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Simulating the Sandwaves Moving with a Ultra-High Resolution Three Dimensional Hydrodynamic Model

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ABSTRACT

An ultra-high horizontal resolution (about 200m) three-dimensional ocean model is developed to simulate the bottom current of observation area with size of 40 kilometers. The model takes tidal force, surface wind and baroclinic effect into account and adopts grid-nesting technique to achieve the horizontal resolution level. With the current simulated, a sediment transport model is developed and applied in the prediction of small scale sandwaves migration in study area of Beibu Gulf, South China Sea. The migration directions both on the ridge back and the ridge groove that are opposite are successfully predicted.

KEY WORDS: Ultra-high resolution; sediment transport; small scale sand wave; migration; grid-nesting.

INTRODUCTION

The sand waves, with wavelengths from tens of meters to kilometers and heights of several meters, can be found in many sandy shallow seas. Unlike static sand ridges and sandbanks, the sand waves often migrate with speed of up to some tens of meters per year (Nemeth et al, 2002; Besio et al, 2004; Lin et al, 2009a). Their dynamics can endanger some economical activities, such as cables exposed, pipeline spanned, and sea-route stemmed, etc. Sand wave migration simulating is helpful and necessary to the prediction of these above potential dangerous.

Many researchers assumed that interactions of oscillatory tidal flow and an erodible bed should be responsible for the sand wave formation and migration (Hulscher, 1996; Komarova and Hulscher, 2000; Nemeth et al, 2002; Besio et al, 2004; Lin et al, 2009a; Lin et al, 2009b). Hulscher (1996) demonstrated with a three-dimensional morphodynamic model, assuming a constant turbulent viscosity. Komarova and Hulscher (2000) improved this model into a turbulence model, which allows for a variable thickness of the current boundary layer. Later, Nemeth et al (2002), Besio et al (2003, 2004) disrupted the basic symmetry tidal flow and developed an asymmetric vertical circulative water motion model induced by the interactions between steady current or higher-frequency constituents and sinusoidal tidal flow. The extended morphodynamic model can predict the sand wave formation and migration. For large scale sand waves with the wavelength as the same order as the tidal wavelength, Nemeth el al (2002)'s results revealed that a migration of sand wave was normal to its crest and always in the direction of the residual current. For small scale sand wave with wavelength much smaller than tidal wavelength, Lin et al (2009a) built a quasi-3D mechanics model, based on the depth-averaged hydrodynamic equations. The results are shown to be consistent with the observation in the trough of the sand ridge and opposite to the observation in the back of the sand ridge. We think that ascribe this discrepancy is due to ignoring the effect of bed form. As known, the near-bed velocity should depend on the horizontal gradient pressure, sea surface wind, complex topography, and etc. Thus a three-dimensional hydrodynamic model containing above effects is applied in this paper.

We adopt a three dimensional primitive equation ocean model, Princeton Ocean Model (Blumberg and Mellor, 1987, POM for short), to get the real-time flow field in the study area. In order to catch enough information of the seabed topography, grid-nesting technique is used twice to reach horizontal resolution of about 200m which is eight times higher than common high horizontal resolution level. The tidal potential, sea surface wind stress and horizontal pressure gradient are contained in this model. With the current simulated, a sediment transport model is developed and applied in the prediction of small scale sand wave migration of the study area.

PHYSICAL MODEL

Study Area

Beibu Gulf is a semi-closed shallow gulf, and the average water depth is about 50m. The dominating tidal constituents here are K1 and O1. M2 constituent is also concerned in this paper because its nonlinear effect is of certain importance though the magnitude is significantly smaller than K1 and O1 constituents (Fang et al, 1999). Meanwhile, this bay also suffers the monsoon, e.g. the Asia monsoon and the Australia monsoon. The wind orientation is NE in winter S-SSW in summer and reverses both in April and September every year (Hellerman and Rosenstein, 1983). The difference of sea water temperature between surface and sea bottom is larger than 10°C and changing with month. Therefore, the hydrodynamic model needs to consider the influences of K1, O1, M2 constituents, density distribution and the monsoon in order to make it closer to reality.

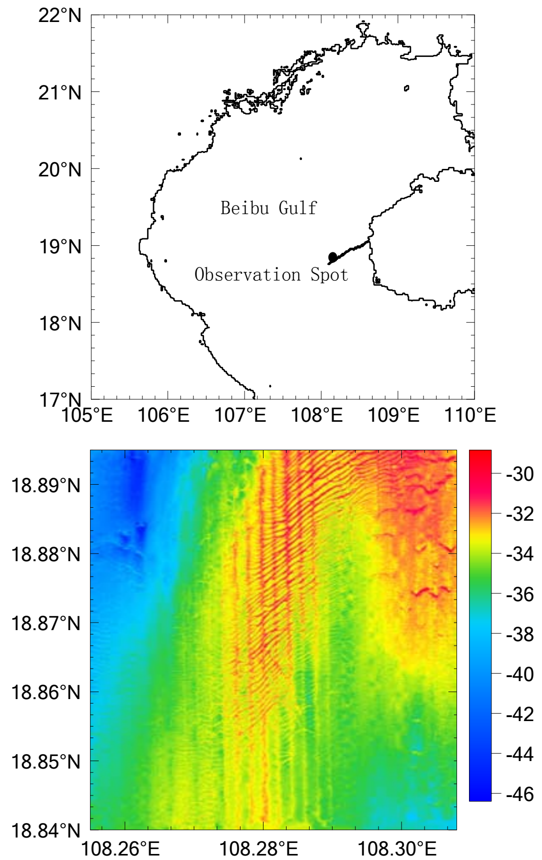

Fig.1. Position and bathymetry of the observation spot (measured in Jul.2004)

From Jul. 2004 to Oct. 2005, the scientists of Chinese Academy of Science (CAS for short) surveyed the bathymetry using multi-beam system in the region from (108°15.24′E, 18°50.29′N) to (108°18.57′E, 18°54.04′N) (Fig.1). This region is nearly 40km^2 in size. There is a ridge with the width of about 1km in the middle. The depth is about 30m at the ridge back and 38m at the ridge groove. There are over 100 sand waves with the wavelengths of about 30m and the heights of less than or equal 2m. These sandwaves in shallow water region should be small scale ones according that their wavelength are much smaller than tidal wavelength. Fig.1 shows the position and multi-beam high-resolution bathymetry data (the longitudinal and latitudinal resolution are both 5m) of the observation region that is chosen as study area. The observations between Jul. 2004 and Oct. 2005 indicate that the sand waves on the ridge back migrate to the north, while the ones in the ridge groove migrate to the south.

Hydrodynamic Model and Nesting Procedure

The numerical ocean model (POM) is applied to simulate the flow field of the Beibu Gulf. In the semi-closed region, the water can enter from the south gulf and exit at the east opening, the other parts are land and can be treat as non-slip boundaries. The bathymetry of the gulf is from ETOPO1 (Amante and Eakins, 2009, horizontal resolution is about 1800m). In the observation are, the bathymetry resolution is enriched with multi-beam data. We clamped the elevation on the lateral open boundaries to simulate tidal forcing and the Orlanski radiation boundary condition (Orlanski, 1976) is used for barotropic and baroclinic velocities. The clamped open boundary elevation is the sum of K1, O1 and M2 constituents, as show in Eq. 1.

η denotes elevation; $f_i, H_i, \omega_i, v_i, g_i$ denote the nodal coefficient, amplitude, frequency, astronomical initial angle, and phase-lag of i constituent separately. These data are from TPXO model (Egbert and Erofeeva, 2002). The sea surface boundary of moment equation in POM is shown in Eq. 2.

$$\frac{K_M}{D}\left(\frac{\partial U}{\partial \sigma},\frac{\partial V}{\partial \sigma}\right)\bigg|_{\sigma=0} = -\left(<wu(0)>,<wv(0)>\right) \qquad (2)$$

U,V denote the longitudinal and latitudinal velocity components; σ denotes the vertical sigma coordinate; K_M denotes the vertical mixing coefficient, $D=H+\eta$, H denotes the water depth below mean sea level; $<wu(0)>,<wv(0)>$ denote the longitudinal and latitudinal sea surface wind stress components, and monthly averaged data interpolated from Hellerman and Rosenstein (1983) are used here. Monthly averaged temperature and salinity data from WOA01 (Boyer et al, 2005) are adopted here to generate background density distribution to calculate the horizontal pressure gradient and held static during the calculation.

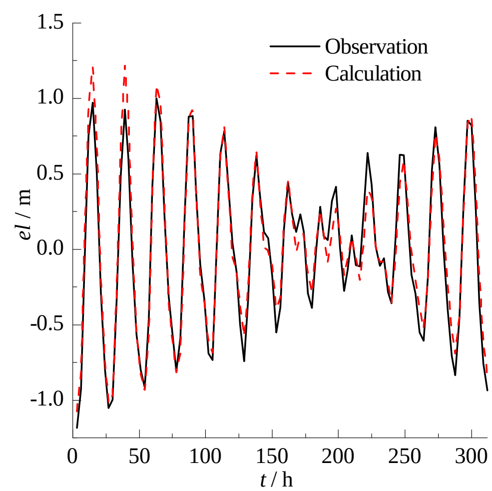

Fig.2. Comparison of time series of elevation

From Aug.21, 2006 to Sep.2, 2006, the scientists of CAS organized another survey and the time series of elevation and velocities at (18°53.765'N, 108°5.614'E) were observed. The data are helpful to verify the above model's ability of simulating the tide and the flow. The calculations under corresponding boundary condition (the wind stresses, temperature, salinity and astronomical initial angle are at the time range from Aug.21, 2006 to Sep.2, 2006) are compared with the observation. Fig.2 shows that the calculation of the time series of elevation is in agreement with the observation. From Fig.3, we can conclude that the model in this paper is able to simulate the time-averaged velocity profile of the study area with considerable accuracy.

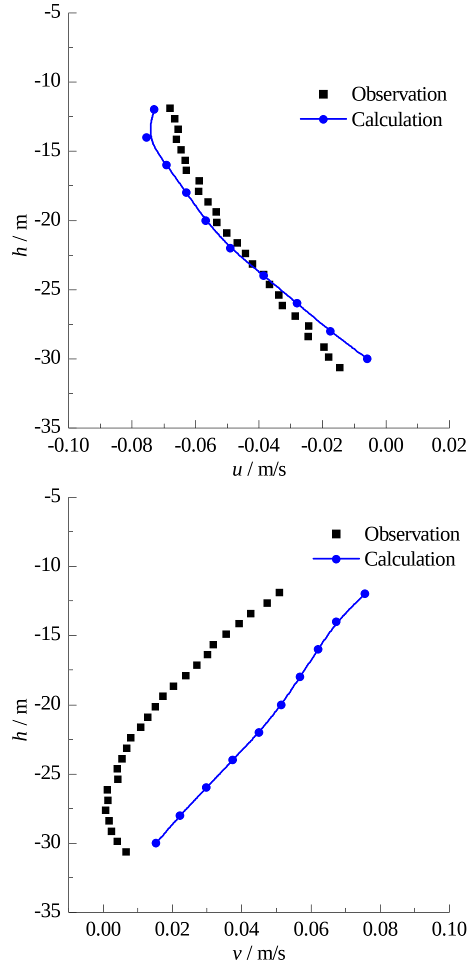

Fig.3. Comparison of time-averaged velocity profiles

To reach horizontal resolution of about 200m, coarse-fine grid-nesting technique is a convenient approach. One-way grid-nesting is used twice. As shown in Fig 4, the whole gulf (Fig.4a, from 105°36′E, 17°36′N) to 110°0′E, 21°41′N) with grid spacing of 1800m forms Coarse Grid Model (CGM for short) and therein the lateral open boundaries are specified in the way mentioned above; Subsequently, the black rectangle area in Fig.4a (zoomed in as Fig. 4b, from 107°51′E, 18°21′N to 108°51′E, 19°21′N) with grid-spacing about 600m forms Medium Grid Model (MGM for short) and therein the lateral open boundaries are interpolated from CGM's calculations; After that, the black rectangle in Fig. 4b (zoomed in as Fig.4c, from 108°03′E, 18°39′N to 108°30′E, 19°06′N) with grid-spacing about 200m forms Fine Grid Model and therein the lateral open boundaries are interpolated from MGM's calculation in real time. The blue rectangles in Fig. 4a, 4b, 4c indicate the observation area (from 108°15.24′E, 18°50.29′N to 108°18.57′E, 18°54.04′N). Grid-nesting technique is proved to be an efficient and accurate way to simulate high-resolution problem when the open boundary values are hard to get and have to be calculated from a larger region model.

The vertical grids are denseness near the sea bed, about 3 grids in 1 meter, which resolve the existence of the sand ridge and its influence on the bottom current field.

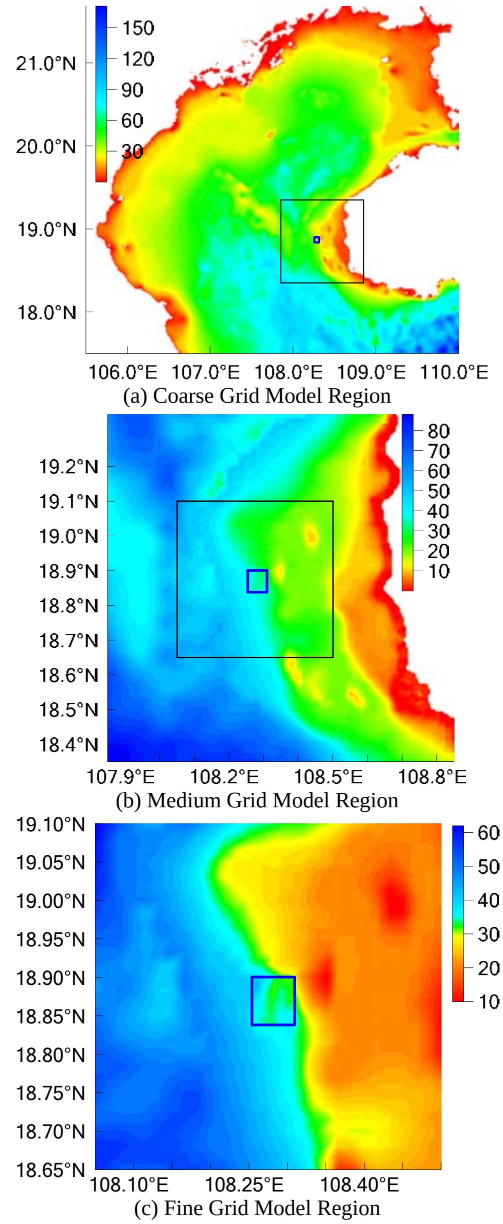

Fig.4. Areas of Coarse Grid, Medium Grid and Fine Grid Models

With the above models, considering the effects of tide, surface wind stresses and baroclinic field and using grid-nesting technique, the three dimensional flow fields of the observation area with the horizontal resolution of 200m can be simulated with considerable accuracy. The simulating current is close to the reality and ensures the feasibility to predict the sandwaves migration.

Sediment Transport Model

In tidal offshore regions, bed load transport is assumed to be dominant in the sediment transport (Nemeth et al, 2002). The law of conservation of sand mass for bed load transport reads,

$$\frac{\partial h}{\partial t} + \nabla \cdot q = 0 \qquad (3)$$

where h denotes the bottom level with respect to the undistributed water depth, q denotes the volumetric sediment transport vector and can be parameterized by Meyer-Peter-Muller formula plus Heaviside function to make it work for tidal motion:

$$q = 8\left|\frac{\tau_b}{g(s-1)d} - \Theta_C\right|^{3/2} \sqrt{(s-1)gd^3}\,\hbar\left(\frac{\tau_b}{g(s-1)d} - \Theta_C\right) \qquad (4)$$

$$\tau_b = \sqrt{\tau_{bx}{}^2 + \tau_{by}{}^2}$$

where $$q_x = \frac{\tau_{bx}}{\tau_b} q \qquad (5)$$

$$q_y = \frac{\tau_{by}}{\tau_b} q$$

here g denotes the gravity constant; $s = \rho_s / \rho$ is the relative density of the sediment (ρ_s) with respect to water density (ρ); d is grain diameter; $\hbar$ is the Heaviside function; τ_b is the volumetric bed shear stress; τ_{bx} and τ_{by} are longitudinal and latitudinal components of τ_b separately and Θ_c is the critical Shields parameter and set to 0.047.

Since the velocities profiles are being calculated explicitly, the bottom shear stress can be calculated through follow formula.

$$\tau_{bx,y} = K_M \left(\frac{\partial u}{\partial z}, \frac{\partial v}{\partial z}\right)\bigg|_{z=bottom} \qquad (6)$$

This formulation differs from the formula in which the bottom shear stress is parameterized as a function of bottom velocities as, for instance, given by Komarova and Hulscher (2000).

It is noticed that the current field near the sea bed and the sandwaves migration are calculated separately. The former has used refinements to reach grid spacing of about 200m with bathymetry measured in Jul.2004. The latter is based on a grid spacing about 5m which is interpolated from the hydrodynamic results with grid-spacing about 200m. It is the bottom shear stress Eq.6 that connects the hydrodynamic model and the sediment transport model.

Here, we have calculated the flow fields from Jul. 2004 to Oct. 2005. The effects of the tidal, wind and baroclinicity on residual current have been considered. And the values with month-averaged wind field, temperature and salinity field and astronomic initial angle of tidal constituents are calculated separately for the 16 months. Based on the flow fields of each month we predict the sandwaves migration during this time.

RESULTS AND DISCUSSION

On the basis of above model, calculations give following results. First of all, we compare the position of sandwave crests between the observation and calculation. We divide the study area into two subzones: P1 and P2. Fig.5 indicates their locations. The dash line indicates the position of sand ridge. P1 is just on the ridge back and P2 is in the ridge groove. There is a black line perpendicular to the crests of the sandwaves in each sub zone.

The crests' positions of the sand waves observed and calculated are plotted in Fig.6. From qualitative analysis, the migrating direction is consistent between calculations and observation in most part of the area. For convenience of quantitative analysis, we plotted the sandwaves profiles of P1 and P2 in Fig.7~8. In P1 zone, the sandwaves migrate northward. In P2 zone, the sandwaves migrate southward.

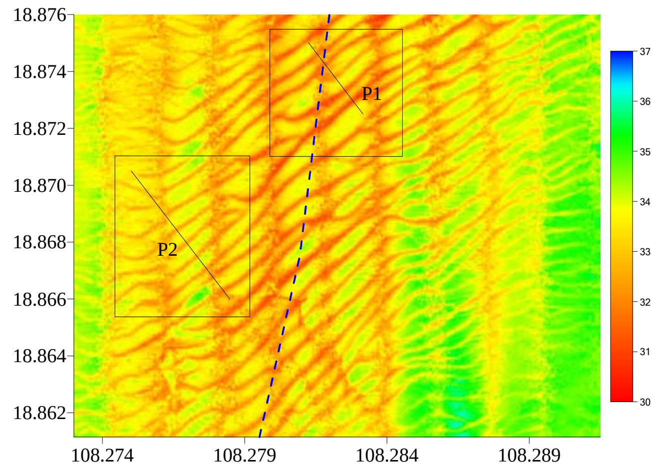

Fig.5. the location of two subzones

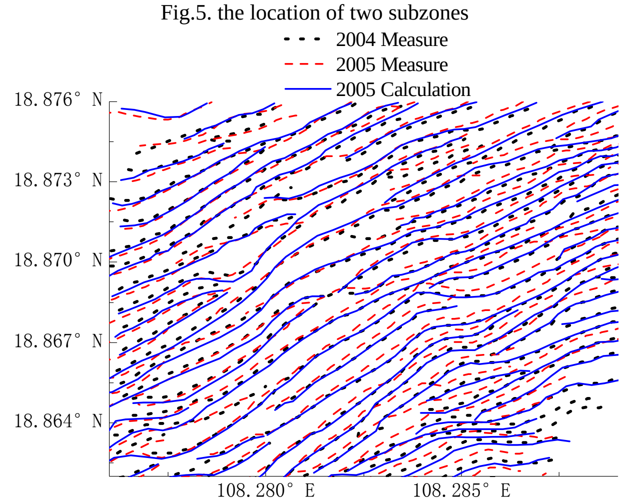

Fig.6. the crests' positions between observation and calculation

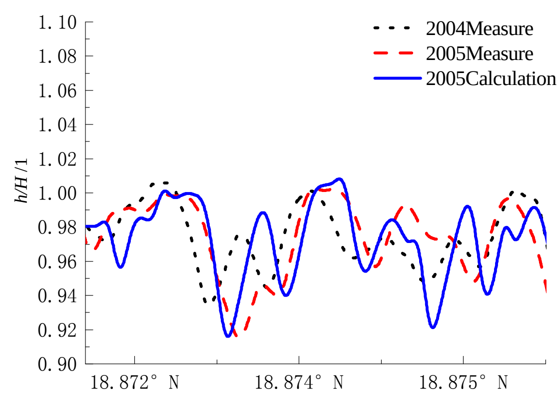

Fig.7. sea bed profile of P1 transect
(left indicates south, H is the average depth)

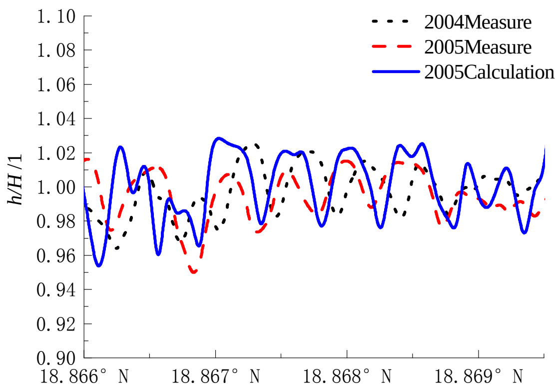

Fig.8. sea bed profile of P2 transect
(left indicates south, H is the average depth)

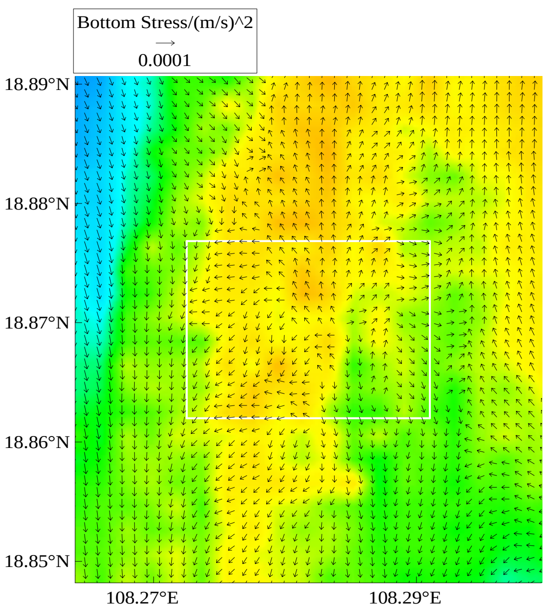

Fig.9. time-average bottom shear stresses
(white rectangle indicates the calculation zone)

In order to explain the phenomena, we draw the time-average bottom stresses in Fig.9. Its directions are consistent with the moving of the position of the crests. It can be concluded that the ridge is near the turning position of the northward and southward bottom stresses. So the migration directions on the ridge back and the ridge groove are opposite. These features cannot be simulated with depth-averaged two-dimensional model or three-dimensional model without sufficient horizontal resolution (Lin et al, 2009a). It is because that the two-dimensional hydrodynamic model which doesn't consider residual current induced by horizontal gradient pressure and complex topography.

We think the success should be due to the ultra-high horizontal resolution three-dimensional hydrodynamic model used here. The finest resolution, about 200m, is 9 times of the common high level (about 1800m). It resolves the ridge well and that is the key feature for the different moving direction between ridge back and ridge groove.

It is concluded that the physical models presented in this paper is able to predict the migration of the offshore small scale sandwave with complex topography and the ultra-high horizontal resolution (about 200m) hydrodynamic model is able to reflect the influence of the topography on the bottom flow filed. However, we notice that the migrating rates seem to be smaller than the observation results at some area. Thus it should pay more attention that there may be some other factors, such as suspension load, would cause the difference between calculation and observation in migrating rate. The reason still needs further discussion in the future.

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