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Development of a wave-current model through coupling of FVCOM and SWAN

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ABSTRACT

A coupled wave-current system has been developed in the present paper based on two open source community models, the Finite-Volume Community Ocean Model (FVCOM) and the Simulating WAves Nearshore (SWAN) using Model Coupling Toolkit (MCT). The coupled system runs on unstructured grids and multiple processors, and information, including water elevations and currents from FVCOM and wave parameters from SWAN, exchanges between FVCOM and SWAN in both on-line and two-way manners. The system was evaluated against laboratory experiments and the evaluation showed that the simulated results agree well with the measured data. Compared to the existing off-line coupling system based on FVCOM and SWAN, the system in the present study is able to accomplish the on-line, two-way coupling, and at the same time, is more efficient for computations and easier to use for the nearshore wave-current simulations.

1. Introduction

Waves and currents commonly interact with each other in coastal waters and play a key role in sediment transport, morphological evolution and pollutant mixing (Rodriguez et al., 1995; Li and Johns, 1998; Bever and MacWilliams, 2013). The interactions are nonlinear and complex (Olabarrieta et al., 2011; Roland et al., 2012; Benetazzo et al., 2013). On one hand, the gradient of wave radiation stresses generates wave-induced currents (Longuet-Higgins, 1970; Garcez-Faria et al., 2000) and thus further influences the mean water level by increasing water levels near the shoreline or decreasing water levels near the wave breaking point (Longuet-Higgins and Stewart, 1964; Guza and Thornton, 1981). Meanwhile, waves in the surf zone can enhance the horizontal mixing and bottom drag. On the other hand, changes in water levels and currents can, in turn, affect the motion and evolution of waves (Dutour-Sikiric et al., 2013; Allard et al., 2014).

A coupling system of waves and currents in a numerical model usually uses the following two ways, one is the off-line coupling and the other is the on-line coupling. For the off-line coupling, the wave model and the current model run independently and the model results are archived separately. The effects of waves on currents or the effects of currents on waves were estimated by using the archived wave or current results. The data can be transferred from one model to the other one (one-way), or exchanged between both the two models (two-way). In the two-way approach, in order to include the nonlinear interactions between waves and currents, it usually uses an iteration manner, for example, Yoon et al. (2004) and Huang et al. (2010), until the solution converges. For the on-line coupling, alternatively, the current and wave models run simultaneously and the information exchanges for calculating interactions at predefined time steps during the program execution, which is a two-way coupling method. Singhal et al. (2013) compared the one-way (current to wave) off-line and two-way on-line coupling methods for the wave-current interactions in Cook Inlet, Alaska. Their results indicated that an online coupling may not be necessary because the effect of waves on currents is marginal at the spatial scale of about 1.5 km. However, simulations of waves over submerged shoal by Yoon et al. (2004) and Zheng et al. (2012) pointed out that only two-way coupled method can account for the wave-induced current and the influence of current on wave distributions. The investigations of a storm surge by a recent study of Staneva et al. (2016) demonstrated that the effects of two-way coupling are clearly more important than that of a one-way coupling, especially in the shallow waters, where nonlinear interactions dominate the wave-current coupling. Compared to the file based coupling with an off-line method, the on-line coupling is likely to be more efficient (Bettencourt, 2002).

Recently, some on-line coupled models for currents and waves have

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been developed. For example, Brown et al. (2011) coupled the modified spectral WAve Model (WAM) to the Proudman Oceanographic Laboratory Coastal Ocean Modeling System (POLCOMS) with an aim to simulate wave-current interactions in shallow waters. Bennis et al. (2011) coupled the spectral wave model of WAVEWATCH III with a 3-D hydrodynamical Model for Applications at Regional Scale (MARS3D). Roland et al. (2009) developed a 2-D coupled wave-current model based on the Wind Wave Model II (WWM-II) and the Shallow water Hydrodynamic Finite Element Model (SHYFEM), which has an unstructured model mesh. The WWM-II model was also coupled with the Semi-implicit Eulerian-Lagrangian Finite-Element (SELFE) ocean model (Roland et al., 2012) and the Regional Ocean Modeling System (ROMS) (Dutour-Sikiric et al., 2013). Wang and Shen (2011) developed a spectral wave model and coupled it to the Finite-Volume Community Ocean Model (FVCOM) of Chen et al. (2003). The Simulating WAves Nearshore (SWAN) model, as one of the most commonly used wave model, has been coupled to different ocean circulation models (Warner et al., 2008b; Liu et al., 2010; Dietrich et al., 2011; Guillou and Chapalain, 2011; Kumar et al., 2012; Bever and MacWilliams, 2013; Allard et al., 2014; Feng et al., 2016). Most of the coupled models based on SWAN are developed on structured meshes except for the models of Bever and MacWilliams (2013), Dietrich et al. (2011) and Feng et al. (2016). Bever and MacWilliams (2013) coupled the SWAN model to the Unstructured Tidal, Residual, and Inter-tidal Mudflat (UnTRIM) hydrodynamic model of Casulli and Zanolli (2005). Dietrich et al. (2011) and Feng et al. (2016) coupled the SWAN model to the depth-integrated ADvanced CIRCulation (ADCIRC) model. In the present paper, another unstructured mesh model, FVCOM, will be coupled with SWAN. Both SWAN and FVCOM are extensively used in coastal and nearshore studies and they are open source community models. Different from Wu et al. (2011), who coupled a finite-volume version of SWAN (called SWAVE) developed by Qi et al. (2009) and FVCOM directly, where SWAVE is a module of FVCOM, in our study, original SWAN is coupled to FVCOM. Original SWAN adopts fully implicit method and is stable for any time step (Zijlema, 2010), while SWAVE uses explicit or semi-implicit method (Qi et al., 2009), which, however, usually requires a smaller time step than SWAN. This indicates that SWAVE is less efficient than SWAN model, and this may largely limit the applications of FVCOM, especially in a situation where waves are important. In the present study, a popular coupling tool, Model Coupling Toolkit (MCT) is used. MCT allows the exchange of distributed data between component models and preservation of the original codes of the individual model as much as possible. It has been used in the coupled system of ROMS (Warner et al., 2008b). It is relatively easy to update the codes of SWAN and FVCOM in the coupled model when the new versions of these two models are released.

The rest of this paper is organized as follow. The models and coupling method are presented in section 2. Model evaluation is given in section 3. Model efficiency analysis is discussed in section 4 and conclusions are drawn in section 5.

2. Approaches to the coupled model

2.1. Models

2.1.1. FVCOM

The FVCOM model, initially developed by Chen et al. (2003), has been successfully applied to studies for regional-scale ocean and coastal areas (Lai et al., 2010). It is discretized using an unstructured triangle mesh in the horizontal direction, and a terrain-following coordinate, sigma coordinate, is used in the vertical. The three-dimensional governing equations with Boussinesq approximation are presented as follows.

$$\frac{\partial uD}{\partial t}+\frac{\partial u^2D}{\partial x}+\frac{\partial uvD}{\partial y}+\frac{\partial u\omega}{\partial \sigma}-fvD=-gD\frac{\partial \eta}{\partial x}-\frac{D}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{gD}{\rho_0}\left(\int_\sigma^0 D\frac{\partial \rho}{\partial x}d\sigma-\frac{\partial D}{\partial x}\int_\sigma^0 \sigma\frac{\partial \rho}{\partial \sigma}d\sigma\right)-\frac{\partial DS_{xx}}{\partial x}-\frac{\partial DS_{xy}}{\partial y}+\frac{\partial S_{px}}{\partial \sigma}+\frac{1}{D}\frac{\partial}{\partial \sigma}\left(K_m\frac{\partial u}{\partial \sigma}\right)+DF_u \tag{1}$$

$$\frac{\partial vD}{\partial t}+\frac{\partial uvD}{\partial x}+\frac{\partial v^2D}{\partial y}+\frac{\partial v\omega}{\partial \sigma}+fuD=-gD\frac{\partial \eta}{\partial y}-\frac{D}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{gD}{\rho_0}\left(\int_\sigma^0 D\frac{\partial \rho}{\partial y}d\sigma-\frac{\partial D}{\partial y}\int_\sigma^0 \sigma\frac{\partial \rho}{\partial \sigma}d\sigma\right)-\frac{\partial DS_{yx}}{\partial x}-\frac{\partial DS_{yy}}{\partial y}+\frac{\partial S_{py}}{\partial \sigma}+\frac{1}{D}\frac{\partial}{\partial \sigma}\left(K_m\frac{\partial v}{\partial \sigma}\right)+DF_v \tag{2}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial \sigma}{\partial x}\frac{\partial u}{\partial \sigma}+\frac{\partial \sigma}{\partial y}\frac{\partial v}{\partial \sigma}+\frac{1}{D}\frac{\partial w}{\partial \sigma}=0 \tag{3}$$

$$\frac{\partial \eta}{\partial t}+\frac{\partial Du}{\partial x}+\frac{\partial Dv}{\partial y}+\frac{\partial \omega}{\partial \sigma}=0 \tag{4}$$

where u, v and w are the velocity components in the horizontal x, y and vertical z directions, respectively; ω is the transformed vertical velocity corresponding to the σ coordinate; η is the water surface elevation; D is the total water depth; f is the Coriolis parameter; ρ_0 is the reference density; ρ is the in situ density; p_a is the atmospheric pressure; K_m is the vertical eddy viscosity; g is the gravitational acceleration; F_u and F_v are the horizontal diffusion terms; and S_{xx}, S_{xy} and S_{yy} represent the components of wave radiation stresses.

Expressions of recent three-dimensional wave radiation stresses of Ji et al. (2017) are adopted here. Their work has improved the expressions of Mellor (2003, 2015) by the terms representing the vertical variation of the dynamic pressure, which were derived through the Lagrangian wave solutions including the bottom slope effects. The horizontal radiation-tress terms in Eq. (1) and Eq. (2) are

$$\begin{aligned}S_{xx}&=kE\left[\frac{k_xk_x}{k^2}F_{CC}F_{CS}+F_{CS}F_{CC}-F_{SS}F_{CS}\right)\right]+\frac{k_xk_x}{k}\frac{c^2}{L}A_RR_{zn}\\S_{yy}&=kE\left[\frac{k_yk_y}{k^2}F_{CC}F_{CS}+F_{CS}F_{CC}-F_{SS}F_{CS}\right]+\frac{k_yk_y}{k}\frac{c^2}{L}A_RR_{zn}\\S_{xy}&=S_{yx}=kE\left[\frac{k_xk_y}{k^2}F_{CC}F_{CS}\right]+\frac{k_xk_y}{k}A_RR_{zn}\end{aligned} \tag{5}$$

where the terms using brackets represent traditional radiation stresses due to waves (Mellor, 2003, 2015; Ji et al., 2017), and the last terms are the surface-roller terms (Svendsen, 1984a). In Eq. (5) k is the wavenumber, with k_x and k_y as the x and y components; c is the phase celerity; L is the wave length; E is the wave energy; and A_R is the roller area, which is calculated based on the formula of Svendsen (1984a).

$$A_R=\frac{\alpha}{\sqrt{2}}H_sLQ_b \tag{6}$$

where H_s is the significant wave height; Q_b is the fraction of breaking waves; and α is a parameter.

R_{zn} in Eq. (5) represents the vertical distribution for wave surface-roller, which is calculated as follows

$$R_{zn}=1-\tanh\left(\frac{2\sigma D}{H_s}\right)^4 \tag{7}$$

Following Ji et al. (2017), the vertical radiation-tress terms in Eq. (1) and Eq. (2) are written as

$$\begin{aligned}S_{px}&=-\left[\frac{1}{2}ga_0M_2\frac{\partial a_0M_1}{\partial x}-\frac{1}{2}kga_0^2\frac{\partial D}{\partial x}(M_2N_1-M_1N_2)\right]\\S_{py}&=-\left[\frac{1}{2}ga_0M_2\frac{\partial a_0M_1}{\partial y}-\frac{1}{2}kga_0^2\frac{\partial D}{\partial y}(M_2N_1-M_1N_2)\right]\end{aligned} \tag{8}$$