Wind Wave Effects On Surface Stress In Hydrodynamic Modeling

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ABSTRACT

Wind, wave and current interactions control the boundary fluxes, momentum and energy exchange between the atmosphere and the ocean, and within the water column. The wind wave effect on surface stress is investigated using a three-dimensional time-dependant ocean circulation model. The POM (Princeton Ocean Model) based model is implemented with realistic coastlines in South China Sea and emphasizes the simulation of physical parameters in the water column. Taking account of the wind waves, an increase in air-sea drag coefficient, reflecting an enhanced sea surface roughness due to increased wave heights, is shown to improve the simulated surface current and the sea surface elevation. It is also found that developing waves with smaller peak periods influenced the surface circulation more significantly.

KEY WORDS: Wave-current interaction; surface stress; ocean circulation model; model coupling.

INTRODUCTION

In the ocean environment, the physical processes governing the water column are influenced by atmospheric flow, currents, surface waves, tides and their mutual interactions. A better understanding of the physical process is essential for studying the chemical and biological processes in scientific and practical applications, such as beach erosion, upwelling, storm surges and transport of various materials. Compared to high cost of field measurements, the numerical model for solving time dependent flows is both effective and economical. Extensive and intensive studies of ocean modeling have been undertaken in last a couple of decades. Ocean models have become an important tool for understanding the seasonal ocean circulation and thermal structure, and for establishing a nowcast system for regional seas.

The South China Sea (SCS) has complex bottom topography and open boundaries. The hydrodynamics in the region is very complicated. Metzger and Hurlburt (1996) first applied a layered model to the SCS and compared upper layer currents and sea levels of the model with the observed data. Recently, Cai et al. (2002) developed a coupled singlelayer/two-layer model to study the upper circulation. An enhanced

understanding of the circulation characteristics has been achieved. Chu and Chang (1997) and Chu et al. (1999) studied the seasonal thermodynamics in the SCS using the POM with limited boundary conditions, monthly mean climatological wind stress data set (Hellerman and Rosenstain, 1983) and bi-monthly variation of mass transport at the open boundaries (Wyrtki, 1961).

Wind wave impact on the ocean circulation is an important aspect of the hydrodynamics. Recent computational studies by Davies and Xing (2000), Xie etc al. (2001) and Moon (2005) bear this point. Their studies show that the wave contributes to local current and sea level changes, and momentum and stratification mixing throughout the whole water column. Moon (2005) also investigated the effects of ocean waves on sea surface temperature simulations. Without considering the wave effect at the surface, the surface stress is a function of wind speed based on the drag coefficient (Large and Pond, 1981). However, the action of wind over the sea induces the exchange of momentum between air and ocean, leading to wave development. Therefore the surface stress would be significantly enhanced by the wind waves. Charnock (1955), Janssen (1989, 1991) and Donelan et al. (1993, 2004) presented various models to calculate surface roughness by taking into account the effects of the surface waves. Most recently, Massel and Brinkman (2001) presented an analytical solution for the wave-induced set-up and flow through simple shoal geometry when water depth is a linear function of distance. The existing empirical knowledge has shown that surface waves enhance the mixing in the upper ocean, which can be applied to the newly derived continuity, momentum and energy equations for more accurate modeling. Mellor (2003) and Qiao et al. (2004) coupled surface wave equations to mixing equations in three-dimensional ocean models. Their result has confirmed a strong wave-induced mixing in both hydrodynamics and temperature. Graig and Banner (1994) and Zhang and Chan (2003) have suggested that surface waves can enhance mixing in the upper ocean. The SCS is monsoon dominated, and surface waves play a significant role in the circulation process.

In the present study, the wind wave effect to the circulation is investigated using a three-dimensional time-dependant POM based model. The model is configured with realistic coastlines and the emphasis is on the simulation of physical parameters in the water column. A third-generation wave model (WAM) is employed to predict the wave parameters. The wind wave effect on the circulation is examined by applying the theory of Janssen (1991) to estimate the effect of waves on the sea surface roughness. The improved formulation of surface stress has been incorporated into the POM model. The simulation results in the period of April - May 2001 show that the surface stress with the consideration of waves increases. It is also found that developing waves with smaller peak periods influenced the surface circulation more significantly than the developed waves.

MODEL DESCRIPTION

Circulation model

The flow equations governing ocean circulation in POM consists of the hydrostatic, the Boussinesq Navier-Stokes equations along with an equation of state which incorporates the temperature and salinity of the fluid velocity. The hydrostatic assumption and the Boussinesq approximation are commonly used in ocean circulation modeling based on the premise that the horizontal extent is much larger than the vertical extent. The governing equations of the continuity equation, the Reynolds momentum equations, the conservation equations for potential temperature and salinity and the turbulent kinetic energy are thus formulated in orthogonal Cartesian co-ordinates with *x* increasing in the eastward direction, *y* increasing in the northward direction and *z* measuring vertically upwards from an undisturbed water level (Mellor, 2003).

Wave model

In the present study, a third-generation wave model, WAM (Komen et al., 1994) was adopted. WAM estimates the evolution of the energy spectrum for ocean waves by solving the wave transport equation explicitly without any presumptions on the shape of the wave spectrum. The net source functions of the whole system takes into account all physical processes which contribute to the evolution of the wave spectrum, representing source terms due to wind input, non-linear wave-wave interaction and dissipation due to wave breaking and bottom friction.

The synthesis of these source terms as expressed in WAM (Komen et al., 1994) signifies the current state of understanding of the physical processes of wind waves, namely that inputs from these processes balance each other to form self similar spectral shapes corresponding to the measured wind wave spectra. Except for the non-linear source term, all the other source terms are individually parameterized to be proportional to the action density spectrum. The non-linear source uses the discrete interaction approximation (DIA) to simulate a non-linear transfer process, representing the four-wave resonant interaction Boltzmann equation and this characterizes the third-generation models.

Models' coupling

Winds blowing at the sea surface constitute an important driving force for ocean currents. Generally, the wind stress at the surface is therefore a necessary forcing parameter for an ocean circulation model. The surface wind stress over the ocean is directly correlated to the wind vectors. Normally, the wave-independent zonal (τ_{sx}) and meridional (τ_{sy}) components of the wave-independent stress are defined as,

$$\tau_{sx} = \rho_{a} C_{D} V_{10} u_{10}$$

$$\tau_{sy} = \rho_{a} C_{D} V_{10} v_{10}$$
(1)

where ρ_a is the air density; (u_{10}, v_{10}) are the (x, y) components of wind speed V_{10} at 10 m above water; C_D is the surface drag coefficient. Initially, the drag coefficient formulation is based on Large and Pond (1981) modified for low wind speeds as suggested by Trenberth (1990):

$$C_{D} = \begin{cases} 2.18 \times 10^{-3} & \text{for } V_{10} \le 1 \text{ m/s} \\ (0.62 + \frac{1.56}{V_{10}}) \times 10^{-3} & \text{for } 1 \text{ m/s} < V_{10} < 3 \text{ m/s} \\ 1.14 \times 10^{-3} & \text{for } 3 \text{ m/s} \le V_{10} < 10 \text{ m/s} \\ (0.49 + 0.065V_{10}) \times 10^{-3} & \text{for } V_{10} \ge 10 \text{ m/s} \end{cases}$$

$$(2)$$

The above equation has been commonly applied in ocean modeling, however it doesn't include the wave effect. As the wind blows over the ocean, surface waves are developed. The developing waves significantly enhance the surface roughness and hence, surface stress due to waves should be considered (Johnson and Vested, 1992; Andrey et al., 2001; Donelan et al., 2004).

The surface stress of airflow over sea waves depends on the sea state. From a consideration of the momentum balance of air it is found:

$$\tau = \rho_a C_D V_{10}^{2}, \tag{3}$$

where C_D can be expressed by the shear velocity definition as:

$$C_D = \{ \kappa / (\ln(z / z_{0s})) \}^2 .$$
(4)

Here $\kappa = 0.4$ and the surface roughness

$$z_{\theta s} = \frac{\alpha \tau}{g} / \sqrt{\left(I - \left(\tau_{w}\right) / \tau\right)}$$
⁽⁵⁾

where α is the Charnock constant (Charnock,1955), τ is the total surface stress and τ_w is the wave-induced stress equals the amount of the momentum going to the waves due to wind.

Because only the developing waves contribute to the surface roughness, the direction of those waves follows the direction of wind closely. Eq. 2 applies the direct paramerisation of C_D on wind speeds, however the improved formulation of Eq. 4 which is indirect paramerisation through a surface roughness height is coupled into the model. Drag coefficient in Eq. 4 is a more physically sound parameter. The surface roughness may vary for the same wind speed, and also associate with water depth, wave age or wind direction. The total shear stress due to wind and wave has been taken into account. By et al. (2001) also proposed a formulation to calculate the shear stress with more complicated consideration of the momentum transfer from the ocean to the atmosphere through the swell.

Coupling procedure

As mentioned above, in this study, there are two types of wave effects incorporated into the hydrodynamic model POM: through surface shear stress. The coupling of the two models takes place in the following sequence. Firstly, wave model calculates the directional wave spectrum and significant wave height with wind inputs. The outputs are then used to estimate the total surface stress by Eqs 3–5. These coupling values are then input into hydrodynamic model to model the circulations. In this study, the coupling process is one-way, which takes place every 1800 s.

APPLICATION DOMAIN

The modified ocean circulation model is applied to the South East Asian Seas. It covers the domain of 99°E-121°E and 9°S-24°N. A horizontal grid resolution of 1/6 degree and 20 Sigma-level are employed. As initial 720-day spin-up period is used, starting from an initial of stationary state with climatological March temperature and salinity field (WOA, 1998), which is driven by the climatological mean wind. From March 01, 2001 (day 721), the analyzed wind fields from ECMWF (European Commission for Medium Weather Forecasting) are applied to drive the model. The results shown in the following sections are in the domain of 115°E-121°E and 13°N-24°N. The study area covers the shallow coastal waters from the southern China coastline to the northern deep basin of South China Sea, as shown in Figure 1.



Fig. 1: The bathymetry in the domain.

Wind waves

In this study, the wave-induced surface and bottom stresses were considered in addition to the effect of currents. The wave model was set up over a larger domain of 99°E-170°E and 9°S-52°N with a bathymetric resolution of 1/6°, spectral resolution of 25 logarithmically spaced frequency components with $f_1 = 0.052$ Hz. The angular resolution is 30°. ECMWF winds at 0.5° resolution are used to drive the model. The model was calibrated and verified by using the available buoy measurements located at (121°55'25''E, 25°5'46''N) over the period of 1st June – 31st October 2001. The buoy wave data (H_s) are shown in a good agreement with the model predictions for the five months period in Figure 2.

Our study period is in April and May 2001, which is the inter monsoon period, when the wind direction is changing from the Northeast monsoon to the Southwest monsoon. During this transition time, a storm occurred during May 11-13, 2001, as shown in Figure 3. A strong northeast wind of about 13 m/s was recorded, extending from the Taiwan Strait to the Luzon Strait, and results the significant wave height and the peak wave period from WAM shown in Figure 4. On May 12, 2001, the significant wave heights reached 3 m in the deep central domain. The peak wave period reached 7 s in the deep basin where the wind-waves were fully developed. However the peak period is only 2.5 - 3.5 s in the shallow coastal water region. The influence of the wind-generated waves on the current is to be investigated.

Influence through the surface stress

The drag coefficients estimated by Eqs. 2 and 4 are used to calculated surface shear stress. Eq. 2 does not taken into account wave effects. The drag coefficient indirectly paramterized through surface roughness is predicted by Eqs. 3-5, where wave effects have be taken into account. Figure 5(a) shows surface shear stress depending only on the wind speed reaches up to $0.3 N/m^2$ on May 12, 2001. However, the surface stress including the wave contribution is illustrated in Fig. 5 (b);

the magnitude of the stress is determined to be up to 0.6 N/m^2 . These results show that the impacts of waves reach a maximum on May 12, 2001 with the rapid intensification of the cyclone. Figs. 5(a)-(b) clearly illustrate that the presence of waves greatly enhance the magnitude of the surface stress. In previous studies, the drag coefficient is shown to increase with wind speed as



Fig. 2: The comparison between the prediction and the buoy observation of significant wave heights over five month's period from June – October, 2001.



Fig. 3: The wind speed at (18N, 118E) in May 2001.

long as storm intensity does not exceed 30m/s (Powell et al., 2003; Donelan et al., 2004; Bye and Jenkins, 2006). In the present study, the maximum wind speed is less than 15 m/s.



Fig. 4: The significant wave height and peak wave period on May 12, 2001.



independent (b) wave-dependent.

Figure 6 further shows the comparison between the surface stresses calculated by Eqs. 2 and 4. Fig. 6(a) illustrates that with the greater wind speed the influence to the surface stress is greater. For low wind speed, the wave effect is not significant, but at wind speeds above 10 m/s, the magnitude of the surface stress can be doubled. Fig. 6(b) indicates that for developing waves with smaller peak periods the surface stress is influenced more significantly than for well developed waves, in agreement with Drennan et al. (2003)'s five recent field campaigns. It can be seen that Eqs. 3-5 includes the contribution of the surface wave to circulations. However, in the present study, the breaking wave induced current and the wave set-up haven't been investigated, which need to be further studied.

The wave-enhanced surface stress results in a greater increase in the surface velocity where the surface stress is enhanced. The maximum difference for surface currents can reach 0.4 m/s in the central part of the domain where the storm has its maximum intensity. The surface elevation also increases in the shallow region and the variation can be up to 0.12 m, which reaches 50% of the surface elevation near the coast.



Fig. 6: (a) The relationship between the wind speed and the surface stress. (b) The relationship of the wind speed, the wave period and the surface stress. (+ without wave effects; * with wave effects)

CONCLUSIONS

The influence of the wind waves on the ocean circulation was investigated. The improved formulation of the surface stress depends on the wind speed and the roughness of the water surface, which is prescribed to update the surface drag coefficient in the circulation model. The knowledge of windwave characteristics was incorporated into the circulation model. Its utility has been examined by presenting results generated in the South China Sea.

When the wave-enhanced surface stress is accounted for in the model, the impact of strong winds is significant for surface current. The present results suggest that waves have significant impacts in shallow regions, and high wave and low peak period conditions. We consider the influence of waves on the circulation through the surface. Comparison with the field measurements show that taking waves into account can improve the correlation between modeled and measured currents from 0.50 to 0.56.

In the present study, we examined only the influence of wind waves on the hydrodynamics. Further study on the sediment transport and the trajectory of water particles is ongoing, to obtain a better prediction capacity of the ocean environment. The effect of wind waves on the thermal dynamics will also be considered in a future study.

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