Computers & Geosciences 100 (2017) 76–86

Contents lists available at ScienceDirect

Computers & Geosciences

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

Research paper

Development of a coupled wave-flow-vegetation interaction model

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ARTICLE INFO

Keywords:
Flexible aquatic vegetation
Coastal hydrodynamics
Numerical modeling

ABSTRACT

Emergent and submerged vegetation can significantly affect coastal hydrodynamics. However, most deterministic numerical models do not take into account their influence on currents, waves, and turbulence. In this paper, we describe the implementation of a wave-flow-vegetation module into a Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system that includes a flow model (ROMS) and a wave model (SWAN), and illustrate various interacting processes using an idealized shallow basin application. The flow model has been modified to include plant posture-dependent three-dimensional drag, in-canopy wave-induced streaming, and production of turbulent kinetic energy and enstrophy to parameterize vertical mixing. The coupling framework has been updated to exchange vegetation-related variables between the flow model and the wave model to account for wave energy dissipation due to vegetation. This study i) demonstrates the validity of the plant posture-dependent drag parameterization against field measurements, ii) shows that the model is capable of reproducing the mean and turbulent flow field in the presence of vegetation as compared to various laboratory experiments, iii) provides insight into the flow-vegetation interaction through an analysis of the terms in the momentum balance, iv) describes the influence of a submerged vegetation patch on tidal currents and waves separately and combined, and v) proposes future directions for research and development.

1. Introduction

Aquatic vegetation (e.g., mangroves, salt marshes, and seagrasses) plays an important role in estuarine ecosystems by acting as a seabed stabilizer, nutrient sink, and nursery for juvenile fishes and invertebrates (Hemminga and Duarte, 2000). They are often referred to as eco-engineers because they modify their physical environment to create more favorable habitat for themselves and other organisms (Jones et al., 1994). For example, seagrasses can reduce sediment resuspension thereby increasing light penetration and potential growth (Carr et al., 2010). Evaluating the resilience of estuarine ecosystems requires greater insight into the interactions between vegetation, currents, waves, and sediment transport. The relevance of aquatic vegetation in coastal protection from extreme events has become a recurring question along with the viability assessment of ecosystem-based management approaches (Barbier et al., 2008; Temmerman et al., 2013).

Previous laboratory and numerical investigations have focused on the blade-to-meadow scale (detailed review by Nepf, 2012). Paired with theoretical analysis, they stand as valuable tools to study vegetated flow dynamics (Fig. 1). However, they do not consider the inherent complexity of realistic environments (e.g., spatial variations of vegetation distribution and bathymetry, nonlinear wave-current interactions). Coastal ocean numerical models can be used to investigate these complex processes, but their resolution often requires parameterizations to account for small (sub-grid) scale turbulent features of the flows, which are particularly important in the presence of vegetation.

The simplest method to account for the influence of vegetation in a depth-averaged flow model is an increase of the bottom roughness coefficient (Ree, 1949; Morin et al., 2000). More recently, vegetation has been parameterized as a source of form drag as opposed to skin friction relevant to sediment transport in the depth-averaged sense (Chen et al., 2007; Le Bouteiller and Venditti, 2014). However, two-dimensional depth-averaged (2DH) approximations cannot account for the complex vertical structure of the flow within and over submerged vegetation (Sheng et al., 2012), especially shear layers at the top of the canopy that enhance vertical mixing (Lapetina and Sheng, 2014; Marjoribanks et al., 2014). To date, few estuary-scale models account for the three-dimensional influence of vegetation on the mean and turbulent flow (Temmerman et al., 2005; Kombiadou et al., 2014; Lapetina and Sheng, 2015), and none are part of an open-source, community model. In addition to exerting drag on the mean flow, aquatic vegetation also attenuates waves. While the bed-roughness approach has been rather successfully applied to simulate wave height decay over vegetation (Möller et al., 1999; de Vriend, 2006; Chen et al.,

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http://dx.doi.org/10.1016/j.cageo.2016.12.010
Received 16 May 2016; Received in revised form 18 August 2016; Accepted 14 December 2016
Available online 15 December 2016
0098-3004/ Published by Elsevier Ltd.

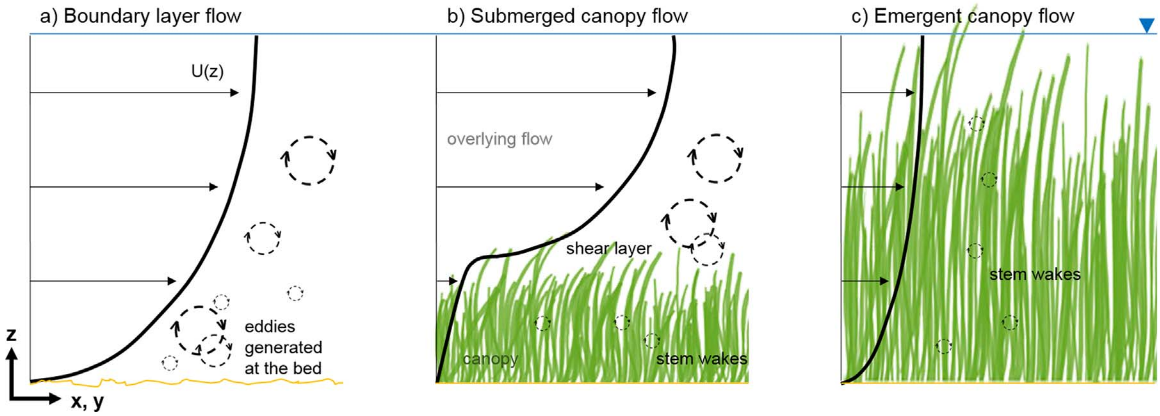

Fig. 1. Sketch of three different flow regimes. The dominant source of turbulence is respectively (from left to right) the bed, the top of the canopy (shear layer), and the stem wakes.

2007), the cylinder approach of Dalrymple et al. (1984) provides a more physically based description of wave dissipation by vegetation and its implementation in spectral wave models has been validated against flume experiments (Mendez and Losada, 2004; Suzuki et al., 2012; Wu, 2014; Bacchi et al., 2014).

The present study aims at providing an open-source process-based modeling framework that allows comprehensive studies of the interactions between hydrodynamics and vegetation, and describing/illustrating the influence of a submerged vegetation patch on currents and waves in an idealized shallow basin. We first detail the implementation of flow-vegetation interaction processes within the models, and then assess the model results using prior studies. We detail the interaction between flow and vegetation for a number of idealized cases, then discuss future avenues of model application and improvement.

2. Methods

The wave-flow-vegetation module described in this paper is implemented as part of the open-source Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) numerical modeling system (Warner et al., 2010), operating on the flow (ROMS) and wave (SWAN) models (Fig. 2) coupled via the Model Coupling Toolkit (MCT) generating a single executable program (Warner et al., 2008a, 2008b). The vegetation parameterizations are successively described in the flow and wave models.

2.1. Flow model

ROMS (Regional Ocean Modeling System) is a three-dimensional, free surface, finite-difference, terrain-following model that solves the Reynolds-Averaged Navier-Stokes (RANS) equations using the hydrostatic and Boussinesq assumptions (Haidvogel et al., 2008):

$$\frac{\partial u}{\partial t}+\vec{v}\bullet\nabla u-fv=-\frac{\partial\phi}{\partial x}-\frac{\partial}{\partial z}\left(\overline{u'w'}-\nu\frac{\partial u}{\partial z}\right)+D_u+F_u \tag{1a}$$

$$\frac{\partial v}{\partial t}+\vec{v}\bullet\nabla v+fu=-\frac{\partial\phi}{\partial y}-\frac{\partial}{\partial z}\left(\overline{v'w'}-\nu\frac{\partial v}{\partial z}\right)+D_v+F_v \tag{1b}$$

$$-\frac{\partial\phi}{\partial z}-\frac{\rho g}{\rho_0}=0 \tag{1c}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1d}$$

where $(u,v,\ w)$ are the velocity vector $\vec{v}$ components in the horizontal (the Cartesian coordinates x and y can be replaced by more general curvilinear coordinate ξ and η, in which case additional metric terms appear in the equations) and vertical (z is actually scaled to sigma-coordinate) directions respectively, f is the Coriolis parameter, ϕ is the dynamic pressure (normalized by the reference density of seawater ρ_0), ρ is the density, ν is the molecular viscosity, $(D_u,\ D_v)$ are the horizontal diffusive terms calculated with the vector Laplacian of the velocity field, and $(F_u,\ F_v)$ are the forcing terms that include wave-averaged forces (Kumar et al., 2012) and vegetation drag force and in-canopy wave-induced streaming (described in the next paragraphs).

The (spatially averaged) vegetation drag force can be approximated using a quadratic drag law:

$$F_{d,\ \ veg,u}=\frac{1}{2}C_D b_v n_v u\sqrt{u^2+v^2} \tag{2a}$$

$$F_{d,\ \ veg,v}=\frac{1}{2}C_D b_v n_v v\sqrt{u^2+v^2} \tag{2b}$$

where ρ is the (total) density of seawater, C_D is the plant drag coefficient (constant assuming a high Reynolds number), b_v is the width of individual plants, n_v is the number of plants per unit area, and (u,v) are the horizontal velocity components at each vertical level in the canopy of height l_v (when upright). A limiter is imposed to prevent the vegetation drag force from having a value large enough to reverse the velocity direction (see also bottom stress limiter due to wetting and drying in Warner et al., 2013).

To quantify the reduction of drag due to the bending of flexible plants, Dijkstra (2012) implemented a lookup table of deflected height and equivalent drag coefficient based on a detailed one-dimensional vertical model of plant motion called Dynveg (Dijkstra and Uittenbogaard, 2010), while Kombiadou et al. (2014) used an empirical formula based on laboratory data of Ganthy (2011) for the height of the bent canopy. In the present study, the more generally applicable (across vegetation species and hydrodynamic conditions) approach of

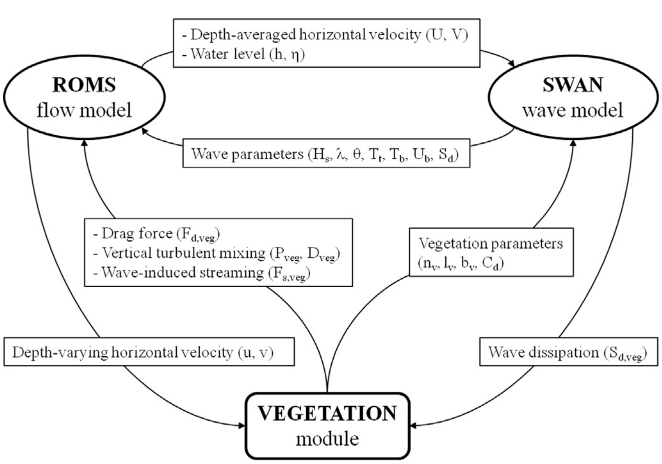

Fig. 2. Diagram showing data exchanges between the flow model, the wave model, and the vegetation module in COAWST.