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Application and validation of a three-dimensional hydrodynamic model of a macrotidal salt marsh

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ABSTRACT

A three-dimensional hydrodynamic model is used to study the relative influence of salt marsh vegetation on flows in a macrotidal estuary using a system of three connected grids that resolve currents in tidal drainage channels incised in a marsh platform. The model incorporates the effects of vegetation on flow drag, parameterized by the stem height, diameter and plant density. Model predictions are compared to novel field observations of macrotidal water levels and tidal currents using pressure and acoustic current sensors over 6 tidal cycles at spring tide, collected in areas of different roughness corresponding to high marsh grass (*Spartina patens*), low marsh grass (*Spartina alterniflora*), and a muddy tidal channel bed. High resolution airborne Lidar and multibeam bathymetry data are used to define the bathymetry and spatially-variable vegetation maps in the multi-domain model. A detailed comparison between field observations and model results is presented, necessary for model validation in this macrotidal environment with large water level gradients and high sensitivity to model input parameter values. The model results indicate that the vegetation plays a major role in controlling flow speed and drainage patterns, especially over the macrotidal marsh platform. Differences in flow resistance between vegetated and un-vegetated areas result in faster flows over un-vegetated areas, with vegetated areas having flow directions locally perpendicular to channels as water levels exceed creek bank elevations and the marsh platform is flooded. Including the marsh grasses in the model causes stronger near-surface currents, significantly weaker near-bed currents, and concentrated flows in the channels resulting in strong vertical variation in the horizontal flow. The results indicate that including the effects of vegetation in a numerical model is crucial in simulating the hydrodynamic conditions over macrotidal salt marsh platforms and in channels.

1. Introduction

Salt marshes form in intertidal zones of coastal regions in mid- to high-latitudes, in areas sheltered from waves which permits both the deposition of fine sediments and the establishment of vegetation (Woolnough et al., 1995). They are a valuable part of estuarine and marine ecosystems, provide critical habitat for organisms (Reed et al., 1999; Mitsch and Gosselink, 2000), and typically contain grasses or low shrubs that adhere to sharp boundaries defined by tolerance to stressors such as changes in salinity (Bertness, 1991). The topography of tidal marshes typically consists of a vegetated marsh platform, dissected by dense networks of un-vegetated tidal channels or creeks, sometimes with levee-basin micro-topography between the drainage channels (Allen, 2000). Tidal channels have been the focus of many studies on flow and sediment transport (e.g. Bayliss-Smith et al., 1979; Bouma et al., 2005; van Proosdij et al., 2006; O'Laughlin and van Proosdij, 2013), but not all of the hydrodynamics takes place in tidal channels as a portion of the water that floods and ebbs from the system is transported over the marsh platform (French and Stoddart, 1992; Davidson-Arnott et al., 2002). Vegetation on the platform reduces tidal flow velocity and turbulence (Leonard and Croft, 2006; Temmerman et al., 2005), dampens wave activity (Augustin et al., 2009; Mariotti and Fagherazzi, 2013; Duarte et al., 2013; Möller et al., 2014) and influences geomorphology (Fagherazzi and Sun, 2004; Bouma et al., 2007; Temmerman et al., 2007; Schwarz et al., 2014). Salt marsh and tidal creek hydrodynamics are driven by the incident tidal water levels and currents, and highly modified by the local topography and vegetation (Temmerman et al., 2005). Consequently flow paths over tidal marshes are complex and have high spatial variability (Christiansen et al., 2000; Townend et al., 2011) and the vertical profile of horizontal flow above the marsh platform is strongly affected by the marsh vegetation (Leonard and Luther, 1995; Shi et al., 1995; Bouma et al., 2005) due to drag induced by the plants (Ozeren et al., 2014). Field observation of flows in tidal marshes are typically limited to measurements in un-vegetated areas or above the vegetation elevation.

Past modelling studies of flow patterns in tidal marshes are idealized, limited to one- or two-dimensions and do not account for the spatial changes in vegetation properties (Allen, 1994; Rinaldo et al., 1999; Fagherazzi and Sun, 2004). More recent three-dimensional modelling

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studies of salt marsh hydrodynamics have investigated microtidal to mesotidal environments (Kusters, 2003; Temmerman et al., 2005; Bouma et al., 2007; Schwarz et al., 2014), but tidal hydrodynamics in a macrotidal salt marsh have not previously been investigated.

In this study a high-resolution three-dimensional hydrodynamic model (Delft3D) coupled to a vegetation module is applied to simulate the impact of plants on flow patterns in a macrotidal salt marsh in the Bay of Fundy, validated with field observations in a tidal channel and in the marsh vegetation. The model accounts for vegetation density, height, and stem diameter, and is used to compute currents across the tidal marsh and estimate the influence of the vegetation on flow routing. This paper provides an overview of the field site and observations (Section 2), a description of the numerical model configuration and the vegetation module (Section 3), an analysis of the model results in comparison with observations with discussion on the influence of vegetation on flow through the tidal marsh (Section 4), and conclusions on the importance of including spatially varying vegetation in hydrodynamic models of macrotidal salt marshes (Section 5).

2. Study area and field observations

The Bay of Fundy is a macrotidal environment on the Atlantic coast of North America, between Nova Scotia (NS) and New Brunswick (NB) in Eastern Canada, renowned for a very large tidal range (e.g., 16.2 m at Burntcoat head, NS) and is a candidate site for tidal energy extraction due to strong currents in the Minas Passage (Ashall et al., 2016). The high tidal range is caused by a near-resonant condition (Garrett, 1972) since the natural period of the basin is very close to the M_2

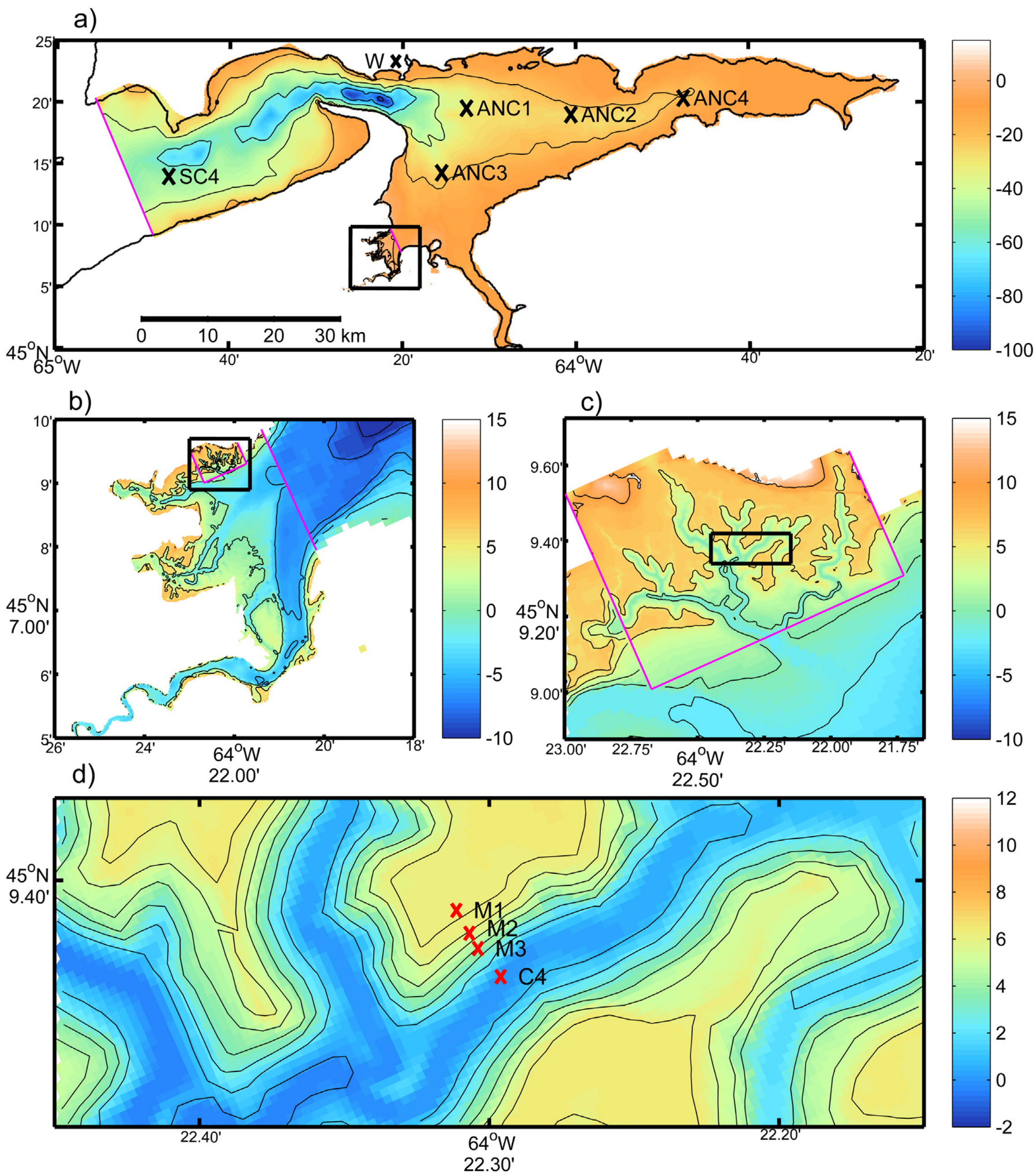

Fig. 1. Model grids, boundaries and bathymetry: a) Minas Basin (outer grid 200 m), b) Cornwallis Estuary (middle grid, 33 m), c) Kingsport Marsh (inner grid, 8 m) and d) instrument locations for point velocity measurement (M1–M3) and current profiles (C4). The outer model boundary (B_{WL}) and internal boundaries are indicated by magenta lines. Topography and bathymetry are shown by colour contours (m, referenced to the CGVD28 vertical datum) and black lines indicate depth contours at intervals of: a) 20 m; b) 7 m; c) 5 m; and d) 1.5 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)