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Development of an unstructured-grid wave-current coupled model and its application

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ABSTRACT

An unstructured grid wave-current coupled model was developed by coupling the SWAN (Simulating Waves Nearshore) wave model and ADCIRC (Advanced Circulation model) ocean model through the Model Coupling Toolkit (MCT). The developed coupled model has high spatial resolution in the coastal area and is efficient for computation. The efficiency of the newly developed SWAN + ADCIRC model was compared with that of the widely-used SWAN + ADCIRC coupled model, in which SWAN and ADCIRC are coupled directly rather than through the MCT. Results show that the directly-coupled model is more efficient when the total number of computational cores is small, but the MCT-coupled model begin to run faster than the directly-coupled model when more computational cores are used. The MCT-coupled model maintains the scalability longer and can increase the simulation efficiency more than 35% by comparing the minimum wall clock time of one day simulation in the test runs.

The MCT-coupled SWAN + ADCIRC model was used to simulate the storm surge and waves during the typhoon Usagi which formed in the western Pacific on September 17, 2013 and landed at Shanwei, China. Three numerical experiments were performed to investigate the effect of wave-current interaction on the storm surge and waves. The results show that the coupled model can better simulate the storm surge and waves when considering the wave-induced radiation stress, the wave effect on the wind stress drag coefficient and the modulation of current and water level on waves. During the typhoon Usagi, the effect of wave radiation stress could result in a maximum of 0.75 m increase in the extreme storm surge, and the wave induced wind stress could cause a −0.82~0.48 m change of the extreme storm surge near the coastal area. Besides, the radiation stress forced currents cannot be ignored either in the study of mass transport at coastal zones. Results of this study are useful for understanding the wave-current interaction processes and the development of the operational prediction technique for storm surge and waves.

1. Introduction

Strong typhoons can cause storm surge and huge waves and thus bring marine disasters to the coastal area where they land. Efficient and accurate marine forecasting systems are of paramount need for adaption of the human society. Numerical model is a powerful tool for storm surge and wave forecasting. Among others, ocean models with unstructured grid are suitable for simulating hydrodynamic processes from global to estuarine scales, particularly for regions with irregular coastline, and a coupled model considering wave-current interaction is more reasonable in the model physics (Huang et al., 2010; Xie et al., 2001; Yin et al., 2009). The increasing computational resource in recent years allows for using numerical models with higher resolution and complexity to improve the simulation and forecast of ocean processes during typhoons.

Nowadays wave-current coupled models have been widely used in oceanographic research. The coupled models can be categorized into structured and unstructured grid models according to their computational grid type, and the coupling can be carried out directly between model components or through a coupler. In a directly coupled system, the model components run on the same CPU cores alternately, and the data is transferred through the computer memory or documents. If a coupler is used, the model components can run on different CPU cores concurrently, and the data is transferred through the coupler. The ROMS+SWAN coupled model developed by Warner et al. (2008) is a structured grid, coupler-coupled model which is successfully utilized in many

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researches (Feng et al., 2011; Bever and Harris, 2014), the coupler they used is the MCT (Model Coupling Toolkit); the directly coupled structured grid model POM + SWAN (Xie et al., 2008) was also used to study the physical mechanism of wave-current interaction; directly coupled unstructured grid model, such as FVCOM + SWAVE (Sun et al., 2013; Wu et al., 2011), SELFE + WWM (Roland et al., 2012) and SWAN + ADCIRC (Dietrich et al., 2011; Dietrich et al., 2012), also showed good performance in the coastal hydrodynamic process modeling. These studies have greatly integrated our knowledge of wave-current interaction, and the importance of wave-current interaction processes in ocean modeling has been increasingly realized.

For the numerical models, the structured grid model cannot fit the complex coastline as well as the unstructured grid model, so the models based on the unstructured grid is preferred in the operational storm surge and wave forecasting system. The SWAN + ADCIRC model developed by Dietrich et al. (2011) is a kind of unstructured grid and directly-coupled wave-current model. This model allows for localized increases in resolution without cost of nested meshes, it also allows the SWAN and ADCIRC components to run on the same unstructured mesh, eliminating the need for interpolation between models. These characteristics make SWAN + ADCIRC an accurate and efficient coupled model (Dietrich et al., 2011; Hope et al., 2013; Sebastian et al., 2014). But it is found that the linear scalability of the directly-coupled SWAN+ADCIRC will be deteriorated when the model is decomposed on number of cores larger than a certain value (Dietrich et al. 2012), which means that the efficiency of the model does not increase when the number of the computational cores are larger than some certain value. The deterioration of the model scalability cannot be avoided, but we would try to make the linear scalability of the SWAN + ADCIRC coupled model maintain longer by changing the coupling method in this study, which will make the coupled model run faster when the computational resource is sufficient enough. Therefore, the primary aim of this study was to develop a coupler-coupled SWAN + ADCIRC model with unstructured grid, and compare the efficiency of the newly coupled model with the existing unstructured grid coupled SWAN + ADCIRC model which uses directly-coupled method. The results should be useful for the model selection of the marine forecasting system.

In this study, we evaluated the computational efficiency of the newly developed model. Also, the newly developed coupled model was used to simulate the storm surge and waves during the typhoon Usagi, and the effect of the wave-current interaction on the storm surge and waves was investigated through several numerical experiments. The rest of the paper is organized as follows. Description of the coupled model and its efficiency tests are provided in Section 2. The model application to the Usagi is introduced in Section 3. The main findings are summarized in Section 4.

2. Methods

The unstructured-grid wave-current coupled model we developed is comprised of three components that include the ocean current model ADCIRC, the wave model SWAN, and the coupler MCT. In this section we describe each of the three model components, the wave-current physical processes in the model physics, and the test of computational efficiency of the coupled model.

2.1. Ocean model

The ocean current model component used in this study is the Advanced Circulation model, based on unstructured computational grid and finite-element difference method (ADCIRC) (Westerink et al., 1991). This model can simulate the process of inundation by wetting and drying grid, it can also compute the overflow and throughflow for barriers in the ocean. A subgrid scale obstruction parameterization has been developed and implemented in ADCIRC to solve the problem of small scale flow around obstructions such as bridge pilings. These features make ADCIRC a wonderful tool in coastal hydrodynamic modeling. The ADCIRC model has been widely used in the world in the past two decades (Blain et al., 1998; Feng et al., 2012; Westerink et al., 1991). Water levels and currents in the model are computed through solution of the vertically-integrated continuity equation and the vertically-integrated momentum equations separately. In the coupled model we developed, the ADCIRC component is forced by the wind stress, surface pressure, wave-induced radiation stress and the tidal elevation through the open boundary conditions.

In the uncoupled ADCIRC model, wind stress is the function of wind speed. The wind drag coefficient is calculated by the Garratt formula (Garratt, 1977),

$$C_d = 0.001(0.75 + 0.067W), \tag{1}$$

where C_d is the wind drag coefficient and W is the wind speed magnitude. Studies show that, the effect of surface waves should be taken into account when calculating the drag coefficient (Liu and Perrie, 2013; Xie et al., 2001; Yin et al., 2009). So, a new formula presented by Donelan et al. (1993) is adopted in the coupled model to calculate C_d, which accounts for the wave effect,

$$C_d = \left(\frac{K}{ln10 - lnZ_0}\right)^2,\ z_0 = 3.7 \times 10^{-5}\frac{W^2}{g}\left(\frac{C_p}{W}\right)^{-0.9}, \tag{2}$$

where C_p is the wave speed which corresponds to the peak frequency; $\frac{C_p}{W}$ represents the wave age; g is the gravitational acceleration; W represents the wind speed; K is the Karman constant and equals 0.4. The value of C_d is limited to 0.0025 when the wind speed exceeds 33 m/s (Donelan et al., 2004).

The wave-induced radiation stress is calculated according to Longuet-Higgins and Stewart (1962, 1964), as the way in the SWAN + ADCIRC coupled model of Dietrich et al. (2011). Other details of the ADCIRC model computational algorithms are described in Luettich and Westerink (2004).

2.2. Wave model

The wave model component is SWAN (Simulating WAves Nearshore), which is a spectral wave model designed for shallow water area (Booij et al., 1999). Version of the unstructured grid SWAN model, based on the work of Zijlema (2010), is implemented in the coupled model we developed, thus SWAN and ADCIRC model can run on the same computational grid.

SWAN solves the action balance equation (Holthuijsen, 2008), in which the action density is conserved when the currents presents, thus allowing the input of ocean currents and water level. Time and spatial varying currents and water level can influence the propagation of surface waves. To account for the effect of wave-current interaction on the waves, the ocean currents and water level provided by the ADCIRC are sent to SWAN in the coupled model.

2.3. MCT coupler

The coupler used in the coupled model we developed is the Model Coupling Toolkit (MCT; Jacob et al., 2005; Larson et al., 2005), which is a set of open-source software tools to create coupled models. MCT provides a Fortran-based object and a collection of library routines which can reduce the effort required to couple several parallel models into a parallel coupled model. The model component can run sequentially or concurrently under the control of MCT, and the data can be transferred between model components through MCT. MCT has been successfully used in the coupled model of COAWST (Warner et al., 2010).