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NUMERICAL SIMULATION OF TYPHOON WAVES AROUND THE WATERS OF THE YANGTZE ESTUARY —— A CASE STUDY OF TYPHOON RUSA AND TYPHOON SINLAKU

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Abstract: The third-generation wave model SWAN, which is based on the energy balance theory, is applied to the waters around the Yangtze Estuary for simulation of typhoon waves. SWAN wave model in curvilinear grids is better for complicated topographies than that in rectangular grids. Due to the complicated topographies in the Yangtze Estuary, curvilinear grids are adopted. Calculating precision can be improved by using curvilinear grids, not adding much calculating quantity simultaneously. Typhoon waves around the waters of the Yangtze Estuary are numerically modelled under the weather of Typhoon Rusa and Typhoon Sinlaku. A comparison with the significant wave height processes at an outer-sea buoy shows that SWAN model has good applicability in the waters around the Yangtze Estuary. Distributions of significant wave height of typhoon waves in the Yangtze Estuary, during the Typhoon Rusa and Typhoon Sinlaku have been analyzed respectively in the paper. The results can well reflect some characteristics of typhoon-wave propagation and wave height distribution, which means that typhoon waves around the waters of the Yangtze Estuary can be rationally simulated by SWAN wave model.

Key words: SWAN wave model; Yangtze Estuary; Typhoon waves; Numerical simulation

1. INTRODUCTION

Tropical cyclone (sometimes named as typhoon), which often brings gales, heavy rains and surges, is one of the most serious catastrophic weathers for the coastal areas of China. The Yangtze Estuary can be attacked by typhoons almost every year. During a typhoon, storm surges stir up large quantity of sediments, which may lead to the erosion of tidal flats. Some of the raised sediments can move into navigation channels and deposit there. Typhoon waves have great effects on some longshore or offshore structures and frequently cause losses of people and country. So it is of great importance to simulate rationally typhoon waves around the waters of Yangtze Estuary. The influence of typhoons can occur every year from May to November, especially from July to September. There are three types of typhoons, i.e. moving-west type, turning type and landing type, according to different paths of northwest pacific typhoons that affect the south-east coast of China. The moving-west typhoons, which generate in the northwest Pacific and move for the southeast mainland of China, have little effect on the region of the Yangtze Estuary. While the typhoons of turning type and landing type affect greatly on this region and the happening frequency is very high. Typhoon Rusa and Typhoon Sinlaku belong to turning type and landing type, respectively.

According to wave theory, wave numerical models can be divided into three types, i.e. mild-slope equation model, Boussinesq equation model and energy balance equation model. Based on the assumption of mild-slope condition, Berkhoff (1972) derived a classic two-dimensional (2-D) linear mild-slope equation by means of perturbation expansion method. This elliptic equation can describe wave effects of refraction, diffraction, reflection and shoaling, but can only apply to very small water regions. Later, many expansion-type mild-slope equations were induced, e.g. parabolic equation by neglecting wave reflection (Radder, 1979; Kirby, 1986), nonlinear mild-slope equation by introducing the nonlinear effects (Kirby and Dalrymple, 1987; Zhao and Anastasiou, 1993; Nadaoka and Nakagawa, 1994; Isobe, 1994), etc. Boussinesq equation, a 2-D nonlinear shallow-water wave equation, which reflects the balance between dispersion and nonlinearity can consider refraction, diffraction, reflection and shoaling, and has its high-order types (e.g. Wei, et al., 1995; Madsen and Schaffer, 1998). The equation can only adapt to small regions because of its high request for grid density within one wave length. It cannot be used for long time scale calculation for the reason of stabilization. Energy balance model is a wave spectrum model based on the principle of energy conservation. Many physical processes, e.g. wind wave generation, bottom friction dissipation, wave breaking, wave-wave interaction, etc., but not accounting for wave diffraction, can be expressed by different source terms, which simplifies the wave dynamics. In calculation, the model has no rigorous request for spatial step and temporal step, so it can apply to bigger regions and to long time scale calculation. Along with better understandings of these physical processes and different parameterized forms, models developed from the first-generation to the third-generation. The WAM model (WAMDI Group, 1988) and the WAVEWATCH model (Tolman, 1989) are the famous third-generation wave models for global-scale applications. For near-shore applications, such as the regions of coasts, lakes and estuaries, the SWAN wave model by TU Delft (Booij et al., 1996) was modified from third-generation models, especially from the WAW model. It includes more flexible options on the parameters for different processes.

The SWAN wave model has been used for numerical simulations of typhoon waves in coastal waters of Taiwan (Chen, et al., 2002; Shan-Hwei, et al., 2002). In this paper, the model is applied to the waters around the Yangtze Estuary for modelling typhoon waves. The curvilinear grids are adopted for fitting the complicated coasts and topographies in the regions of Yangtze Estuary, which can improve calculating precision, not adding much calculating quantity simultaneously. Taking two typhoons in sequence, i.e. Typhoon Rusa and Typhoon Sinlaku, as examples, typhoon waves around the Yangtze Estuary are numerical simulated. Significant wave height processes are verified at an outer-sea buoy. In the end, the calculated results are discussed and analyzed.

2. SWAN WAVE MODEL

In SWAN the waves are described with the 2-D wave action density spectrum $N(\sigma,\theta)$. Accounting for currents in the model, wave action is conservational, while energy density $E(\sigma,\theta)$ is not conservational. The relationship between them is: $N(\sigma,\theta)=E(\sigma,\theta)/\sigma$, in which σ is the relative frequency and θ is the wave direction. In Cartesian coordinates, governing equation, i.e. spectral action balance equation, can be expressed as:

$$\frac{\partial}{\partial t}N+\frac{\partial}{\partial x}c_xN+\frac{\partial}{\partial y}c_yN+\frac{\partial}{\partial\sigma}c_\sigma N+\frac{\partial}{\partial\theta}c_\theta N=\frac{S}{\sigma} \tag{1}$$

The first term in the left-hand side of this equation represents the local rate of change of action density in time, the second and third term represent propagation of action in geographical space (with propagation velocities c_x and c_y in x- and y-space, respectively). The fourth term represents shifting of the relative frequency due to variations in depths and currents (with propagation velocity c_σ in σ-space). The fifth term represents depth-induced and current-induced refraction (with propagation velocity c_θ in θ-space). The expressions for these propagation speeds are taken from linear wave theory.

In spherical coordinates, the governing equation changes into:

$$\frac{\partial}{\partial t}N+\frac{\partial}{\partial\lambda}c_\lambda N+(\cos\varphi)^{-1}\frac{\partial}{\partial\varphi}c_\varphi\cos\varphi N+\frac{\partial}{\partial\sigma}c_\sigma N+\frac{\partial}{\partial\theta}c_\theta N=\frac{S}{\sigma} \tag{2}$$

with longitude, λ and latitude, φ.

The term S ($= S(\sigma,\theta)$) at the right hand side of Eq. (1) and Eq. (2) is the source term in terms of energy density representing the effects of generation, dissipation and nonlinear wave-wave interactions. In detail, it includes the linear and exponential growth of wind input, energy dissipation by whitecapping, bottom friction and depth-induced breaking, quadruplet wave-wave interactions and triad wave-wave interactions.

The integration of the action balance equation has been implemented in the SWAN wave model with the finite difference schemes in all five dimensions (time, geographic space and spectral space). The equations can be numerical solved by iteration in the four quadrants. More detailed descriptions can be gained from the SWAN user manual (Holthuijsen et al., 2000).

3. TYPHOON WIND FIELD

Symmetrical typhoon wind model is adopted in this paper. Atmospheric pressure field due to typhoons can be expressed as (Fujita, 1952):

$$P = P_\infty - (P_\infty - P_0)\left[1+\left(\frac{r}{R_0}\right)^2\right]^{-\frac{1}{2}} \tag{4}$$

in which P_0 is the central low pressure, P_∞ is the atmospheric pressure in the far field of the typhoon, r is the distance to the typhoon center, R_0 is a parameter characterizing the typhoon system and can be adjusted according to the radius of the maximum wind speed.

Gradient wind can be gained through the relationship with atmospheric pressure:

$$W_1 = \sqrt{\frac{f^2r^2}{4}+\frac{r}{\rho_a}\frac{\partial P}{\partial r}} - \frac{fr}{2} \tag{5}$$

where f is the Coriolis parameter and ρ_a is the air density.

Wind due to the moving of typhoon can be represented by:

$$\overrightarrow{W}_2 = e^{-\pi r/500000}\begin{bmatrix} V_x \\ V_y \end{bmatrix} \tag{6}$$

where V_x and V_y are the velocity components of the moving of typhoon center.

So the composed typhoon wind field can be expressed as:

$$\overrightarrow{W} = c_1 W_1 \begin{bmatrix} -\sin(\phi+\beta) \\ \cos(\phi+\beta) \end{bmatrix} + c_2 \overrightarrow{W}_2 \tag{7}$$

in which ϕ is the angle between the direction of east and the line to the typhoon center, β is the angle between the direction of gradient wind and the direction of sea-surface wind, c_1 and c_2 are correcting parameters.

4. APPLICATION TO THE WATERS AROUND YANGTZE ESTUARY

4.1 MODEL SETTINGS

In this paper, taking Typhoon Rusa and Typhoon Sinlaku, which are the two typhoons happened continuously in the summer of year 2002, as examples, typhoon waves are simulated by using SWAN wave model. Nonstationary mode in spherical coordinates is adopted in the model. Two calculating regions, the larger one, the East China Sea (141×196), and the smaller one, the waters around the Yangtze Estuary (75×100), are defined for nesting computation. Their calculating grids are shown in Fig. 1 and Fig. 2, respectively. Grids of the smaller region are generated by doubling grids of the larger region in the corresponding place. In the smaller region, maximum grid spacing is 8855m at outer-sea, while minimum grid spacing is 366m within the Yangtze Estuary. 22 exponentially spaced frequencies from 0.125 Hz to 1 Hz with 60 evenly spaced directions (6° resolution) for a time step of 15 min are adopted. Two paths of typhoons are shown in Fig. 3, where symbol star represents the outer-sea buoy. The model runs from 26 August to 8 September, in total 13 days including these two typhoon processes. Other parameters use default values in the model.

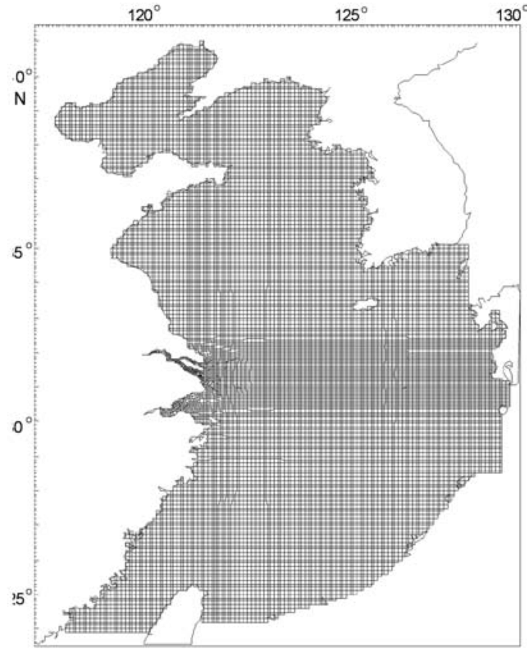

Fig. 1 Grids for East China Sea

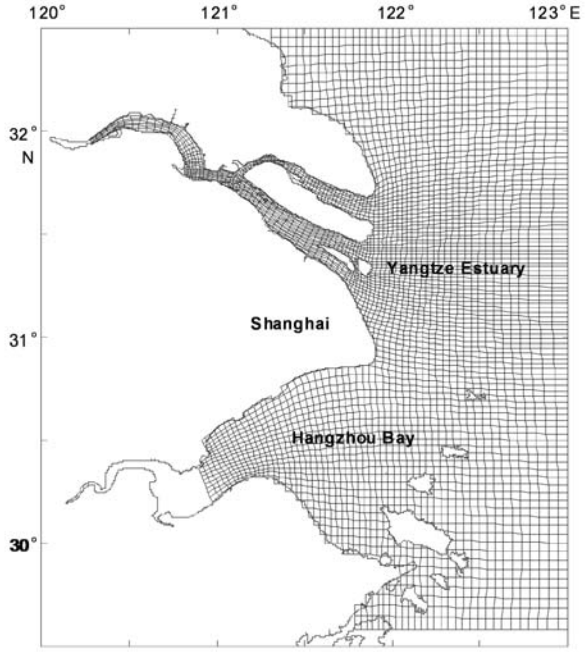

Fig. 2 Grids for the waters around Yangtze Estuary

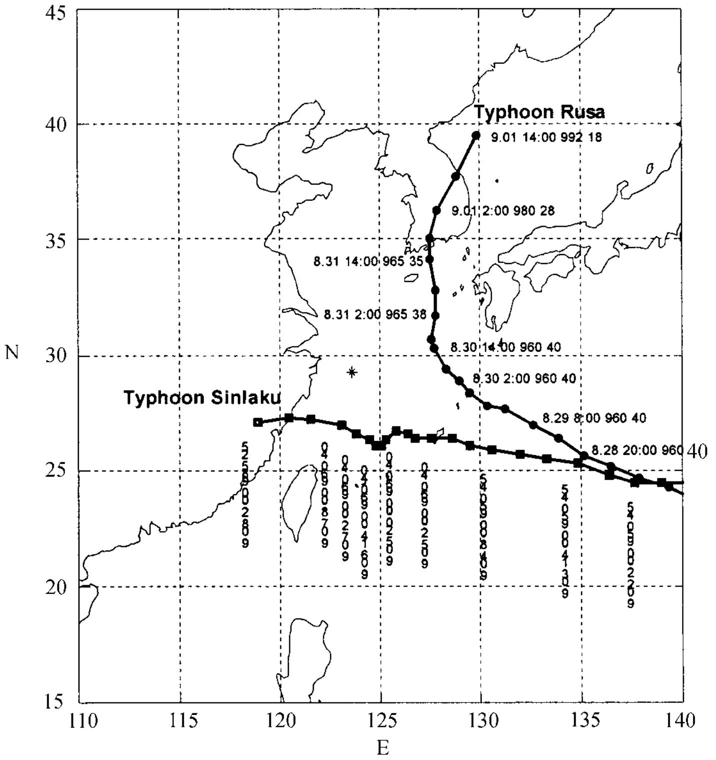

Fig. 3 Paths for Typhoon Rusa and Typhoon Sinlaku, and buoy location (symbol star)

4.2 BRIEF INTRODUCTION OF TYPHOON RUSA AND TYPHOON SINLAKU

At 08:00, 8 August, 2002, No.15 tropical storm, Rusa, was generated at the location of 16.3°N, 161.3°E, and moved northwest. At 20:00, 25 August, it was strengthened to become a typhoon, and moved northwest continuously with further stronger intensity. On 26 August, the typhoon developed into its strongest stage at 20:00, with center air pressure 950 hpa and near-center maximum wind velocity 45 m/s. On 30 August, the typhoon began moving northward at about 600 km away from the coasts of Shanghai at 08:00, with lower intensity. In the dusk of 31 August, Rusa landed at the southern coasts of Korea, passed through the south-east parts of Korea into Japan Sea, and decayed into low-pressure.

At 14:00, 29 August, 2002, No.16 tropical storm, Sinlaku, was generated at the location of 18.3°N, 155.3°E, and moved northwest. At 20:00, 31 August, it was strengthened to become a typhoon. At 14:00, its moving direction changed into WNW. At 02:00, 2 September, the typhoon developed into its strongest stage. On 5 September, its moving velocity slowed down and intensity decayed a little. During 40 hours after that, moving velocity kept very slow because sea subtropical high-pressure broke and driven airflow was not obvious. Till 8:00, 7 September, Typhoon Sinlaku accelerated by airflow at the edge of continental subtropical high-pressure. At 08:00, the typhoon began moving northward at about 600 km away from the coasts of Shanghai. About 18:30, the typhoon went ashore at the coasts of Zhejiang province, with center air pressure 960 hpa and near-center maximum wind velocity 40 m/s. After that, its intensity decayed rapidly and became low-pressure at 08:00, 8 September.

4.3 MODEL VERIFICATION

Shown as Fig. 3, the buoy locates at the outer sea with little effects of the coasts. So the observed data at the buoy are representative, that is, the verification of observed data can reflect the applicability of SWAN wave model in the waters around the Yangtze Estuary. Comparisons of calculated value (dashed line) with observed data (solid line) at the buoy are illustrated in Fig. 4. The comparison of wind velocity shows that the calculated wind velocity is fitting well with the observed data, which means that typhoon wind dominates during typhoon periods. At the beginning, the typhoon center is far from the Yangtze Estuary and wind fields are controlled by background wind with little typhoon effect. The calculating results are smaller than the observed data because symmetrical wind mode is adopted in the calculation of wind field, not accounting for the effects of background wind field due to data limitation. During the period of Typhoon Sinlaku, the measured variety of wind speed is complicated. The reason may be that the effects of background wind and the asymmetry of typhoon wind are neglected. Based on rational simulation of wind fields, typhoon waves can be modeled by SWAN model. The results show that the variety trend of wave height and the variety of wind speed are accordant basically. At the beginning, the calculated wave height remains small, like the situation of wind speed, because of the neglect of background wind. Along with the accretion of wind speed, the calculated results accord well with the observed data during the period of Typhoon Rusa. During the period of Typhoon Sinlaku, the variety trend of the calculated wave height is in reasonable agreement with that of the measurements. The model overestimates at the second peak of wave height during Sinlaku because of the neglect of background wind and the asymmetry of typhoon wind. In all, the simulated results are reasonable in the waters around the Yangtze Estuary, which also means that SWAN wave model has good applicability for the regions near the Yangtze Estuary.

4.4 RESULT ANALYSES

Distributions of wind field and significant wave height at two times during Typhoon Rusa and Typhoon Sinlaku, respectively, which are shown in Fig. 5, can reasonably reflect some characteristics of typhoon-wave propagation and wave height distribution. The propagation direction of typhoon waves is in agreement with the wind direction. For instance, wind direction at the first time is from northward and wind direction at the second time is from eastward, while wave directions at these two times are southward and westward, respectively.

As for the distributions of wave height, the more closing with the typhoon center, the bigger wave height will be, vice versa. At the first time, the center of Typhoon Rusa locates at the east of the Yangtze Estuary, and significant wave heights around the Yangtze Estuary gradually become smaller from east to west. At the second time, the center of Typhoon Sinlaku locates at the south-east of the Yangtze Estuary and the distance to the coasts is smaller than that at the first time, which causes that significant wave heights are bigger that those at the first time and its variety trend is being smaller from south-east to north-west. Typhoon Rusa has some intensity, but the losses due to Rusa are very small because Rusa is far from the coasts. On the other hand, Typhoon Sinlaku meets with the spring tide and its affecting area is very wide. Sinlaku is one of the strongest typhoons among those which have effect on the eastern coasts of China in five years.

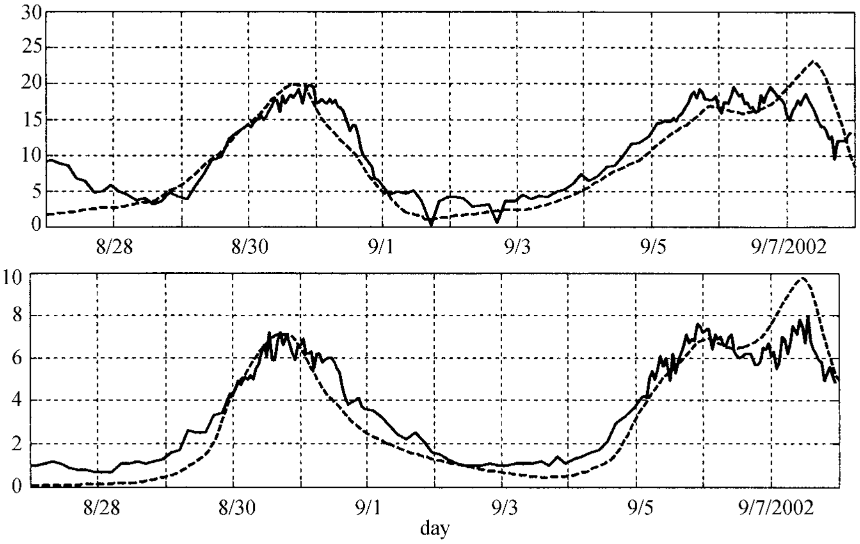

Fig. 4 Comparisons of calculated data (dashed line) with observed data (solid line) at the buoy

5. SUMMARY

The third-generation wave model SWAN, is introduced in this paper for numerical simulation of typhoon waves in the waters around the Yangtze Estuary. Curvilinear grids are adopted for fitting the complicated coasts. Based on reasonable calculation of typhoon wind fields, typhoon waves under the effects of Typhoon Rusa and Typhoon Sinlaku are modelled. The model is verified by observed wave data at the outer-sea buoy. Distributions of significant wave height at two times during Typhoon Rusa and Typhoon Sinlaku, respectively, are analyzed, which shows that typhoon waves around the waters of Yangtze Estuary can be rationally simulated by SWAN wave model.

But what should be pointed out is that SWAN wave model is based on the theory of energy balance, not accounting for the effect of wave diffraction. By using SWAN model in the mouth bar region of the Yangtze Estuary, some calculation errors may occur because of the complex topographies and lots of shoals there. For reasonable calculation of the complicated wave fields in the Yangtze Estuary, one possible solution is that a mild-slope equation model can be nested in SWAN model and SWAN model can provide the boundary conditions, through which the merits of these two types of wave models can be made full use of.

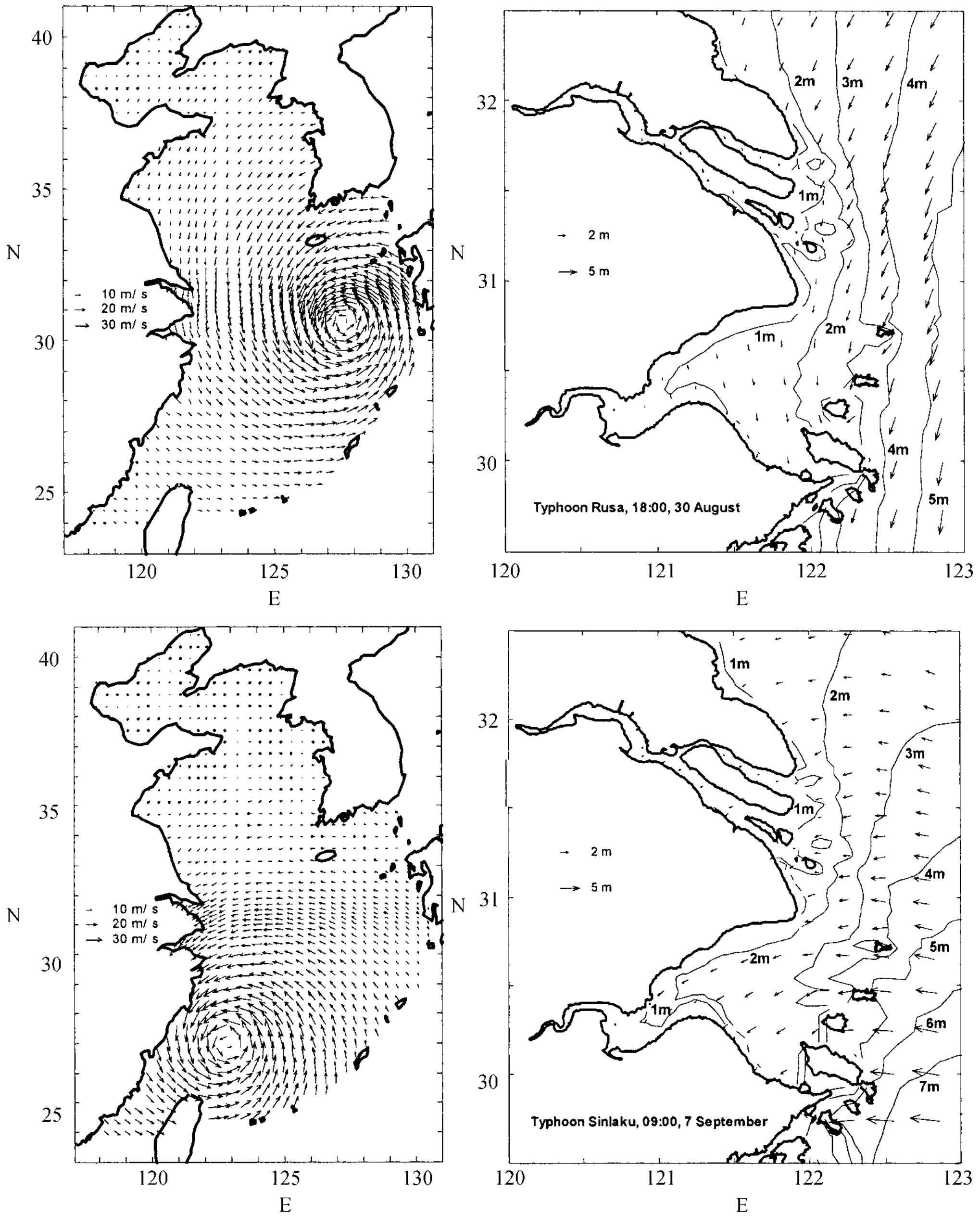

Fig. 5 Typhoon wind fields and distributions of wave height and wave direction near Yangtze Estuary

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