MAUSAM, 48, 4 (October 1997), 595-608

551.465.755 : 519.872(265.72)

Research and application of numerical models of typhoon surges in China Seas

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सार — इस शोधपत्र में टाइफून महोर्मि के तीन संख्यात्मक मॉडलों के विषय में संक्षिप्त चर्चा की गई है। पहले मॉडल का नाम पाँच-बेसिन मॉडल (एफ. बी. एम) है । दूसरे मॉडल का नाम स्लोश (SLOSH) [समुद्र (Sea), झील (Lake), थलोपरि महोर्मि (Overland Surges) और हरीकेन (Hurricane)] है । लेखकों और संयुक्त राज्य अमेरिका के जेलेस्नियांस्की आदि (1992) द्वारा एक संयुक्त परियोजना में चीन के समूचे तट के लिए पाँच स्लोश (SLOSH) - प्रकार के बेसिनों का विकास किया गया । दो मॉडलों को टाइफून महोर्मि के वास्तविक समय के लिए पूर्वानुमान हेतु प्रयुक्त किया गया है । तीसरा मॉडल एक नवीन विकसित मॉडल है, जिसमें फ्लेथर और हीप्स (1975) द्वारा आप्लावन विधि की उत्पत्ति की गई और खगोल विज्ञानिक ज्वार-भाटे को शामिल किया गया। एक बहु-खंड ग्रिड प्रणाली विकसित की गई ।

ABSTRACT. In this paper, three numerical models of typhoon surge are discussed briefly. The first one is called Five-basin Model (FbM). The second one is called SLOSH (Sea, Lake, and Overland Surges from Hurricanes). 5 SLOSH-type basins covering the entire China coastlines were developed in a joint project between authors and Jelesnianski *et al.* (1992) of U.S.A. The two models have been used in real-time forecasting of typhoon surge. The third one is a new developing model in which inundation using the scheme originated by Flather and Heaps (1975) and astronomical tide was included. A multiple nested grid system was developed.

Key words — Storm surge, Numerical model, Simulation, Prediction

1. Introduction

Among the littoral countries of NW Pacific Ocean, the hazard from typhoon surges in China is of highest frequency and most severe. The disastrous regions comprise almost the whole coastal area. National Marine Environmental Forecasting Centre (NMEFC) is responsible for issuing the storm surge prediction for the whole country and new techniques of storm surge prediction have been developed carefully. Modelling experiments are being increasingly used in the world (Wang and Yu 1995, Tatsuo Konishi 1995), but a perfect model should satisfy the following technical requirements.

The distributions of pressure and wind field, which describe the forcing fields, should be of high accuracy as far as possible; the computed basin should be big enough and the grid step of the mesh small enough so that the nature of storm surge along the coast is described perfectly; the model is to give a reasonable computed results, easy to operate, and the format of model outputs are good enough to describe the variation of storm surges in time and space; in addition, all the physical parameters, such as, drag coefficient of wind, the coefficient of bottom friction etc. have never been adjusted when they were decided. Efforts have been made to embody the above requirements in setting up and choosing the models.

2. Five-basin Model (FbM)

The model has been developed based on the authors' research of storm surge models in a closed sea, semi-closed sea and open sea (Wang 1988, Yin 1985, Wang 1989).

2.1. *The Basic Equations of FbM*

The model is two-dimensional in space (2D). The basic equations of motion and continuity incorporating finite amplitude and dropping the advective terms are:

$$\frac{\partial U}{\partial t} = -g(h+\zeta)\frac{\partial \zeta}{\partial x} - \frac{1}{\rho_\omega}(h+\zeta)\frac{\partial P_a}{\partial x} + \frac{\tau_{ax}-\tau_{bx}}{\rho_\omega} + fV \tag{1}$$

$$\frac{\partial V}{\partial t} = -g(h+\zeta)\frac{\partial \zeta}{\partial y} - \frac{1}{\rho_\omega}(h+\zeta)\frac{\partial P_a}{\partial y} + \frac{\tau_{ay}-\tau_{by}}{\rho_\omega} - fU \tag{2}$$

$$\frac{\partial \zeta}{\partial T} = -\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y} \tag{3}$$

where the XOY plane coincides with the still water level; the Z axis is vertical and positive in a downward direction; t denotes time; P_a the atmospheric pressure; g the acceleration due to gravity; ρ_ω the density of water; ζ the surface elevation surge above the still water level; h the water depth below the still water level; f the Coriolis parameter and U, V are defined as follows :

$$(U, V) = \int_{-\zeta}^{h} (u, v)\, dz \tag{4}$$

where, u, and v are the x and y components of the current velocity respectively.

$$\vec{\tau_a} = \rho_a r_a^2 |\vec{W}| \vec{W} \tag{5}$$

$$\vec{\tau_b} = \rho_a r_a^2 |\vec{V}| \vec{V} - \beta \vec{\tau_a} \tag{6}$$

where $\vec{\tau_a}$ indicates the vector of surface stress due to wind; $\vec{\tau_b}$ represents the stress due to bottom friction; τ_{ax}, τ_{ay} are the components of $\vec{\tau_a}$ in the x and y directions, and τ_{bx}, τ_{by} are the components of $\vec{\tau_b}$ in the x and y directions. $\vec{W}$ indicates the wind vector at the anemometer height, r_a^2 shows the drag coefficient of wind, and r_b^2 the coefficient of bottom friction, takes the same value as $r_a^2\,(2.6\times10^3)$, β is a constant (β = 0.35), $\vec{V}$ is the vector of depth-mean current.

$$\vec{V} = u\vec{i} + v\vec{j} = \frac{U}{(h+\zeta)}\vec{i} + \frac{V}{(h+\zeta)}\vec{j} \tag{7}$$

The finite-difference mesh has been used in this model (Wang *et al.* 1992). At the coast, for the boundary conditions we have zero of the volume transport per unit width (U or V) normal to the boundary. At the boundaries of water, ζ is equai to the equilibrium height of sea surface corresponding hydrostatically to the fall of atmospheric pressure (static height), *i.e.* 1 hPa of atmospheric pressure fall causes 1 cm of sea surface rise. The formula is given below :

At the boundaries of water

$$\zeta = \frac{10^3}{\rho_\omega g}(P_\infty - P_a) \tag{8}$$

where P_a is the atmospheric pressure at a point on the boundaries.

The initial conditions for all the calculated points are as follows :

At t = 0, ζ is equal to static height; no motion of water ($U = V = 0$). The time step: Δt = 300s; the grid step ΔS = 13.89 km. The computations are stable.

2.2. *The Typhoon Model*

The method of non-dimensional analysis for widely used formulae of the pressure distribution in a typhoon area was employed to choose the representative ones out of them.

In this model, the atmospheric pressure distribution in a typhoon area is chosen to be represented by Fujita's and Takahashi's formulae,

$$P_r = (P_\infty - P_0)\left(1 - \frac{1}{\sqrt{1+2(r^2/R^2)}}\right) + P_0,\ 0 \le r \le 2R \quad \text{(Takahashi 1939)} \tag{9}$$

$$P_r = (P_\infty - P_0)\left(1 - \frac{1}{1+r/R}\right) + P_0,\ 2R \le r \le \infty \quad \text{(Fujita 1952)} \tag{10}$$

where P_0 is the central pressure of typhoon, R is the radius of maximum wind of typhoon.

The basic wind field is assumed to be represented by Veno Takeo's (1981) formula :

$$\vec{V}_{sm} = v_x \exp\left(-\frac{\pi}{4}\frac{|r-R|}{R}\right)\vec{i} + v_y \exp\left(-\frac{\pi}{4}\frac{|r-R|}{R}\right)\vec{j} \quad (11)$$

where v_x, v_y are the components of the speed of typhoon in x and y directions.

Finally, the wind distribution in a typhoon area is as follows :

$$w_x = c_1 v_x \exp\left(-\frac{\pi}{4}\frac{|r-R|}{R}\right) - c_2\left\{-\frac{f}{2} + \sqrt{\frac{f^2}{4} + 10^3\frac{2\Delta P}{\rho_a R^2}\left[1+2\left(\frac{r^2}{R^2}\right)\right]^{-3/2}}\right\} \times\left[(x-x_c)\sin\varphi + (y-y_c)\cos\varphi\right], \ (0 \le r \le 2R) \quad (12)$$

$$w_y = c_1 v_y \exp\left[-\frac{\pi}{4}\frac{|r-R|}{R}\right] - c_2\left\{-\frac{f}{2} + \sqrt{\frac{f^2}{4} + 10^3\frac{2\Delta P}{\rho_a R^2}\left[1+2\left(\frac{r^2}{R^2}\right)\right]^{-3/2}}\right\} \times\left[(x-x_c)\cos\varphi + (y-y_c)\sin\varphi\right], \ (0 \le r \le 2R) \quad (13)$$

$$w_x = c_1 v_x \exp\left(-\frac{\pi}{4}\frac{|r-R|}{R}\right) - c_2\left\{-\frac{f}{2} + \sqrt{\frac{f^2}{4} + 10^3\frac{\Delta P}{\rho_a r(1+r/R)^2 R}}\right\} \times\left[(x-x_c)\sin\varphi + (y-y_c)\cos\varphi\right], \ (2R \le r \le \infty) \quad (14)$$

$$w_y = c_1 v_y \exp\left(-\frac{\pi}{4}\frac{|r-R|}{R}\right) - c_2\left\{-\frac{f}{2} + \sqrt{\frac{f^2}{4} + 10^3\frac{\Delta P}{\rho_a r(1+r/R)^2 R}}\right\} \times\left[(x-x_c)\cos\varphi + (y-y_c)\sin\varphi\right], \ (2R \le r \le \infty) \quad (15)$$

where $\Delta P = P_\infty - P_0$ (pressure drop in hPa); r, R in cm and v_x, v_y, w_x, w_y in cm/s; $r = \sqrt{(x-x_c)^2 + (y-y_c)^2}$, x_c, y_c represent the position of typhoon center, c_1, c_2 are constants (c_1 = 1.0, c_2 = 0.8), and φ (20°) is the inflow angle.

Many comparable computations show that the models of pressure and wind field chosen by the authors are successful, which were used in the computations corresponding to them for the oil-exploited regions of South China Sea and sea wave of Yellow Sea.

2.3. *Computed results*

2.3.1. *Simulation*

The model has been applied to 5 basins, covering whole of coastal area of China Seas (Fig. 1). The model can give outputs of hourly storm surge and wind (speed and direction) at any grid point of computed basin according to the requirements.

The model was successfully applied to simulate 45 historical typhoon surges affecting China coastal areas. The correlation was set up by use of computed and actual peak surge data from 240 tidal gauges. The peak surge correlation is as follows:

$$Y = 0.89\ X + 15.3\ \text{(cm)} \quad (16)$$

with correlation coefficient of 0.946 and standard deviation of 27.9 (cm). Here, Y is observed and X is computed value. The correlation diagram is shown in Fig. 2

The correlation of occurrence time (TT) due to peak surges is as follows :

$$TT = 1.08\ T - 1.48\ \text{(hour)} \quad (17)$$

with correlation coefficient of 0.980, and standard deviation of 1.26 hours. Here, TT is occurrence time of actual peak surge and T is computed value of occurrence time. The correlation, is shown in Fig. 3.

Only one simulated case is shown here. The typhoon Wayne (No. 8616) made a track on Lei Zhou Bandao of Guang Dong Province. The satisfactory results were given by the numerical simulation at almost all of tidal gauges (Figs. 4-6).

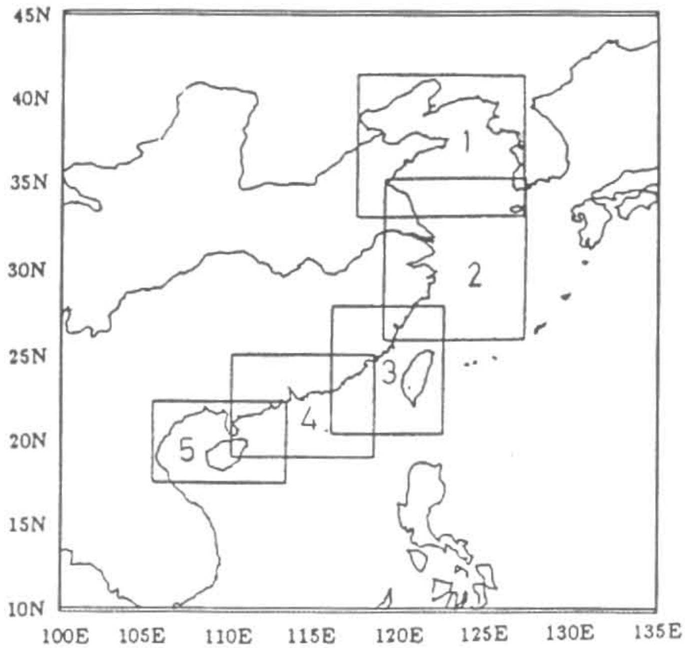

Fig. 1. Computed basins along China Sea's coastlines

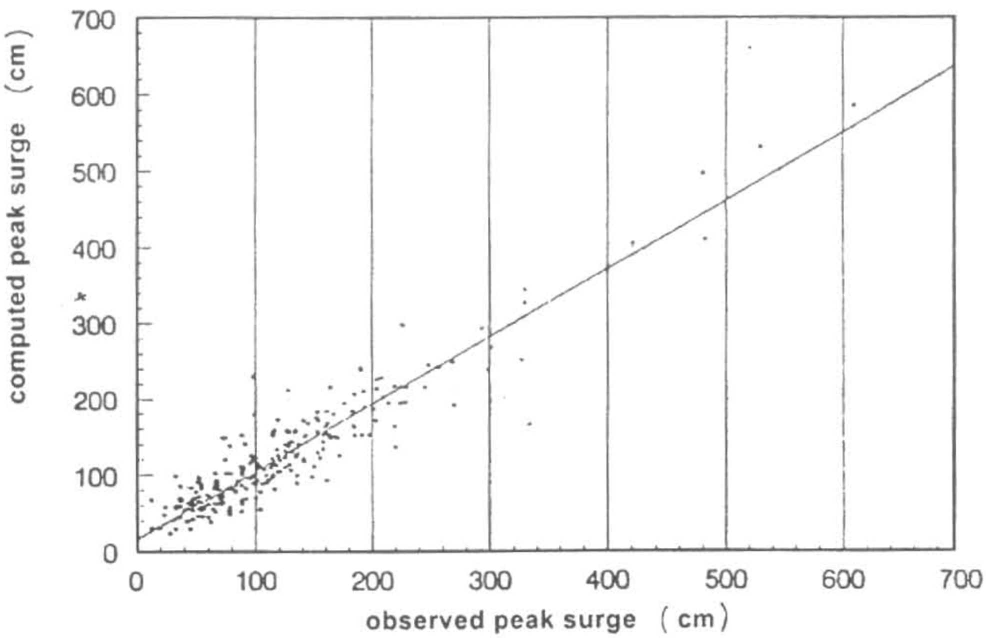

Fig. 2. The correlation between observed and computed peak surges from 240 tidal gauge stations affected by 45 historical typhoons

2.3.2. *Real-time forecasts*

From 1988 to 1995, NMEFC made 297 real-time storm surge forecasts using 77 typhoons' tracks with FbM. So long as the typhoon parameters (latitude and longitude of typhoon centre, central pressure and radius of maximum wind of a typhoon) in 6 hour interval are correct enough, the numerical model forecast can give rather accurate results, with a very important effect in real-time prediction. The model outputs are:

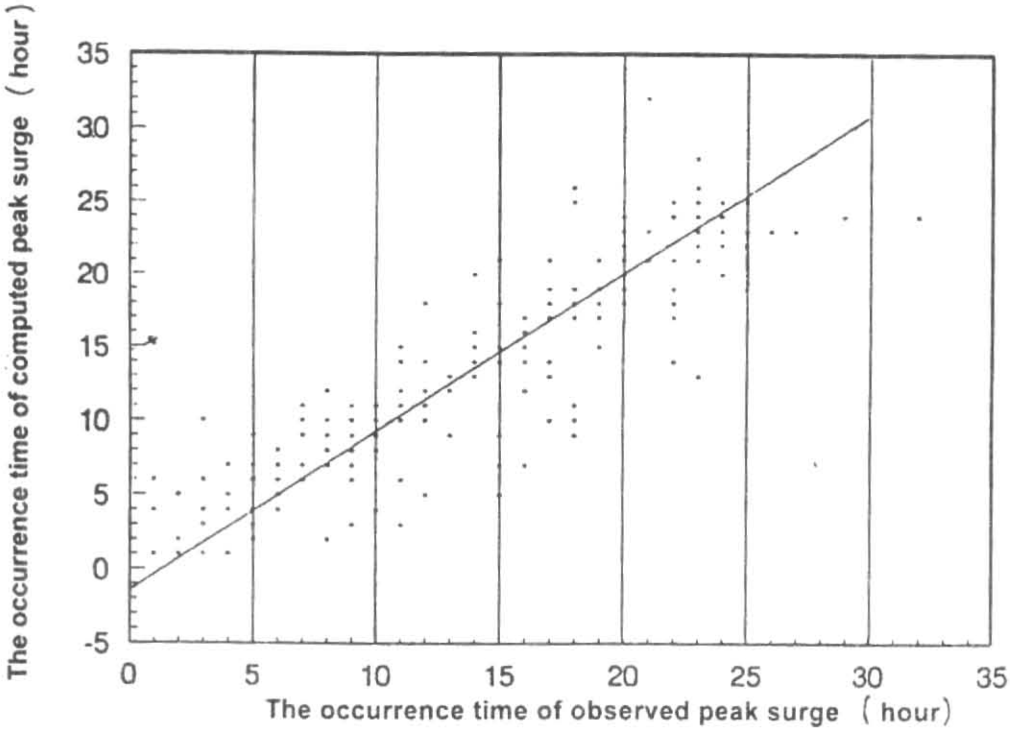

Fig. 3. Same as in Fig. 2 but for the correlation of occurrence time of peak surge

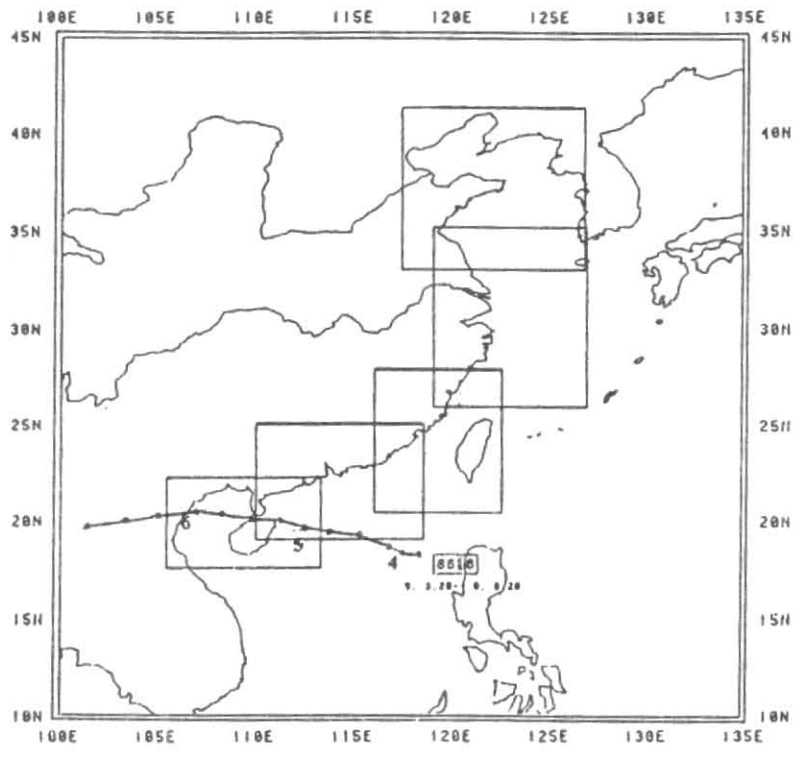

Fig. 4. Track of typhoon No. 8616 during the period 3-6 September 1986 (20h) in 6-hourly interval (Beijing Time)

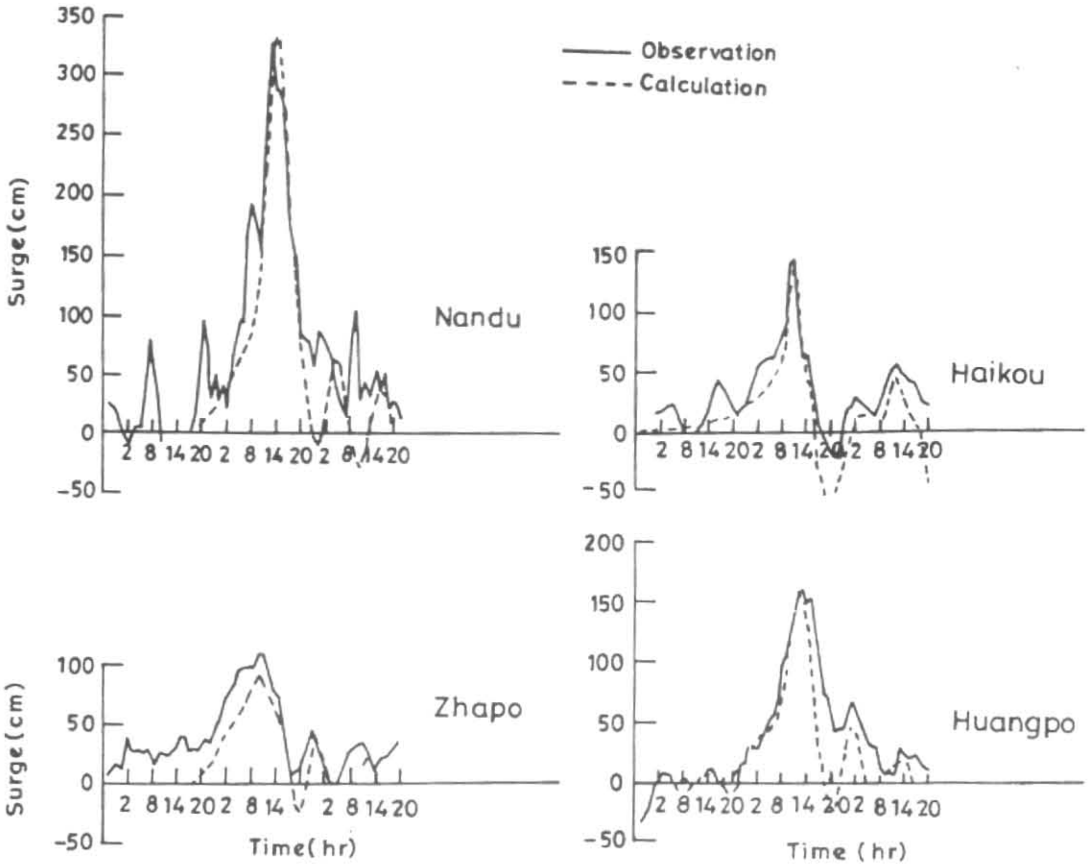

Fig. 5. Time variation of storm surge at four tidal gauges during the passage of typhoon No. 8616 (Time 9, 3.21-9, 6.20)

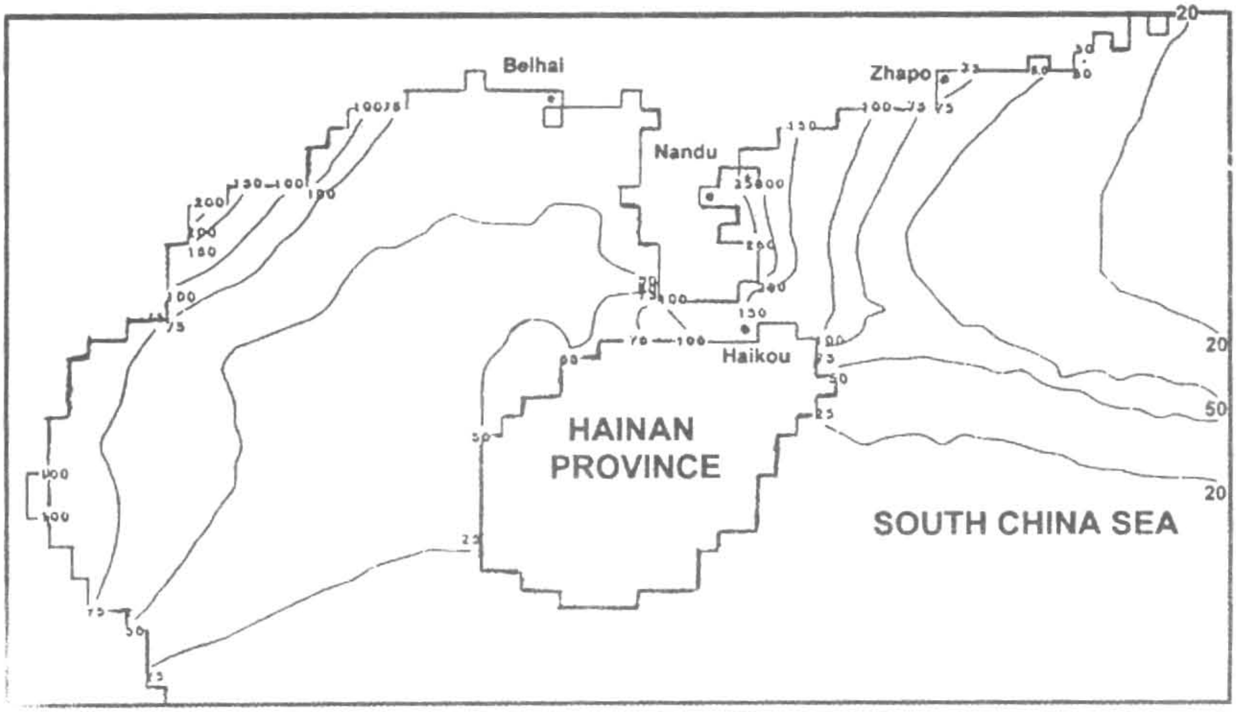

Fig. 6. Contoured surface envelope of highest computed surges during the passage of typhoon No. 8616

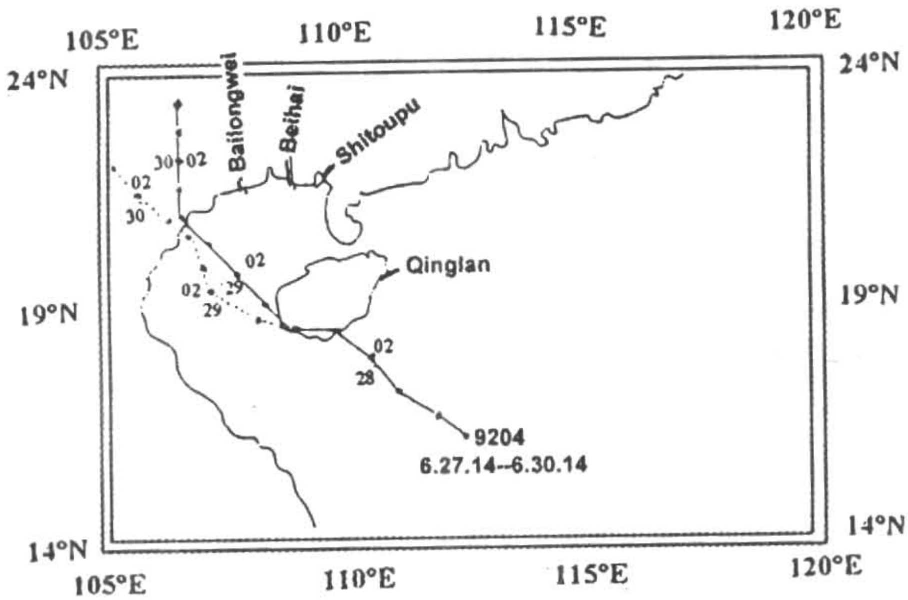

Fig. 7. Typhoon No. 9204 tracks from 27-30 June 1992 in 6-hour interval (solid line forecasted, dotted line observed)

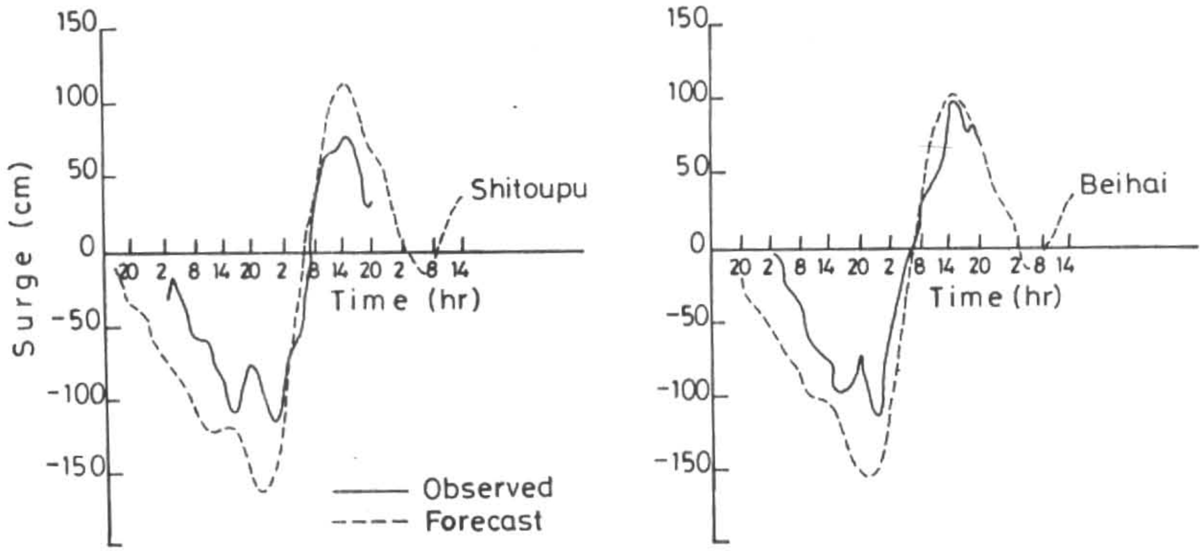

Fig. 8. Time variation of storm surge at two tidal gauges during the passage of typhoon No. 9204

the table of typhoon parameters, hourly surge and wind at the grid points corresponding to the tidal gauges, and highest computed surges at each grid point for the whole basin. Such outputs fully represent the features of storm surges in time and space.

There is only one case of real-time surge forecast to show here (Figs. 7-9). It may be seen that the real-time surge forecast for the typhoon Chuck (No. 92-04) fits well with the observation.

3. SLOSH Model

The originators of SLOSH are Jelesnianski et al. (1992) of U.S.A. The model is designed to compute storm surge in a two-dimensional area covering water bodies, ocean, bays and inundated terrain. A simple, curvilinear orthogonal co-ordinates (polar/elliptical/ hyperbolic) grid scheme is used. The original aim of SLOSH was to forecast hurricane storm surges in real time. Because the co-ordinate grid has high resolution

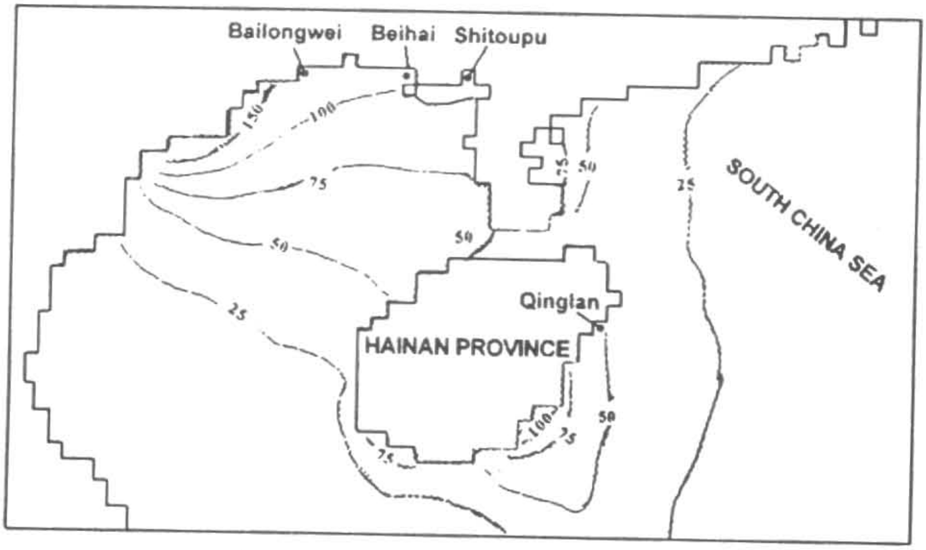

Fig. 9. Contoured surface envelope of highest computed surges for typhoon No. 9204

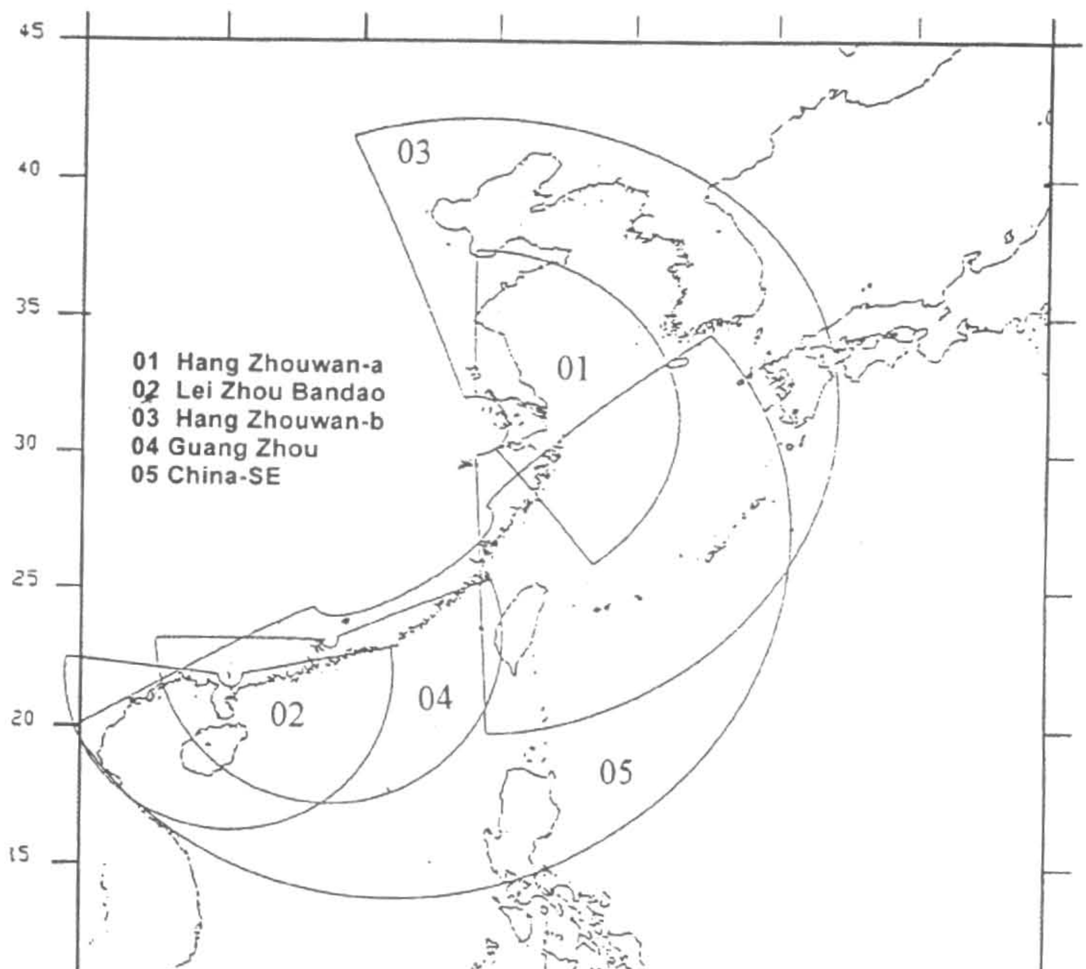

Fig. 10. SLOSH basins along China Seas coastlines

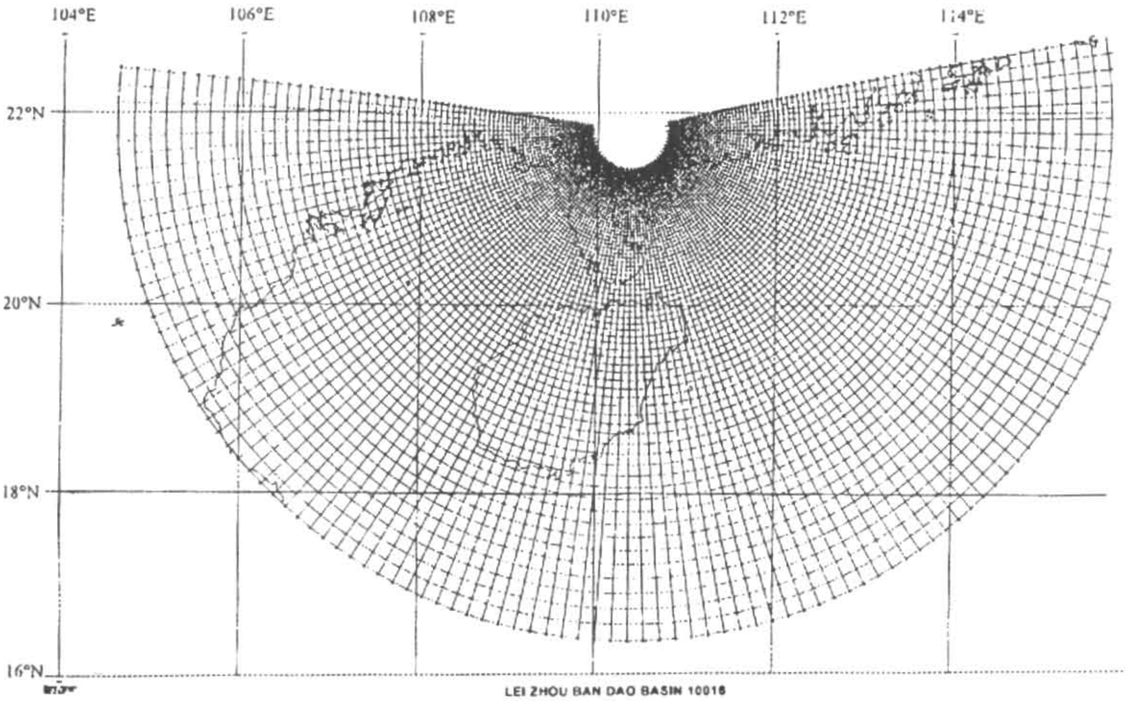

Fig.11. A plane, polar coordinate system for Lei Zhou Bandao

TABLE 1

The grid point number for each basin

Basin No.	Basin Name	Total Grid Points	Coordinate system
01	Hang Zhouwan-a	80*110	polar
02	Lei Zhou Bandao	80*106	polar
03	Hang Zhouwan-b	101*147	polar
04	Guang Zhou	18*96	polar
05	China-SE	102*200	ellipse

near shore, the model has ability to calculate the storm surge not only on the continental shelf, but also over inland water bodies, inland terrain, and up rivers. It deals with overtopping of both the natural and man-made barriers by the sea water flood. Such barriers would include sea walls, leaves, dunes, spoil banks, etc. The model also allows sub-grid channel flows and those through barrier cuts. Verification runs of SLOSH model done for hurricane in the U.S. indicate that the accuracy is well within ± 20% of the observed tide gauge values, when astronomical tide is removed. The SLOSH model now plays a very important role in real-time forecasting and evacuation planning for U.S.'s coastal communities.

A joint project between the authors and Jelesnianski *et al.* (1992) on storm surge was developed under the China-US Marine and Fisheries Protocol - Technical Exchange on Storm Surge Modelling. Under this program, five overlapping basins of SLOSH model for the China Seas have been developed (Table 1). The basin No.1 and No.2 were completed in 1989. The last three basins were completed in 1995.

Fig. 10 shows the full display of the China's five SLOSH basins. Fig. 11 shows one of them which is a plane, polar coordinate system for Lei Zhou Bandao.

The simulation for several remarkable surge cases of China Seas has been completed with SLOSH, but there is only one case to show here. The case is typhoon Joe (No. 8007) which struck the Lei Zhou Bandao (peninsula) of Guang Dong Province. Storm surge of 5.86 m was recorded at the Nandu tidal gauge station - the highest value recorded in China. The simulated surges coincide with the observations perfectly (Fig. 12).

Two basins (Nos. 1 & 2) have been used in real-time forecast since 1989. The real-time forecasts

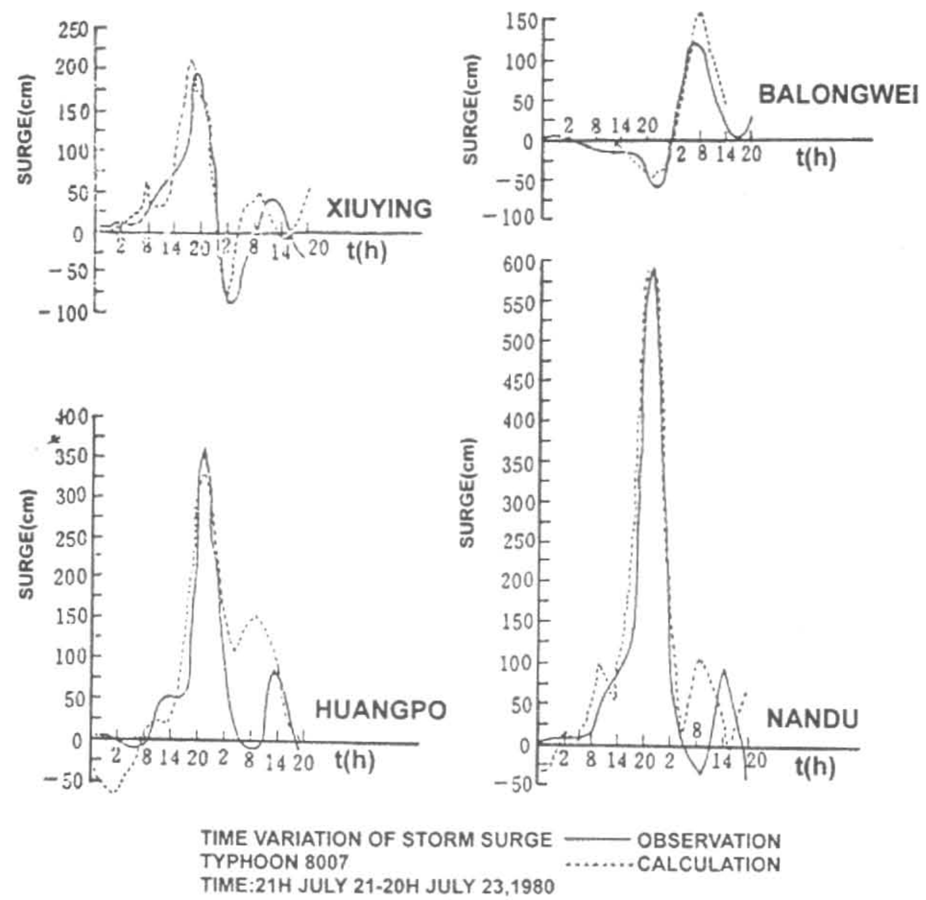

Fig. 12. Comparison of observed and computed surge at four gauges for typhoon Joe (8007), 1980

for typhoons No. 8905, 8909, 8913, 9106, 9111 etc. have been carried out successfully owing to typhoon tracks and their intensity forecasted accurately and used to prevent storm surge disasters successfully. (The Figures are omitted).

4. The New Developing Model

4.1. *Basic Equations*

In geographical co-ordinates, the basic depth-averaged equations governing tide surge motion may be written in the form :

$$\frac{\partial \zeta}{\partial t}+\frac{1}{R\cos\varphi}\left(\frac{\partial(Du)}{\partial\theta}+\frac{\partial(Dv\cos\varphi)}{\partial\varphi}\right)=0 \qquad (18)$$

$$\frac{\partial u}{\partial t}+\frac{u}{R\cos\varphi}\frac{\partial u}{\partial\theta}+\frac{v}{R}\frac{\partial u}{\partial\varphi}-\frac{uv\tan\varphi}{R}-fv$$

$$=-\frac{g}{R\cos\varphi}\frac{\partial\zeta}{\partial\theta}-\frac{1}{\rho R\cos\varphi}\frac{\partial p_a}{\partial\theta}+\frac{1}{\rho D}(F_s-F_b) \qquad (19)$$

$$\frac{\partial v}{\partial t}+\frac{u}{R\cos\varphi}\frac{\partial v}{\partial\theta}+\frac{v}{R}\frac{\partial v}{\partial\varphi}-\frac{u^2\tan\varphi}{R}+fu$$

$$=-\frac{g}{R}\frac{\partial\zeta}{\partial\varphi}-\frac{1}{\rho R}\frac{\partial p_a}{\partial\varphi}+\frac{1}{\rho D}(G_s-G_b) \qquad (20)$$

where t - time

θ, φ - east-longitude and latitude

ζ - elevation of the sea surface

u, v - components of the depth-mean current

F_s, G_s - components of τ_s, the wind stress on the sea surface

F_b, G_b - components of τ_b, the bottom stress

P_a - atmospheric pressure on the sea surface

D- total water depth

ρ - density of sea water, assumed uniform

TABLE 2

Grid system for storm surge numerical model

Region	First	Second	Third
Time step	360 sec	120 sec	20 sec
Grid size	1/10°, about 11 km	1/30°, about 3.7 km	1/180°, about 0.6 km
No. of grid	55 × 100, 5500	150 × 145, 21750	135 × 135, 18225
Longitude	117° –127° E	117° 30′- 122° 20′E	117° 30′- 118° 15′E
Latitude	35° 30′-41° N	37°-41° N	38° 30′- 39° 15′N

R - radius of the earth

g - acceleration of gravity

f - coriolis parameter ($f = 2\,\omega \sin \varphi$)

The above equations are closed by relating bottom stress τ_b, to the depth mean current, V, using a quadratic law

$$\tau_b = C_b \rho V | V | - \beta \tau_s \tag{21}$$

where $C_b = 2.6 \times 10^{-3}$ is a friction parameter, $\beta = 0.35$ is a constant. The relating wind stress, τ_s, to the wind velocity, W, also using a quadratic law

$$\tau_s = C_D \rho_a W | W | \tag{22}$$

where ρ_a is the density of air and C_D is a drag coefficient.

$$C_D = 2.6 \times 10^{-3} \tag{23}$$

We use the same typhoon model as FbM.

4.2. *Scheme and Method of Computation*

ADI finite difference scheme with Arakawa C mesh is used to integrate Eqns. (18) to (20).

It is well known that in order to calculate the storm surge accurately, the domain of computation must be large enough to cover storm scale, making water boundary more accurate. But when the surges propagate to shallow water region, for example, continental shelf, bay, and estuary and the impact of coastal configuration and water depth is very important on surge. Hence, we have designed multiple grid system to calculate the storm surge in Bohai Sea. As shown in Table 2, the entire region is divided into three subregions, within each subregion difference time step size and grid size are used.

In the computation of the first grid system (coarse grid), initial conditions take the form of "cold start" condition

$$\zeta = u = v = 0 \text{ at time } t = 0 \tag{24}$$

Coastal boundary condition is

$$V_n = 0 \tag{25}$$

where V_n is the component of current along the outward-directed normal to the boundary. Open-sea boundary condition is a "radiation" condition,

$$V_n \pm \sqrt{g/H}\zeta = 0 \tag{26}$$

where H is the depth of water, ζ is elevation of sea surface.

In the computation of the 2nd grid system (fine grid), coastal boundary is same as coarse grid, but the open-sea boundary is as follow:

$$\zeta = \zeta_t + \zeta_{1i} \tag{27}$$

where ζ_{1i} is the elevation of sea surface along the fine grid open-sea boundary which is interpolated from coarse grid. ζ_t is the sum of the four main tidal constituents of M_2, S_2, K_1, O_1 expressed as follows :

$$\zeta = \sum_{i=1}^{4} f_i H_i \cos\left[\sigma_i t + (V+u)_i - g\right] \tag{28}$$

In the computation of the 3rd grid system (finest grid), open-sea boundary is

$$\zeta = \zeta_{2i} \tag{29}$$

where $\zeta = \zeta_{2i}$ is the elevation of sea surface along the finest grid over-sea boundary which is interpolated by fine grid. As to the coastal boundary which moves with the rising and falling surge, we used the technique presented by Flather and Heaps (1975) to determine the 'wet' or 'dry' boundary. Meanwhile, the one dimension flow (river) and one dimension barriers (dike) are considered in this model.

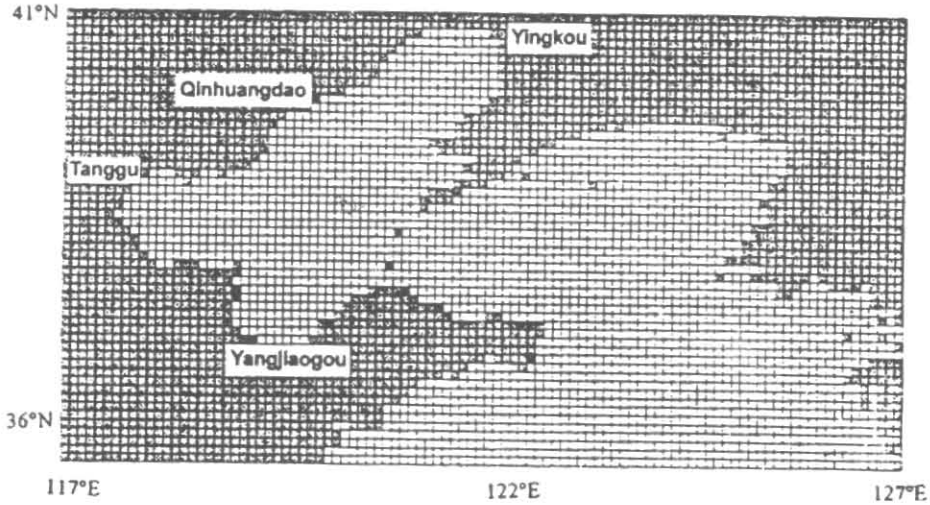

Fig. 13. The coarse grid system

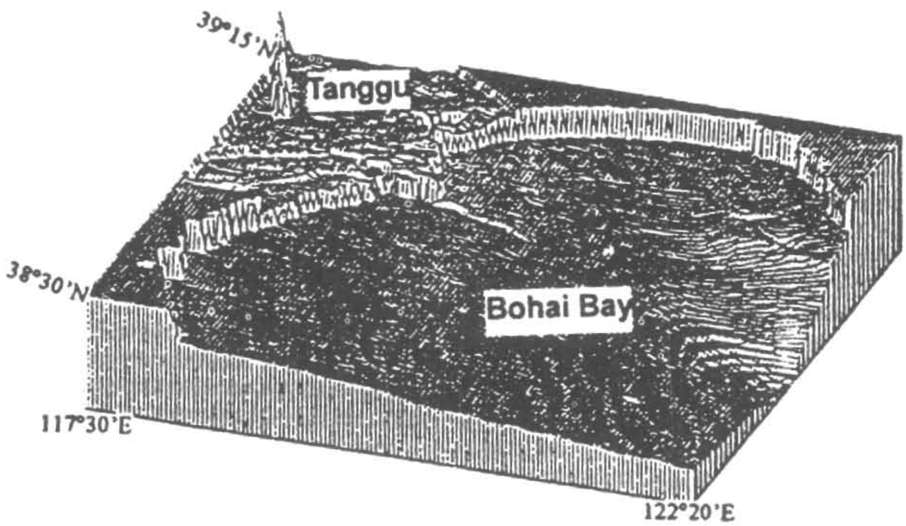

Fig. 14. Topography of the finest grid region

The method of two grid system exchanging information is as follows :

(1) First and second grid system-The first grid system only gives the boundary value of 2nd grid system.

(2) Second and third grid system-Not only the 2nd grid system supplies the boundary value of the 3rd grid system, but also the new results of 3rd grid system update the old results of 2nd grid system. This method not only eliminates the parasitic wave between the two grid system boundaries which makes computation stable, but also makes large grid system calculation more precise. In this method both large and small grid system must be calculated at the same time.

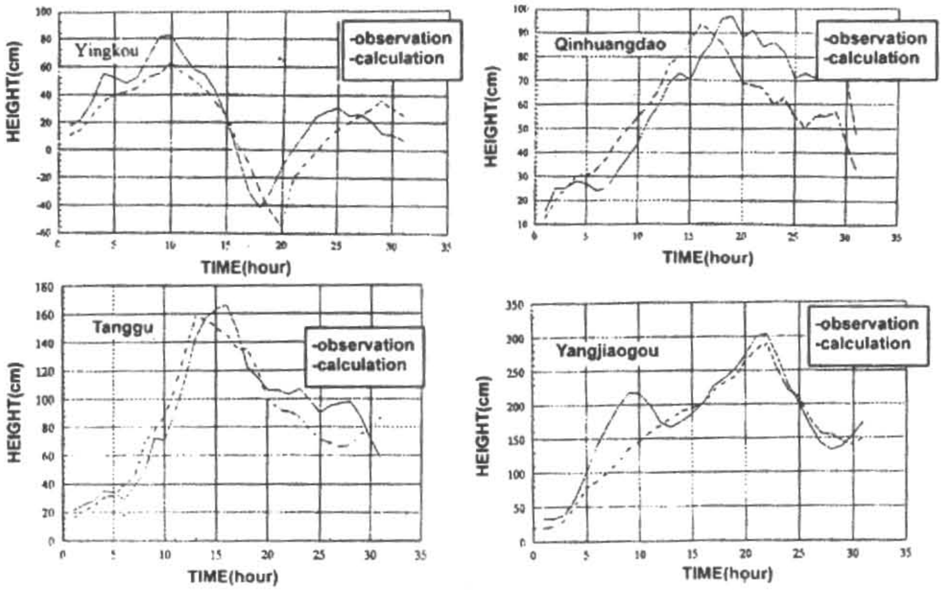

Fig. 15. Comparison of observed and computed surge at four gauges for typhoon polly (9216), 1992

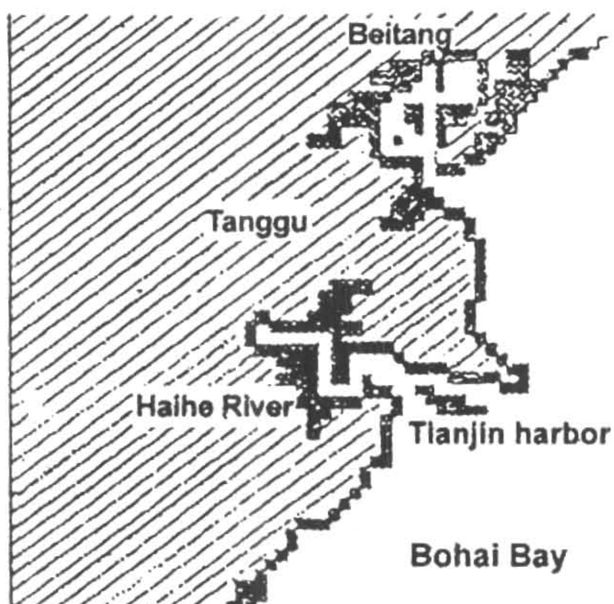

Fig. 16. The maximum inundation regions at Tanggu district during the period of typhoon polly

4.3. *Simulation of storm surge due to typhoon Polly (9216)*

The computational grid of the numerical model in coarse grid is shown in Fig. 13. Fig. 14 shows the three dimension feature of Tianjin region including low lying coastal land for inundation.

This model is used to simulate the surge generated by No. 9216 typhoon. Fig. 15 shows the comparison between the computed and the observed surge elevations at Tanggu, Yangjiaogou, Yingkou and Qinhuangdao, respectively. We can see that the computed elevation curve looks quite similar to the observed one at each station, except for the first peak at Yangjiaogou tidal gauge station.

Fig. 16 shows the distributions of maximum flood range. The main inundation region is located along the estuary of Haihe River etc. which is in agreement with the observed one.

To summarize, this model can reproduce the water levels and flooding during the No. 9216 typhoon with good accuracy.

5. Conclusions

The simulation and real-time forecasts of FbM show that the computational methods of atmospheric pressure distribution and wind field in a typhoon area are satisfactory. The numerical typhoon surge model, partial overlapping technique of adjacent basins, and selected finite-difference methods are suitable and have advantages of saving computational time and memory of a computer. In addition, the model has advantages of easily operating a novel format of model outputs for the user.

In general, simulated cases of SLOSH are quite successful. They show that the parameterized wind field of the model can describe the sea surface wind field of severe typhoon in the China Seas. It is very important that SLOSH model can describe the features of each basin's topography in high resolution and calculate overland surges.

The new storm surge model has been developed and applied to the Bohai Sea, which allows for inundation due to surge and astronomical tide at the same time using the simple algorithm introduced by Flather and Heaps (1975). Multiple nested grid system is used in this model for improving the computational accuracy and two different interactive methods between two grid system are used. The simulation indicates that the model is quite useful.

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