timucuan salt marsh, located along the lower St. Johns River in Duval County in northeastern Florida (Fig. 1). The marsh system is located to the north of the lower 10–20 km of the St. Johns River, where the river is engineered and the banks are hardened for support of shipping traffic and port utility. The creeks have changed little from 1929 to 2009 based on surveyed data from National Ocean Service (NOS) and the United States Army Corps of Engineers (USACE), which show the creek layout to have remained essentially the same since 1929. The salt marsh of the Timucuan preserve, which was designated the Timucuan Ecological and Historic Preserve in 1988, is among the most pristine and undisturbed marshes found along the southeastern United States seaboard (United States National Park Service (Denver Service Center), 1996). Maintaining the health of the approximately 185 square km of salt marsh, which cover roughly 75% of the preserve, is important for the survival of migratory birds, fish, and other wildlife that rely on this area for food and habitat.

The primary habitats of these wetlands are salt marshes and the tidal creek edges between the north bank and Sisters Creek are dominated by low marsh, where *Spartina alterniflora* thrives (DeMort, 1991). A sufficient biomass density of *S. alterniflora* in the

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