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A TWO-WAY INTERACTIVE MOVABLE NESTED MESH MODEL FOR TYPHOON TRACK PREDICTION①

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ABSTRACT

A limited area primitive equation model, designed for typhoon track prediction and based on two-way interactive, movable and nested mesh techniques, is developed in this paper. A detailed description is presented of the nesting strategy, terrain treatment and noise control measures. Also, several new methods are proposed. This model has been tested with case experiments under operational environments, and high forecast skill on typhoon tracks has been obtained.

Key words: typhoon track, numerical model forecast, two-way movable nested mesh

Ⅰ. INTRODUCTION

Dynamical and numerical prediction of typhoon tracks is a developing trend in making prediction of typhoon tracks (Anthes, 1982) . Using nested mesh model in this aspect has the following properties: (1) the stronger gradient fields that feature a typhoon can be well defined in a higher resolution mesh model, and (2) the large-scale steering flow that plays significant roles in influencing typhoon movement can be described with a lower resolution in a larger model domain to save operational costs. Through two-way interactions between the high and the low resolution models the impact of large-scale flow on a typhoon and the influence of the typhoon on the large-scale flow circulation can be coupled each other, leading to a fast forecast of typhoon tracks due to less computation involved, a critical factor that operational applications require.

This paper describes the development of a two-way, movable and nested numerical model for typhoon track prediction, which is based on a limited-area precipitation forecast model of the National Meteorological Center. The nesting procedure, terrain treatment and noise control techniques used in the model are presented. Experimental case forecasts of typhoon tracks using the model are also demonstrated.

Ⅱ. OUTLINES OF THE MODEL

A primitive equation model in σ (in the vertical) and latitude-longitude(in the horizontal) coordinate system is adopted. It is formulated in 15 levels and C-type staggering grid mesh. The model physics includes horizontal diffusion, surface boundary friction, large-scale precipitation and cumulus parameterization. An economical explicit scheme for time integration (Tatsumi, 1983) and a lateral boundary scheme of Davis (1976) are

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used.

The coarse mesh model (CM) has a horizontal resolution of 1. 875°, and the model domain consists of 27×41 grid points. The fine mesh model (FM) has a horizontal resolution of 0. 46875° with the domain size of 41×41 grid points. So the ratio of grid length of CM to FM is 4:1. The vertical structure for both CM and FM is identical. The model is initialized using a nonlinear normal mode method. To improve the description of typhoon characteristics at initial time, a bogus typhoon is introduced into the initial fields of both CM and FM models (Wang et al. , 1996).

Ⅲ. NESTING PROCEDURE

1. *Time integration*

Time integration of the nested model is as follows. The latest CM variables are obtained by integrating CM model in longer time step. Then the latest CM tendencies are spatially and temporarily interpolated to prepare the data for updating FM lateral boundary (see section 3. 2 for details). The FM model integrates successively four times in shorter time step (here assuming that the time step ratio of CM to FM is also 4), each step followed by updating the FM boundary using the above interpolated CM tendencies, until reaching the time level same as that of CM. At this time level a feedback operation of the forecasted FM solutions to CM solutions is carried out (see section 3. 3 for details). After the steps above one cycle of integration of the nested mesh model is completed. The longer time step is set to 7. 5 minutes here in this paper.

2. *Forcing of FM by CM: interface interpolation*

The interface structure of the nested mesh model is complex because of the C-type staggered-grid mesh used. There are four types of interface structure for five model variables (surface pressure p_s, wind components u, v, temperature T and specific humidity q); each type corresponds to one interpolation scheme. The most simple one is for T and q that are obtained directly from cubic spline interpolation of corresponding CM variables along four FM interfaces. The same is true for p_s interpolation along western and southern FM interfaces, but a two-step scheme is required to obtain interpolated p_s value along eastern and northern FM interfaces: a parabolic interpolation between three points perpendicular to the interface followed by a cubic-spline interpolation along the interface. The procedure of obtaining u and v values along FM interfaces is similar to that of p_s stated above.

3. *The influence of FM on CM: feedback*

Over a portion of the CM domain where the FM domain overlaps one another, the CM forecasts are superseded by the corresponding latest smoothing FM forecasts. This feedback procedure is required based on the understanding that forecasts from a higher resolution model should be superior to that from a lower resolution model. For the nested model for typhoon track prediction, such feedback operation becomes necessary in order to avoid large prediction errors due to significant deviations between the forecasted CM and FM fields without feedback. The feedback for T, q and p_a is made by a nine-point smoothing operator:

$$\begin{aligned} X_{J,I} = & x_{j,i} + 0.5\mu(1-\mu)(x_{j,i+2} + x_{j,i-2} + x_{j+1,i} + x_{j-1,i}) \\ & + 0.25\mu^2(x_{j+1j,i+2} + x_{j+2,i-2} + x_{j-1,i+2} + x_{j-1,i-1} - 4x_{j,i}, \end{aligned} \quad (1)$$

where $X = (T, q, p_s)$ denotes CM variables; x is the corresponding FM variables; the subscripts J, I define the same CM position as j, i on the FM. A value of 0.5 is used for smoothing coefficient μ. Revised nine-point smoothing operators are adopted for feedback of u and v as their grid positions in CM and FM do not coincide.

4. *Treatment of terrain*

A feedback on mass fields existing in a two-way nested mesh model means additional constraint on CM and FM terrain heights, and therefore it is necessary to adjust the terrain heights accordingly. The terrain elevations for both CM and FM, respectively denoted by H and h, are derived from interpolation of a 1°x1° global terrain dataset. If these terrain heights are introduced directly, the feedback processes of mass fields from CM to FM using operator (1) may produce incompatible CM mass fields. One solution to this problem is to ensure that the operator (1) will also hold for h and H fields wherever the FM may be situated. A scheme proposed by Zhang et al. (1986) is used here to adjust H and h.

At coincident points the CM and FM terrain values are expressed by $H_{J,I}$ and $h_{j,i}$, respectively. In general, the nine-point averaged value, $\bar{h}_{j,i}$, of the FM terrain about j, i is not equal to the original FM value at the same point, i.e., $\bar{h}_{j,i} \neq h_{j,i}$. The difference is defined by

$$\Delta h = \bar{h}_{j,i} - h_{j,i}. \tag{2}$$

Using Δh, an adjustment is applied to $h_{j,i}$ or $H_{J,I}$, so that

$$H'_{J,I} = h'_{j,i} = \bar{h}'_{j,i}, \tag{3}$$

where values with prime denote the adjusted terrain heights. For a constant c, the c part of Δh is used to adjust $\bar{h}_{j,i}$, and the remaining $(1-c)$ part to $h_{j,i}$. That is

$$\begin{aligned} H'_{J,I} &= \bar{h}_{j,i} - c\Delta h, \\ h'_{j,i} &= h_{j,i} + (1-c)\Delta h. \end{aligned} \tag{4}$$

These adjustment processes make the left equality in (3) hold. In order that the right equality in (3) also holds, the terrain at surrounding eight FM points should be adjusted by a value Δz,

$$h'_{j+m,i+n} = h_{j+m,i+n} - \Delta z, \tag{5}$$

$$n, m = 0, 1, -1; n, m \text{ not zero simultaneously.}$$

Substitution from (4), (5) into (1) with $\mu = 0.5$, one can easily get a relation between Δz and Δh,

$$\Delta z = (c + 1/3)\Delta h. \tag{6}$$

We choose $c = 0$, and $\Delta z = \Delta h/3$. That is, the $H_{J,I}$ and $h_{j,i}$ at the coincident points are replaced by the nine-point smoothed value $\bar{h}_{j,i}$, while the terrain height surrounding eight FM points are subtracted by amount $\Delta h/3$. Comparison of the terrain after the above manipulation with that before the processing show small differences in magnitude. For instance, the standard deviations of CM and FM height changes before and after the terrain treatment over the entire model domain are only 18.5 m and 6.4 m.

5. *Noise control*

Almost all finite-differenced primitive equation models require some measures of controlling spurious growth of short-wavelength energy . Noise control is even more important for the nested mesh model discussed here because of various origins of noise that exist in the model . For instance, the high-frequency noise may come from the imbalance caused by interpolation-feedback processes over CM and FM overlapping area and/or from FM movement (see section 4). Thus additional means of noise control should be applied to this model.

1) SURFACE PRESSURE ADJUSTMENT ALONG FM INTERFACE OVER LAND

As stated in section 3. 2, the solution along FM interface are obtained from interpolated CM forecasts. If the point on FM interface is over land, the existence of terrain will affect the interpolated p_s on that point because the disturbance in the mass field could be caused by imcompatibility between the interpolated mass field and the terrain heights. Thus to reduce terrain effect on interface grid over land the interpolated p_s value is adjusted after Bender et al. (1993).

Denoting the terrain height on FM interface by Z_0, the corresponding terrain height is obtained using the same interpolation scheme for p_s in section 3. 2 on the same point by Z_1, the terrain height difference is

$$\Delta Z = Z_1 - Z_0.$$

Then, the interpolated surface pressure p_s is replaced by height-adjusted value:

$$p_s' = p_s\left(1 + \frac{\Gamma \Delta Z}{T_0}\right)^{g/\Gamma R}, \tag{7}$$

where T_0 is the near surface air temperature; Γ is the lapse rate (6. 5 K km^{-1}); R is the gas constant; g is the acceleration of gravity. We can see from (7) that for $\Delta Z = 10\,\mathrm{m}$ the error of p_s is about 1 hPa.

2) NEWTONIAN RELAXATION

In order to reduce the incompatibility between the interpolated value on FM interface and the forecast within the FM domain, an implicit Newtonian relaxation suggested by Zhang et al. (1986) is applied to the forecast at points next to the nest interface. At these points, the tendency of variable x is modified as

$$\frac{\partial x}{\partial t} = \cdots - \frac{(x - \bar{x})^{n+1}}{\tau}, \tag{8}$$

where x^{n+1} is the latest forecast of x; $\bar{x}$ is the reference value obtained from a four-point average of value around x; τ is the relaxation time with the value of 5-10 times of integration time step.

3) HORIZONTAL DIFFUSION AND INTERFACE ADJUSTMENT FOR SPECIFIC HUMIDITY

Specific humidity q is a sensitive forecast variable. Using general horizontal diffusion scheme for q in a finite-differenced primitive equation model may lead to anomalous q forecast, which may in turn lead to anomalous forecast of other variables. This problem is particularly serious near model boundary. Thus a special diffusion scheme, which is similar to that in HIRLAM model (Kallberg, 1989), is used for q.

Horizontal diffusion for $x = (u, v, T)$ is the two-order nonlinear scheme:

$$\frac{\partial x}{\partial t} = \cdots + K_x |\nabla^2 x| \nabla^2 x, \tag{9}$$

where the diffusion coefficient K_x is $2.5\times10^{14}\mathrm{m^2s^{-1}}$ for CM and $0.7\times10^{14}\mathrm{m^2s^{-1}}$ for FM. The same diffusion scheme is applied to q, but an increased level-dependent value is assigned to the diffusion coefficient K_q,

$$(K_q)_k = (K_q)_{k-1} \cdot \min(0.4\frac{N}{k},2), \quad (K_q)_1 = \gamma K_x, \tag{10}$$

where N is the total number of the model level; K is the vertical index pointing downward; γ is a parameter with value of 1000 for CM and 2000 for FM. It is obvious from (10) that the value of K_q reaches maximum at model's middle and upper level which is much greater than the value of K_x.

In addition, the predicted q value near the model boundary is further subjected to an adjustment:

$$q' = q_s + \lambda n(q - q_s), \quad 0 \leqslant n \leqslant 6 \quad \text{if } q > q_s, \tag{11}$$

where q_s is the saturation specific humidity; q' is the adjusted value of q; n stands for the number of grid interval accounted from zero at the outermost boundary to the interior; λ is set to 0.1. The preceding treatment for q improves the forecast effectively.

Ⅳ. MOVING STRATEGY

The consideration for moving FM model is to keep a typhoon always in the central portion of FM domain. This is done by shifting FM model whenever current position of a typhoon deviates from its previous position by more than one CM grid length (1.875°). To simplify coding, shifting directions are limited toward the normal direction of east, south, west and north, and shifting toward other directions can be realized by doing the preceding normal shifting twice. Every hour a check is made to determine whether the FM model should be moved , for an average typhoon moving in less than 1.875° per hour. After shifting, the solutions on four row grid points at the leading edge of the FM domain are renewed from the interpolation of the CM solution, which include the latest forecasts and tendencies of all five variables. Before moving the FM model the central position of a typhoon should be known. This is estimated from the minimum point of sea level pressure. To enhance positioning precision, a surface fitting of the sea level pressure with 0.1°×0.1° resolution is made prior to finding the minimum of sea level pressure.

Ⅴ. EXPERIMENTAL FORECAST

Five case forecasts from two typhoons in 1992 have been made using the nested mesh model described above. Cases A and B are taken from the northwest-moving typhoon Eli, and are initialized respectively at 0000 UTC 11 July and 0000 UTC12 July. Cases C, D and E are taken from the northwest- to northeast-moving typhoon Janis and are started at 0000 UTC 5 August, 0000 UTC 6 August and 0000 UTC 7 August, respectively. To run the model in environment similar to operational forecast conditions, the lateral boundary solutions of the CM model are updated successively by the interpolated tendencies which are derived from the global forecast model's output at 3h interval. Table 1 lists the prediction errors of typhoon track and the average errors. Fig. 1 shows the real and forecast typhoon track for cases B and E. It is found from the table

Table 1. Typhoon track prediction errors (km).

Time (hours)		0	6	12	18	24	30	36	42	48
	A	4.9	24.2	52.8	136.4	188.9	185.6	212.2	219.8	198.2
	B	9.8	46.3	77.1	85.5	55.0	26.3	104.4	146.4	148.6
CASE	C	5.7	76.5	144.3	204.6	235.7	271.0	352.2	449.7	510.9
	D	8.6	49.1	71.0	155.9	161.5	152.5	188.7	189.5	191.0
	E	13.5	36.6	27.7	44.4	61.2	111.0	110.9	194.7	314.8
Average error		8.5	46.5	74.6	125.4	140.5	149.3	193.7	240.0	272.7

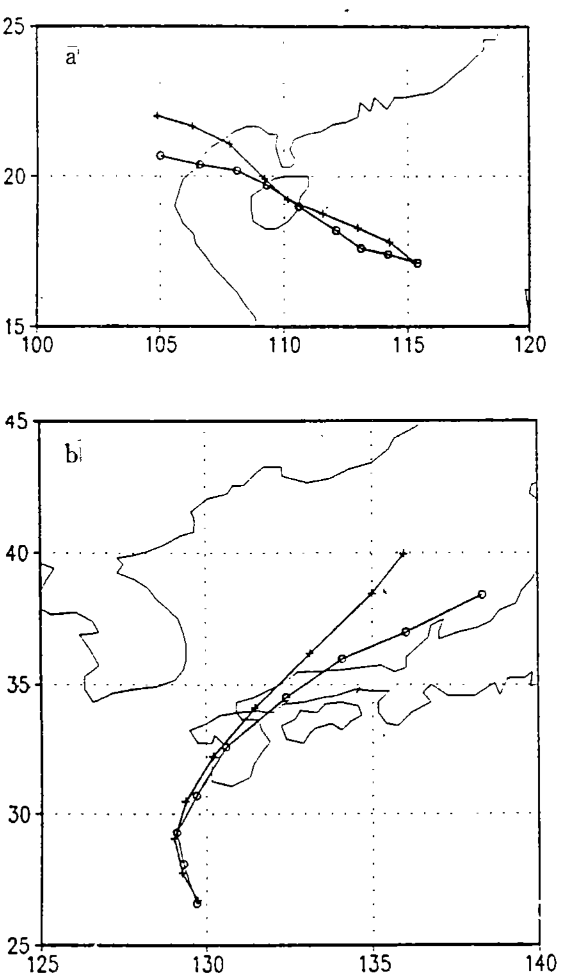
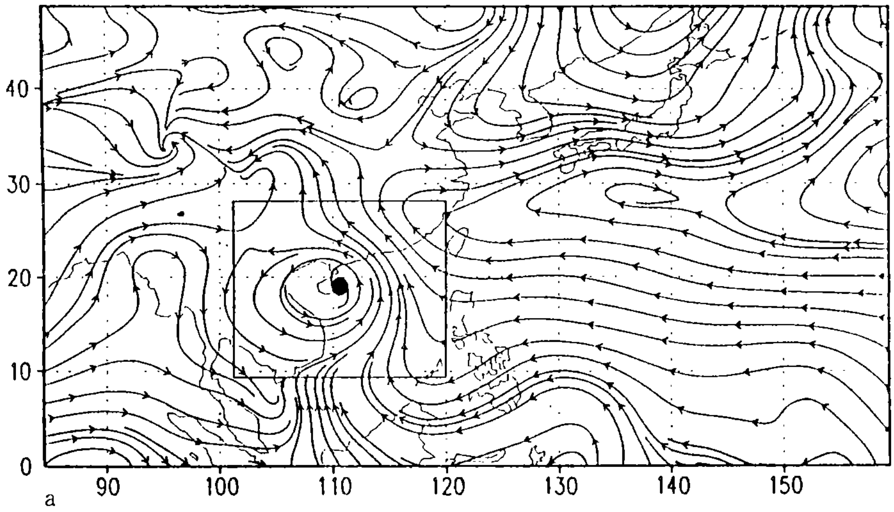


Fig. 1. Observational versus forecast typhoon tracks. (a) case B, (b) case E. Symbol o represents observational positions, symbol + denotes forecast positions. The time interval between symbols is 6h. Numerals along abscissa and ordinate stand for longitude and latitude, respectively.

and the figure that the typhoon tracks are forecasted fairly well as compared to the realistic tracks, with the average track errors only 140.5 km and 272.7 km at 24 h and 48 h, respectively, a result much better than that obtained from other usual models currently used. These results indicate that the nested mesh model development and its application to forecasts of typhoon tracks have been successful.

For brevity, only 24h forecasted streamlines of case B are shown in Fig. 2 as a representative of field forecasts. For the FM streamlines forecast (Fig. 2b) the typhoon exists as clear cyclonic convergent inflow with a significant asymmetric pattern that is demonstrated by the stronger wind on northwest side and the weaker wind on southeast side of the typhoon center, which features a mature typhoon quite well. For the CM streamlines (Fig. 2a), the forecasted typhoon is seen to be centered near Hainan Island, just a little west of the observational position (see Fig. 1a for reference), and the flow crossing the FM interfaces varies continuously and smoothly.

As indicated in Table 1, although the average track errors are small, there are different levels of forecast skill for different cases. For example, case B has shown very high forecast skill after 24h that results



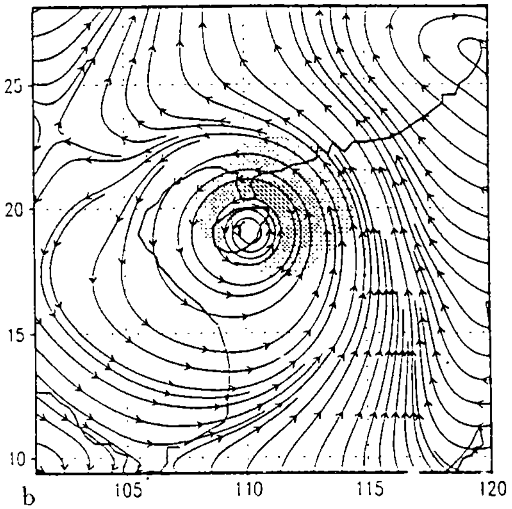


Fig. 2. Forecasted 24h 850-hPa streamlines for case B. (a) CM model. Within the figure domain the line frame represents FM boundaries, and typhoon symbol indicates the observed typhoon center position at the same time with forecast. (b)FM model. Area with the wind speed above 25 ms^{-1} and 30 ms^{-1} is lightly and heavily shaded respectively.

from the track crossing of the forecasted one and the observational one at about 30h. However, case C has given an erroneous track forecast which might be caused by the unrealistic prediction of large-scale circulation (or steering flow) when the typhoon was over the far eastern part of the north-western Pacific, an area with sparse data.

Ⅵ. CONCLUSIONS

In this paper, a new two-way interactive, movable and nested mesh model for typhoon track prediction has been developed on the basis of the Natinal Meteorological Center's limited-area precipitation forecast model. A detailed description is presented of nesting procedure, terrain treatment and noise control techniques for the nested mesh model, in which several new ideas and methods are proposed. Five experimental case forecasts have shown that this model's ability in predicting typhoon tracks is quite satisfactory. Also, the model has maintained the compatibility between forecasted CM and FM solutions as well as the continuity and smoothing of solutions near inner interfaces.

The nested mesh structure with a high length ratio 4 of coarse grid to fine grid in the model discussed here means large resolution difference between the CM and FM. This requires several measures to prevent the model from noise. To reduce as far as possible the impacts of these measures on model's behaviour and in the meanwhile maintain a stable operation on the model, a more advanced and suitable interpolation-feedback strategy should be studied and introduced into the model. Finally, more experimental case forecasts are needed in order to further improve and test this model.

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