TEST OF A TROPICAL LIMITED AREA NUMERICAL PREDICTION MODEL INCLUDING EFFECT OF REAL TOPOGRAPHY

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ABSTRACT

In this paper, a tropical limited numerical prediction p.e. model in sigma coordinate is developed. The predicted variables are deviations from a rest reference atmosphere. This transformation is of benefit in reducing truncation error and guarantees computational stability after the very steep real topography is introduced into the model. The numerical tests with this model show that the large-scale obstacle of the Tibetan Plateau is not negligible in forecasting tropical systems like the South China Sea typhoon.

I. INTRODUCTION

Years ago, we designed a tropical limited 4-layer primitive equation model (p.e. model) with pressure as the vertical coordinate and applied it to routine forecasting (Wang et al, 1986). In this model, the ground is considered as plain and only very simple physical processes are included. However, the synoptic and dynamic studies indicate that the influence of the Tibetan Plateau and other mountains in the south and south-east Asia on the evolution of tropical systems is not negligible. In order to improve forecasting in the tropical regions, a new sigma-coordinate tropical limited area p.e. model, in which the effects of topography and heating by condensation are taken into account, is developed. The predicted variables of this new model are deviations from a rest reference atmosphere. This transformation may reduce the computational truncation error of pressure gradient force in sigma coordinate, and guarantee the computational stability, even if the very steep real terrain is introduced into the model. With the observational data collected during the FGGE period in 1979, several cases of forecasting are implemented. The results are encouraging. The introduction of real topography (called high topography hereafter) does improve the prediction of some tropical systems, e.g. typhoons over the South China Sea.

In this paper, after a brief description of this model, the impact of the introduction of the high topography on the prediction of the South China Sea typhoon is discussed with a forecasting case.

II. DESCRIPTION OF MODEL

1. *Fundamental Equations*

We assume a rest reference atmosphere, of which the temperature and geopotential height depend only on the pressure and satisfy the hydrostatic relation, i.e.

$$d\tilde{\phi}/dP = -R\tilde{T}/P, \tag{1}$$

R being the specific gas constant of the dry air. The temperature and geopotential of the real atmosphere may be expressed as:

$$T(t,x,y,p) = \tilde{T}(p) + T'(t,x,y,p),$$
$$\phi(t,x,y,p) = \tilde{\phi}(p) + \phi'(t,x,y,p), \tag{2}$$

where the variables with prime are the deviations from the values of the reference atmosphere, and

$$|T'| \ll |\tilde{T}|, \quad |\phi'| \ll |\tilde{\phi}|. \tag{3}$$

For convenience we also assume that

$$R^2\tilde{T}/g\left(g/C_p + g\frac{d\tilde{T}}{d\tilde{\phi}}\right) = C_0^2 = \text{const}, \tag{4}$$

and the value of C_0^2 should be so chosen that $\tilde{T}$ and $\tilde{\phi}$ are as close to the mean state of the tropical atmosphere as possible. The standard surface pressure $\tilde{p}_s$ may be calculated from the elevation of topography after the relation $\phi_s = \tilde{\phi}(\tilde{p}_s)$. Because the reference atmosphere is stationary, the equations describing the state and motion of the atmosphere may be replaced by the equations of the deviations from the reference atmosphere (Zeng Qingcun, 1979, 1985). In sigma coordinate, the replacement with the deviation may effectively reduce the computational truncation error of the calculation of horizontal pressure gradient forces. As indicated by Zeng et al. (1985), after deducting the stratification of the reference atmosphere a new energy constraint, i.e. conservation of the total effective energy holds. In this circumstance, the magnitude orders of the total kinetic energy and the total effective potential energy are close, and small change in geopotential field does not cause tragical increase of the kinetic energy. This property seems favorable for overcoming the computational difficulties around steep mountains.

Vertical independent variable σ is defined as

$$\sigma \equiv (p - p_T)/\pi, \quad \pi \equiv p_S - p_T, \tag{5}$$

here p_S is the surface pressure, p_T is the pressure on the top of the atmosphere, which is set to 100 hPa in this model. In such defined coordinates the prediction equations are as follows.

$$\frac{\partial}{\partial t}\left[\frac{\pi u}{m}\right] - m\left[\frac{\partial}{\partial x}\left(\frac{\pi u}{m}u\right) + \frac{\partial}{\partial y}\left(\frac{\pi v}{m}u\right)\right] + \frac{\partial}{\partial\sigma}\left(\frac{\pi\dot{\sigma}}{m}u\right) - \pi\frac{\partial\phi}{\partial x} + RT_e\frac{\partial\pi}{\partial x} - f^*\frac{\pi v}{m} = F_u + D_u, \tag{6}$$

$$\frac{\partial}{\partial t}\left[\frac{\pi v}{m}\right] - m\left[\frac{\partial}{\partial x}\left(\frac{\pi u}{m}v\right) + \frac{\partial}{\partial y}\left(\frac{\pi v}{m}v\right)\right] + \frac{\partial}{\partial\sigma}\left(\frac{\pi\dot{\sigma}}{m}v\right) - \pi\frac{\partial\phi}{\partial y} + RT_e\frac{\partial\pi}{\partial y} + f^*\frac{\pi u}{m} = F_v + D_v, \tag{7}$$

$$\frac{\partial}{\partial t}\left[\frac{\pi T}{m}\right] + m\left[\frac{\partial}{\partial x}\left(\frac{\pi u}{m}T\right) + \frac{\partial}{\partial y}\left(\frac{\pi v}{m}T\right)\right] + \frac{\partial}{\partial\sigma}\left(\frac{\pi\dot{\sigma}}{m}T\right) + \left(-\frac{C_0^2\pi}{Rp} - \frac{\kappa T_e}{\sigma}\right)\left(\frac{\pi\dot{\sigma}}{m} + \frac{\sigma\dot{\pi}}{m}\right)$$
$$= D_T + \frac{\pi}{m}Q, \tag{8}$$

$$\frac{\partial \pi}{\partial t}+\int_0^1 m^2\left[\frac{\partial}{\partial x}\left(\frac{\pi u}{m}\right)+\frac{\partial}{\partial y}\left(\frac{\pi v}{m}\right)\right]d\sigma=0, \tag{9}$$

$$\frac{\partial \phi}{\partial \sigma}=-\frac{RT_e}{\sigma}. \tag{10}$$

$$\dot{\sigma}=-\frac{1}{\pi}\int_0^{\sigma} m^2\left[\frac{\partial}{\partial x}\left(\frac{\pi u}{m}\right)+\frac{\partial}{\partial y}\left(\frac{\pi v}{m}\right)\right]d\sigma+\frac{\sigma}{\pi}\int_0^1 m^2\left[\frac{\partial}{\partial x}\left(\frac{\pi u}{m}\right)+\frac{\partial}{\partial y}\left(\frac{\pi v}{m}\right)\right]d\sigma, \tag{11}$$

$$T_e=\frac{\pi\sigma}{p}T=\frac{\pi\sigma}{\pi\sigma+p_t}T. \tag{12}$$

The primes in the upper right corner of all deviations have been neglected. m is the Mercator's map projection factor; D_u, D_v and D_T are the horizontal diffusion terms of u, v and T; F_u, F_v are the frictional terms; and Q is the heating source. The expressions of these terms will be given later.

2. *Mesh System and Spatial Difference*

In the horizontal, the Arakawa's semi-staggered B grid is adopted. The horizontal grid distance is 333.333 km. The whole domain consists of 40 × 28 grid points extending from 28.7°S to 45.3°N, and from 50°E to 167°E. The model includes six equidistant vertical layers. The vertical distribution of variables is shown in Fig. 1.

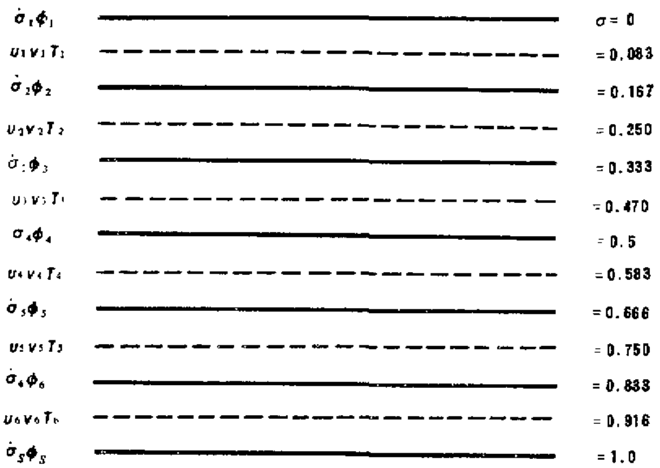


Fig. 1. Vertical distribution of predicted variables.

Much attention is paid to preserving the integral properties of the model when the difference approximation of the nonlinear terms is introduced. For example, the nonlinear term of the zonal momentum equation is

$$A_u=-m\left\{\delta_x\left[\overline{\left(\frac{\bar{\pi}^x\bar{u}^y}{m}\right)\bar{u}^x}\right]^{xy}+\delta_y\left[\overline{\left(\frac{\bar{\pi}^y\bar{v}^x}{m}\right)\bar{u}^y}\right]^{xy}\right\}-\delta_\sigma\left[\overline{\frac{\pi\dot{\sigma}}{m}}^{xy}\bar{u}^\sigma\right], \tag{13}$$

where $(\overline{\ \ })^x$ represents the mean operation along X direction, and $\delta_x(\ \ )$ represents the finite difference operation in the same direction. Other notations have similar meaning.

The finite difference approximation of the continuity equation is

$$\frac{\partial \pi}{\partial t} = -\sum_{\sigma=0}^{1} m^2 \left[\delta_x \left(\frac{\bar{\pi}^x \bar{u}^y}{m} \right) + \delta_y \left(\frac{\bar{\pi}^y \bar{v}^x}{m} \right) \right] \Delta\sigma, \tag{14}$$

The difference schemes given above guarantee to conserve the total mass and no false energy sink or source is introduced by the nonlinear terms. It has been mentioned that with the deviation to the reference atmosphere used in the model, a new energy constraint, i.e. the conservation of the total effective energy (sum of the kinetic energy, the effective potential energy and the effective surface potential energy) holds. This constraint is much stronger than the conservation of the total energy. Following the GCM developed by Zeng et al. (1985), we derive the following finite difference approximations of the pressure gradient force terms in two momentum equations and the adiabatic compression term in the thermodynamic equation which fit into the mesh system and are compatible with each other in the sense of energy transformation.

$$P_{Gx} = \overline{\bar{\pi}^x \delta_x \phi}^{y\sigma} - \sigma\, \overline{\delta_\sigma \bar{\phi}^x \delta_x \pi}^y$$

$$P_{Gy} = \overline{\bar{\pi}^y \delta_y \phi}^{x\sigma} - \sigma\, \overline{\delta_\sigma \bar{\phi}^y \delta_y \pi}^x$$

$$A_d = -\frac{C_0^2 \pi}{RP_k} \left(\overline{\omega^1}^\sigma + \omega^{11} \right) \tag{15}$$

$$\omega^1_{k+\frac{1}{2}} = -\sum_{1}^{k} \left(\delta_x (\bar{\pi}^x \bar{u}^y) + \delta_y (\bar{\pi}^y \bar{v}^x) \right)_k$$

$$\omega^{11}_k = \sigma \left(\overline{\bar{u}^y \delta_x \pi}^x + \overline{\bar{v}^x \delta_y \pi}^y \right)_k .$$

Here P_{Gx} and P_{Gy} represent pressure gradient force terms in two momentum equations and A_d represents the adiabatic term in thermodynamic equation.

It is easy to demonstrate that the above difference approximations preserve the conservation of the total effective energy. The results of forecasting experiments show that the treatment of deducting the stratification of the reference atmosphere and preserving the conservation does relief the computational difficulties caused by introduction of the real steep topography around the Qinghai-Tibet Plateau.

3. *Physical Process*

(1) *Friction and diffusion*

The horizontal diffusion terms of momentum and thermodynamic equations are

$$D_u = \frac{K_u}{m} \nabla (\pi \nabla u), \quad D_v = \frac{K_v}{m} \nabla (\pi \nabla v), \quad D_T = \frac{K_T}{m} \nabla (\pi \nabla T), \tag{16}$$

where K_v and K_T are diffusion coefficients of momentum and heat respectively and both are set to $1.5 \times 10^5\ m^2/s$. In order to suppress fast moving waves excited by the boundary conditions, the value of the diffusion coefficient is enlarged to 6.5×10^5, 4.5×10^5 and $2.5 \times 10^5\ m^2/s$ on the grid points of the outmost second, third and fourth circles.

The vertical diffusion of momentum due to friction is

$$\vec{F}=-\frac{\pi g}{m}\left(\frac{\partial\vec{\tau}}{\partial\sigma}\right), \tag{17}$$

where τ is the frictional stress defined as

$$\tau=\begin{cases}0 & \text{on upper levels}\\ \rho_s C_D|\vec{v}_s|\vec{v}_s & \text{on the ground.}\end{cases} \tag{18}$$

The drag coefficient C_D is relevant to the characteristic of the surface, and the wind speed on the surface is proportional to the wind speed on the lowest model level.

(2) *Hydrological cycle*

The equation of the water vapor is

$$\frac{\partial}{\partial t}\left(\frac{\pi q}{m}\right)=-m\left[\frac{\partial}{\partial x}\left(\frac{\pi u}{m}q\right)+\frac{\partial}{\partial y}\left(\frac{\pi v}{m}q\right)\right]-\frac{\partial}{\partial\sigma}\left(\frac{\pi\dot{\sigma}}{m}q\right)+W, \tag{19}$$

q being the specific humidity and W being the variation of water vapour due to phase change.

There are two kinds of condensation processes included in the model, i.e., large-scale condensation and cumulus convection. Thus the diabatic heating and the source of water vapor consist of two parts, i.e.

$$Q=Q_l+Q_c,\quad W=W_l+W_c, \tag{20}$$

the subscript l representing the large-scale condensation, and the subscript c representing the cumulus convection.

The large-scale condensation occurs if the relative humidity is greater than 90% in stable atmosphere. All condensed water is assumed to fall as precipitation. A modified Kuo's scheme (1974) is used for parameterization of cumulus convection. The fundamental condition of convection is positive convergence of water vapour in conditionally unstable atmosphere. The authors plan to discuss the influence of condensation on the evolution of tropical systems in another paper; therefore no further description on the condensation processes is given here.

4. *Time Intergration*

The Matsuno scheme and the leap-frog scheme are alternately applied for the time integration. Matsuno scheme is used in the earliest six hours. Then, in each successive six hours, Matsuno scheme is adopted for the first one hour and the leap-frog scheme is used for the remainder five hours. The pressure gradient force is smoothed over the consecutive three-time steps, i.e.

$$\hat{P}_G^K=(1-2\alpha)P_G^K+\alpha(\hat{P}_G^{K-1}+P_G^{K+1}), \tag{21}$$

where P_G^K is the unsmoothed value of the pressure gradient force at time step K and $\hat{P}_G^K$ is its smoothed value. The value of α is 0.263. This procedure of time averaging developed by Shuman (Brown and Campana, 1978) has proved to be very successful in suppressing the high-frequency oscillation.

III. CASE STUDY—THE IMPACT OF HIGH TOPOGRAPHY ON THE MAINTENANCE OF THE SOUTH CHINA SEA TYPHOON

Several forecasting experiments have neen performed with the data of FGGE in 1979.

The results are encouraging. The method adopted here to reduce the truncation error of the pressure gradient force and the procedure of time average make it possible for the model to use the very steep real high topography (Gates and Nelson, 1975) without any computational difficulty. It was supposed that the topography has only very little impact on the short range forecasting of tropical systems and that this impact may well be reflected with modeled topography of which the elevation is much lower than that of real mountains. Actually this is not the case. Here a forecasting case of Oct. 1st, 1979 is studied in order to discuss the impact of the high topography on the prediction of the South China Sea typhoon.

At 00 GMT, October 1st, a north to north-east flow ahead of a well-developed ridge prevailed in the eastern portion of China. Meanwhile, the ridge line of the western Pacific subtropic high was located at 21°N. There was also a tropical depression with maximum wind speed of 12 m/s over the South China Sea (see Fig. 2). This depression developed into a typhoon shortly afterwards.

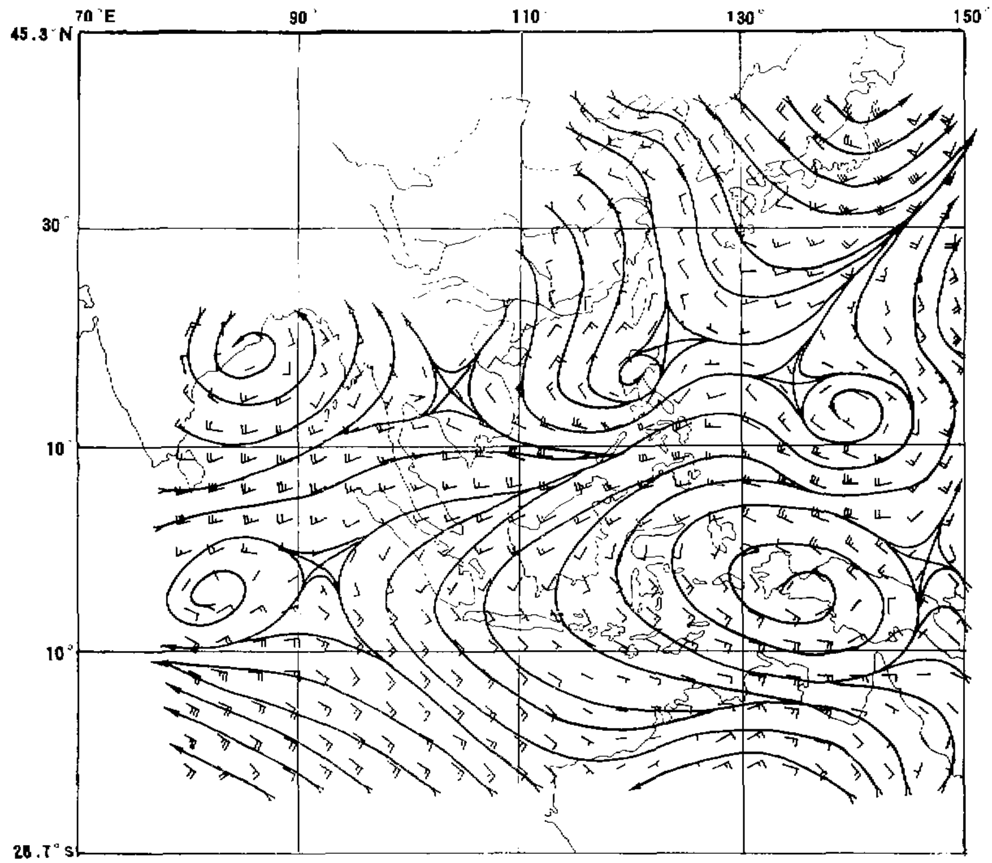


Fig. 2. 850 hPa wind field at 00 GMT, Oct. 1st, 1979.

The 24-hour forecasts of wind field on 850 hPa level with and without terrain included in the model are given in Fig. 3a and Fig. 3b respectively. The cyclonic circulation over the South China Sea disappears in the prediction by the model without terrain, while the cyclonic circulation is intensified in the model with terrain.

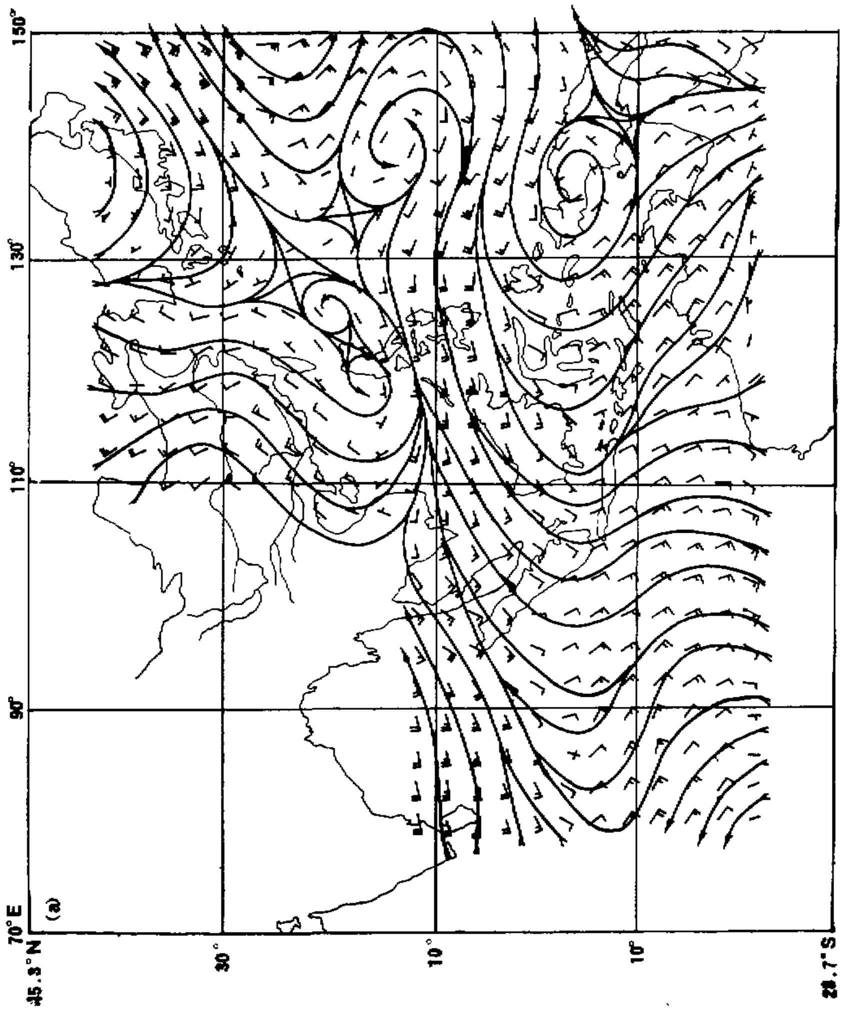
Whether or not the South China Sea typhoon exists is not the only difference between the predicted wind fields with and without terrain. The comparison of Fig. 3a and b shows that the low-level ridge and the northeast flow over the eastern portion of the Chinese continent and the South China Sea are maintained while the terrain is included in the model. The synoptic studies indicate that this low-level north-easterly is one of the necessary conditions for the genesis and intensification of the South China Sea typhoons. However, the low-level high and the north easterly ahead of the high can not be maintained while the terrain is removed. In this case, the north westerly behind the main trough over the eastern Asia reaches low latitudes and prevails over South China and the South China Sea. The synoptic studies show that the genesis of the South China Sea typhoon is impossible in such a situation.

The predicted upper-level flow patterns with and without terrain are very different too. Figure 4a and b are the 24-hour forecasts of 200 hPa wind fields with and without terrain. It can be seen that the predicted location of ridge line of the South Asian High by the model with terrain is to the north of the location without terrain, and that the main upper trough over eastern Asia moves faster in the model with terrain than in the model without terrain.

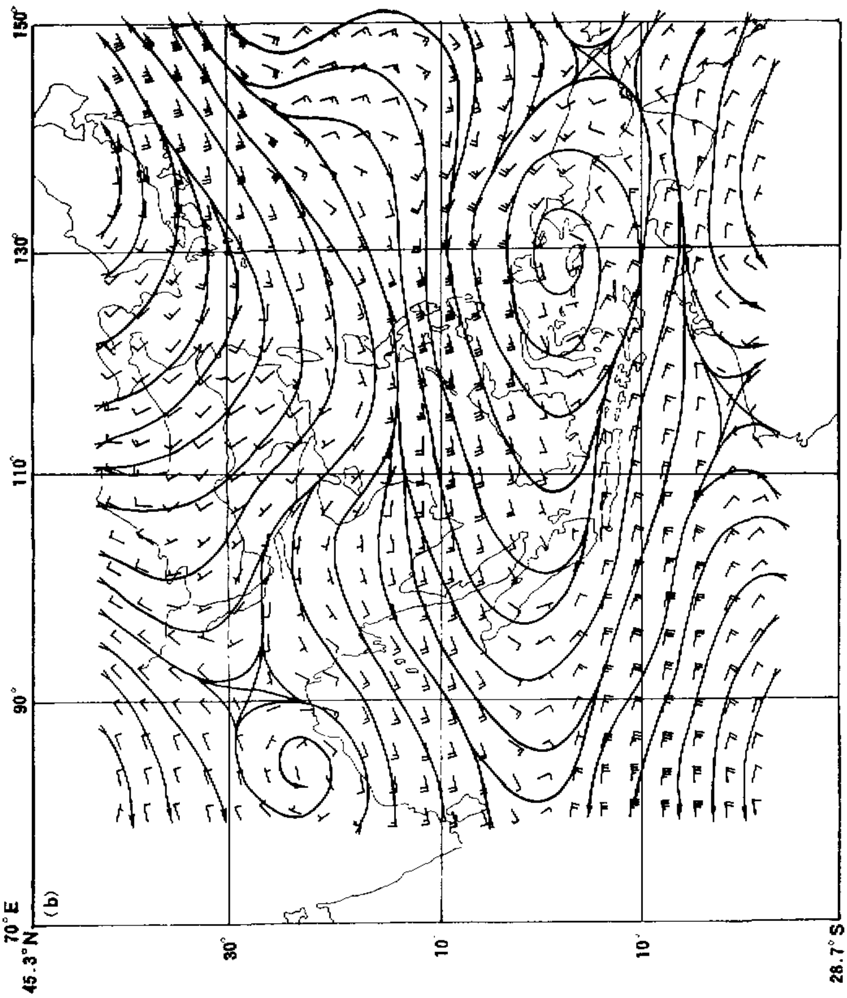
In order to compare the impact of different mountains on the evolution of the typhoon, a forecasting test with a model which includes only the mountains to the north of 23°N is implemented (the figures are ignored here). It is found that the impact of mountains to the south of 23°N on the evolution of typhoon is not recognizable with the spatial resolution currently used. In other words, the impact of terrain is mainly due to the large-scale obstacle of the Tibetan Plateau. In the case studied here, the effect of the topography on the typhoon seems indirect: the existence of the Tibetan Plateau makes it possible for the north-easterlies over South China and the South China Sea to maintain and then causes a background in favor of the formation of the typhoon over the South China Sea. No matter whether the connection between the typhoon and the topography is indirect, the impact is undoubtedly very important.

It is very interesting that the capability of the model to reflect the impact of topography on tropical systems depends upon the elevation of mountains, especially the elevation of the Tibetan Plateau used in the model. Presented in Fig. 3c is the predicted 850 hPa wind field by a model in which topographic elevation is multiplied by a factor 0.6 (called low topography). It can be seen that the north-easterlies still prevail over South China and the South China Sea, but become weaker and the typhoon is replaced by a trough. This is the evidence of the fact that the low topography is not able to reflect the full impact of the real topography on the evolution of the tropical systems.

After making these forecasting tests we may conclude that, on the one hand, the tropical numerical model should include the effect of the topography and, on the other, the elevation of the modeled mountain should not be reduced too much. Otherwise the effect of topography on the tropical systems cannot be correctly forecasted with the model.



150°
130°
110°
90°
70°E
(a)
30°
10°
10°


150°
130°
110°
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70° E
45.3° N
(b)
30°
10°
10°
28.7° S

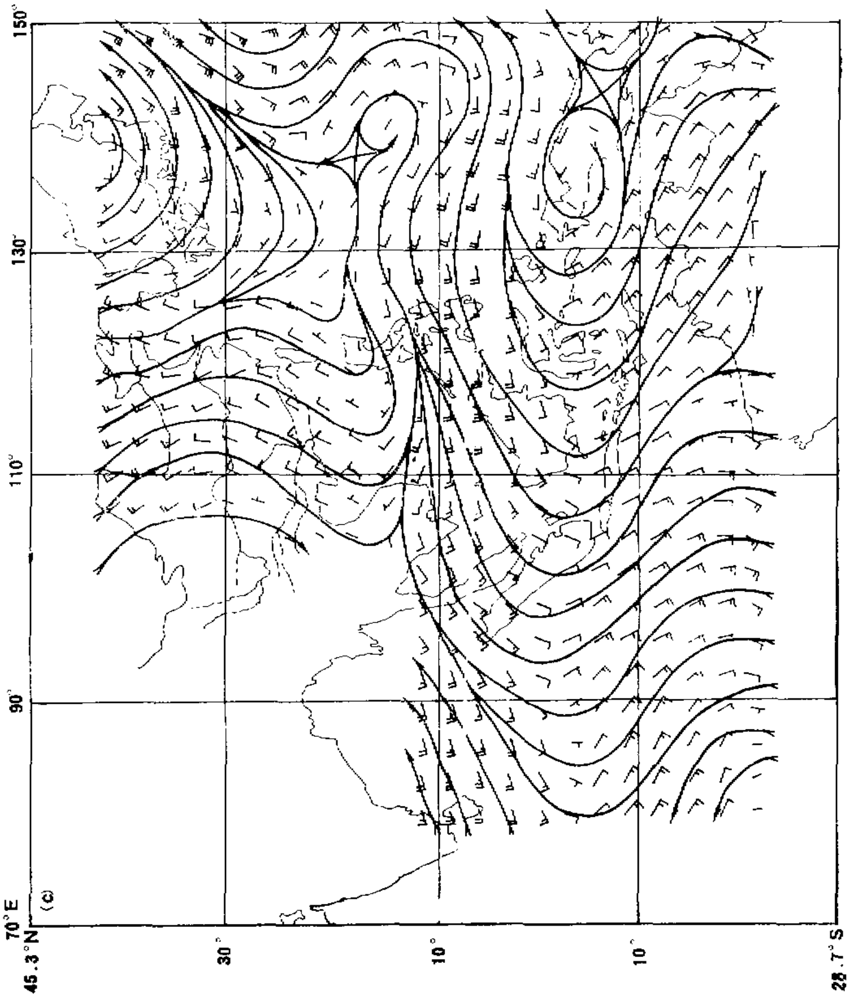
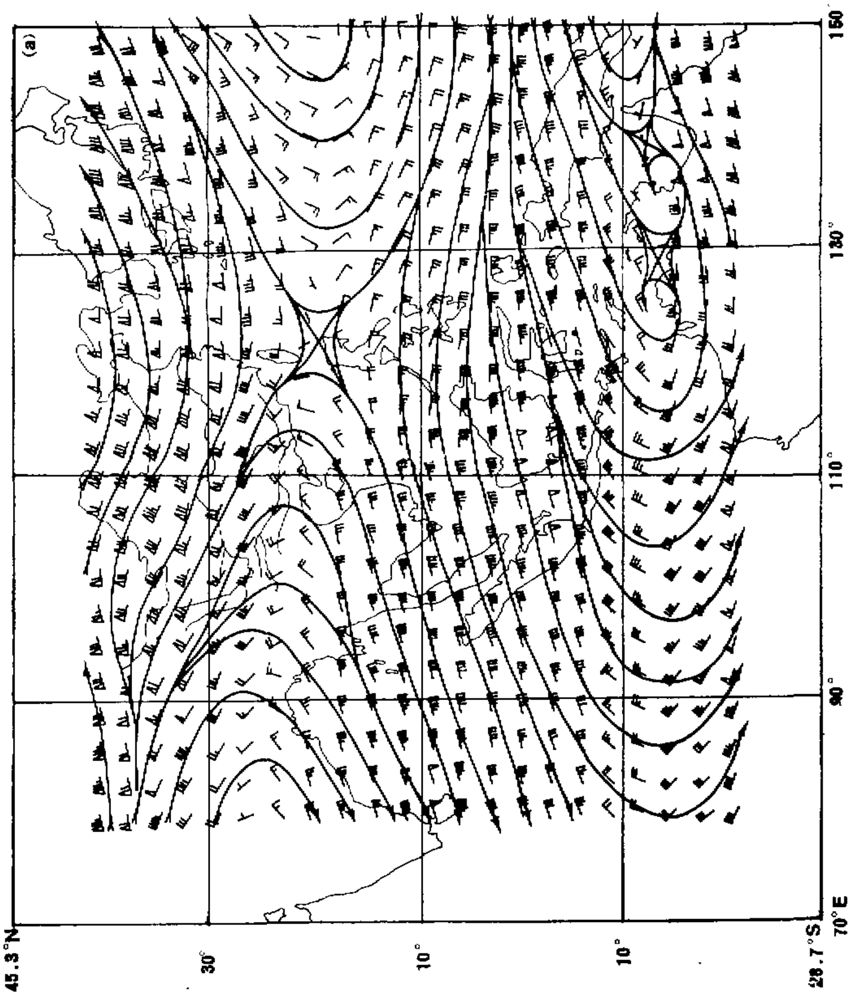


Fig. 3. The 24-hour prediction of 850 hPa wind field:
(a) with high topography, (b) without topography, (c) with low topography.


(a)
45.3°N
30°
10°
10°
28.7°S
70°E
90°
110°
130°
150°

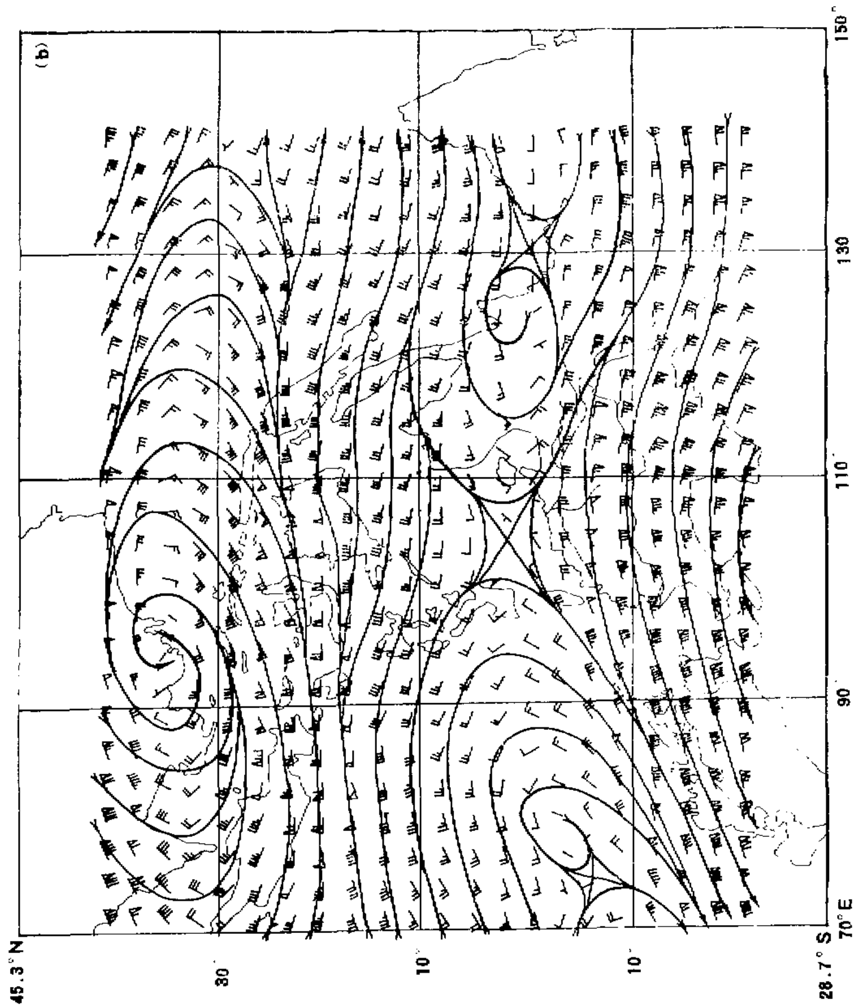


Fig. 4. The 36-hour prediction of 200 hPa wind field.
(a) with high topography, (b) without topography.

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