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EXPERIMENTAL STUDY ON A DYNAMIC ASYMMETRICAL TYPHOON INITIALIZATION SCHEME BASED ON 4D-VAR

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Abstract: Axisymmetric bogus vortexes at sea level are usually used in the traditional bogus data assimilation (BDA) scheme. In the traditional scheme, the vortex could not accurately describe the specific characteristics of a typhoon, and the evolving real typhoon is forced to unreasonably adapt to this changeless vortex. For this reason, an asymmetrical typhoon bogus method with information blended from the analysis and the observation is put forward in this paper, in which the impact of the Subtropical High is also taken into consideration. With the fifth-generation Penn State/NCAR Mesoscale Model (MM5) and its adjoint model, a four-dimensional variational data assimilation (4D-Var) technique is employed to build a dynamic asymmetrical BDA scheme to assimilate different asymmetrical bogus vortexes at different time. The track and intensity of six summer typhoons much influenced by the Subtropical High are simulated and the results are compared. It is shown that the improvement in track simulation in the new scheme is more significant than that in the traditional scheme. Moreover, the periods for which the track cannot be simulated well by the traditional scheme can be improved with the new scheme. The results also reveal that although the simulated typhoon intensity in the new scheme is generally weaker than that in the traditional scheme, this trend enables the new scheme to simulate, in the later period, closer-to-observation intensity than the traditional scheme. However, despite the fact that the observed intensity has been largely weakened, the simulated intensity at later periods of the BDA schemes is still very intensive, resulting in overly development of the typhoon during the simulation. The limitation to the simulation effect of the BDA scheme due to this condition needs to be further studied.

Key words: numerical weather prediction; typhoon initialization scheme; 4D-Var; asymmetrical typhoon; simulation of typhoon track and intensity

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1 INTRODUCTION

Precise prediction of typhoon track is a giant challenge to numerical prediction. Other than the inaccurate comprehensive description of ocean-atmosphere interaction and convection in model physical processes, another important reason is the lack of large amounts of observation data on sea level, making it impossible for the internal dynamical and thermal structures of tropical cyclones as well as the large-scale circumfluence background to be described in detail[1]. Due to the lack of large amounts of data, large-scale analysis fields available in operation usually contain a weak typhoon vortex, whose location is often inaccurate. It is therefore necessary to introduce a bogus vortex to better reflect the actual structure. Next is how the operations of typhoon numerical prediction operations are carried out at home and abroad. First, the typhoon center location is analyzed to eliminate weak and inaccurate disturbance vortexes. Then, a variety of observational information is used to construct a three-dimensional vortex which is then embedded into the initial analysis field of the model. The bogus methods may not be the same at various operation centers, but the common goal is basically to design a symmetric vortex and to add some kind of asymmetric components which can characterize the movement of the vortex and its environmental flow (See Qu and Ma[1] for actual operational practices). Lots of work showed that these typhoon initial schemes can greatly improve the level of typhoon track

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forecasting[1-4].

With the development of the 4D-Var technique[5-7], Zou et al. proposed a Bogus Data Assimilation (BDA) method to consider sea-level axisymmetric vortexes as "observational data"[8]. With 4D-Var techniques, the bogus vortex gradually adapts to the background field by dynamic adjustment and automatically generates a three-dimensional asymmetric typhoon circulation structure. The BDA scheme has been further studied and better results are achieved by some meteorologists[9-11], but some problems still need to be addressed: (1) An axisymmetric vortex cannot fully reflect the specific characteristics of individual typhoons; (2) the bogus vortex is static and forces the developing typhoon to, unreasonably, adapt to it in the assimilation window; and (3) it is still a quasi-symmetric vortex in the sea-level field of final optimization. As a result, lots of useful information, especially reasonable asymmetrical components, have been neglected.

Thus, to improve the BDA, it is necessary to introduce a new kind of asymmetric bogus data that takes into account the mobile characteristic of typhoons and fully integrates information from observation and background data.

2 THE ASYMMETRICAL TYPHOON BOGUS METHOD

2.1 *Theoretical analysis of the asymmetric bogus method*

According to Hu et al.[12], in the polar coordinate with the origin set at the typhoon center, by considering the surface friction, assuming that the typhoon is in a mature and steady state, and considering the impact of typhoon mobility on the curvature radius in the inertia term, the horizontal motion equations of any surface-level air particle (r,θ) within the typhoon area are:

$$v_\theta^2/r + v_\theta v_s \sin\alpha/r + fv_\theta = d\partial p/\partial r - F_r \quad (1)$$

$$v_r v_\theta/r + v_r v_s \sin\alpha/r + fv_r = -d\partial p/r\partial\theta + F_\theta \quad (2)$$

where p is the pressure, d is the specific capacitance, v_s is the typhoon's moving speed, α is the included angle between typhoon's moving direction and the lines connecting the typhoon center with the point of interest, with the counter-clockwise direction set at positive. v_θ and v_r are the tangential wind and radial wind of the moving typhoon respectively. Suppose v_θ' and v_r' are the tangential wind and radial wind of a static typhoon, then $v_\theta = v_\theta' - v_s\sin\alpha$, $v_r = v_r' - v_s\cos\alpha$. According to the state equation of moist air, $d = R_d T_v/p$, while R_d is the dry air constant. As temperature T and water vapor mixing ratio q_v are provided by the analysis fields, virtual temperature $T_v = T(0.622+q_v)/[0.622(1+q_v)]$ is obtained. F_r and F_θ are the friction in the r and θ direction respectively. Suppose that the friction coefficient is k, wind $V=\sqrt{v_\theta^2+v_r^2}$, and sea surface friction can be roughly expressed as kV. Suppose the inward deflection angle is β, the deviation angle between frictional resistance and the opposite direction of actual wind vector is φ, with the geometric relation configuration shown in Fig. 1, then $\cos\beta = v_\theta/V$, $\sin\beta = v_r/V$, and

$$F_\theta = kV\cos(\varphi+\beta) = kV(\cos\varphi\cos\beta - \sin\varphi\sin\beta) = kv_\theta\cos\varphi - kv_r\sin\varphi, \quad (3)$$

$$F_r = kV\sin(\varphi+\beta) = kV(\sin\varphi\cos\beta + \cos\varphi\sin\beta) = kv_\theta\sin\varphi + kv_r\cos\varphi. \quad (4)$$

Submitting Eq. (3) into Eq. (2) obtains

$$v_r = (-d\partial p/\partial\theta + rkv_\theta\cos\varphi)/(v_\theta + v_s\sin\alpha + fr + rk\sin\varphi). \quad (5)$$

Submitting Eqs. (4) and (5) into Eq. (1) and combining the terms yields a unary cubic equation about v_θ as in:

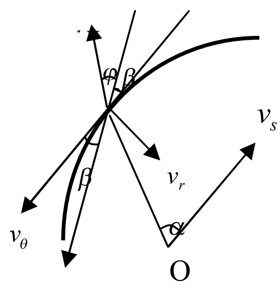

Fig. 1. Relationship between angles and wind directions

$$v_\theta^3 + a_1 v_\theta^2 + a_2 v_\theta + a_3 = 0. \quad (6)$$

Then, make $v_\theta = x - a_1/3$ and transfer Eq. (6) to the Cardan equation of $x^3 + 3\eta x + 2\xi = 0$,

where

$$\eta = (3a_2 - a_1^2)/9,\ \xi = (2a_1^3 - 9a_1 a_2 + 27a_3)/54,$$

$$a_1 = 2(v_s\sin\alpha + fr + rk\sin\varphi),$$

$$a_3 = -fr^2 d\partial p/\partial r - (v_s r d\partial p/\partial r)\sin\alpha - (kr^2 d\partial p/\partial r)\sin\varphi - (rkd\partial p/\partial\theta)\cos\varphi,$$

$$a_2 = (a_1/2)^2 + r^2k^2\cos^2\varphi - rd\partial p/\partial r.$$

For the above Cardan equation, if η =0, $x=\sqrt[3]{2\xi}$; if $\eta \neq 0$, the solution is sought following that of Xing[13]. A sign function $s=\operatorname{sgn}\xi$ is introduced and the values of s take 1, 0, and -1 for the three cases of $\xi>0$, $\xi=0$, and $\xi<0$, respectively. The solving method is shown in Table 1, in which a meaningful real root is chosen with $v_\theta>0$.

Table 1. Solution sought with the Cardan equation

<table>
<tr><td colspan="3">$x^3+3\eta x+2\xi=0$，$\eta\neq 0$
A unified parameter $\tau=(\operatorname{sgn}\xi)\sqrt{|\eta|}$ is introduced and the parameters of μ and $\phi=\mu/3$ are also introduced together with the Hyperbolic function depending on the situation presented below.</td></tr>
<tr><td colspan="2">$\eta<0$</td><td rowspan="2">$\eta>0$</td></tr>
<tr><td>$\xi^2+\eta^3<0$</td><td>$\xi^2+\eta^3>0$</td></tr>
<tr><td>$\cos\mu=\xi/\tau^3$</td><td>$\cosh\mu=\xi/\tau^3$</td><td>$\sinh\mu=\xi/\tau^3$</td></tr>
<tr><td>$x_1=-2\tau\cos\phi$
$x_2=2\tau\cos(\pi/3-\phi)$
$x_3=2\tau\cos(\pi/3+\phi)$</td><td>$x_1=-2\tau\cosh\phi$
$x_2=\tau\cosh\phi+i\sqrt{3}\tau\sinh\phi$
$x_3=\tau\cosh\phi-i\sqrt{3}\tau\sinh\phi$</td><td>$x_1=-2\tau\sinh\phi$
$x_2=\tau\sinh\phi+i\sqrt{3}\tau\cosh\phi$
$x_3=\tau\sinh\phi-i\sqrt{3}\tau\cosh\phi$</td></tr>
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$\partial p/\partial r, \partial p/\partial\theta$ must be known to calculate v_θ, v_r in Eqs. (5) and (6). From various theoretic pressure models, it is generally in the form of

$$r/\lambda(\theta)=F(p,\omega(\theta))$$

or

$$p=G(\omega(\theta),r/\lambda(\theta)). \quad (7)$$

Some conditions need to be satisfied in this paper:

$$F(p_c,\omega(\theta))|_{r=0}=0, \quad (8)$$

$$L(\theta)/\lambda(\theta)|_{r=L(\theta)}=F(p_L,\omega(\theta)), \quad (9)$$

$$\partial V/\partial r|_{r=R(\theta)}=0, \quad (10)$$

$$V_{\max}(\theta)=V|_{r=R(\theta)}=V_{mobs}(\theta). \quad (11)$$

λ,ω is a given function about θ, and p is the sea surface pressure. If $\partial\lambda/\partial\theta=\partial\omega/\partial\theta=0$, the pressure model will be axisymmetric. $L(\theta)$ is the radial distance between the typhoon center and the closed characteristic isobar in the periphery of the typhoon, p_L is the diagnostic pressure, p_c is the observed center pressure, $R(\theta)$ is the MWR (maximum wind radius) in each direction, $V_{\max}$ is the maximum wind related to R, and V_{mobs} is the observed maximum wind. Suppose that

$$q(r,\theta)=r/\lambda(\theta),$$

then

$$\partial p/\partial r=(\partial G/\partial q)(\partial q/\partial r), \quad (12)$$

$$\begin{aligned}\partial p/\partial\theta&=(\partial G/\partial\omega)(d\omega/d\theta)\\&+(\partial G/\partial q)(\partial q/\partial\lambda)(d\lambda/d\theta)\end{aligned}. \quad (13)$$

When functions F (or G) and $\omega(\theta)$, $L(\theta)$ are given, from Eq. (9), $\lambda(\theta)=L(\theta)/F(p_L,\omega(\theta))$ can be obtained. Submitting these function to Eqs. (12) and (13), the sea surface pressure and wind can be calculated from Eqs. (5), (6), and (7).

2.2 *Implementation of the asymmetric bogus scheme*

In order to utilize the information from the original large-scale analysis field, a closed isobar is selected that reflects the typhoon system as well as the impact of surrounding weather systems in the periphery of the typhoon in the original analysis field to fit $L(\theta)$. The circumference is divided into k_L parts (here k_L=360), and set $h=2\pi/k_L, l=k_L-1$. Suppose the search yields $L_i=L(ih), i=0,1,2,\ldots,l$. Use a five-point sliding smoothing to eliminate the discontinuities, and then Fourier series interpolation fitting is applied to $L(\theta)$. Suppose

$$g(\theta)=L(\theta)-(c_1+c_2\theta),\ 0\le\theta\le 2\pi-h \quad (14)$$

where c_1 and c_2 are constants. From $g(0)=g(lh)=0$, we have $c_1=L(0)$, $c_2=[L(lh)-L(0)]/(lh)$. Odd function expansion of $g(\theta)$ is performed, namely $g(\theta)=-g(-\theta)$, and then with Fourier series expansion it becomes a sine series as in

$$g(\theta)\approx\sum_{n=1}^{m}b_n\sin\frac{n\pi}{l}\theta,$$

$$b_n=\frac{2}{l}\int_0^{lh}g(\theta)\sin\frac{n\pi}{l}\theta d\theta\approx\frac{2}{l}\sum_{i=1}^{l}g(ih)\sin\frac{n\pi ih^2}{l}. \quad (15)$$

From Eqs. (14) and (15),

$$L(\theta)\approx c_1+c_2\theta+\sum_{n=1}^{m}b_n\sin\frac{n\pi}{l}\theta,$$

$$\frac{dL(\theta)}{d\theta}\approx c_2+\sum_{n=1}^{m}\frac{n\pi}{l}b_n\sin\frac{n\pi}{l}\theta, \quad (16)$$

where m is the number of terms of truncated series and its value must be selected appropriately. If the value is too small, the peak characteristics will be smoothed out, and if it is too large the smoothing and filtering function will not work. In this paper m =10.

In order to assign Eq. (7) with a specific form, the Fujita[14] formula is introduced here. In view of the asymmetric nature of a moving typhoon, and to control with wind-profile constraints, Eq. (7) is in the form as shown below:

$$p(r,\theta) = p_m(\theta) - \Delta p(\theta)/\sqrt{1+a(r/r_0)^b} \qquad (17)$$

where p_m is the environmental pressure in the periphery of typhoons, and due to conditional Eq. (8), $\Delta p = p_m - p_c$, r_0 is a typhoon coefficient, and a is the location parameter of MWR. An appropriate value of a enables r_0 to have a practical significance of MWR, namely $r_0 = R(\theta)$. b is the parameter to control maximum gradient wind. The key issue is to determine p_m and r_0.

Changes in environmental pressure over a certain period of time are very small and can be regarded as a constant[12]. Environmental pressure is, however, subject to large-scale systems such as the equatorial high or the Subtropical High, which are obviously different in direction. This paper mainly considers the impact of the Subtropical High. p_m on the near side of the Subtropical High is bigger than that on the farther side. Over the sea far away from land, the motion of a mature typhoon is mainly guided by the Subtropical High to move along the edge of the high. Therefore p_m is estimated by

$$p_m(\theta) = p_\infty - p_a \sin[\theta - (\alpha_0 + \beta_1)] \qquad (18)$$

which means that p_m is in sine-wave oscillations along θ, with an amplitude of p_a. p_∞ is the averaged ambient pressure with a given value of 1 010 hPa[15]. The meanings of α_0, β_1 are shown in Fig. 2; if there is only external force f_e, the typhoon will move along the direction f_e, but the existence of internal force f_i causes the typhoon to move along the direction f_t, which is synthesized from f_i and f_e. The aim here is to relocate the moving direction to direction f_e to have a rough estimate of the impact of the Subtropical High. β_0 is the angle between the actual moving direction and the direction of the internal force, with a positive anti-clockwise direction. Suppose $f_i / f_e = \delta$ due to the relation shown in Fig. 2, $\beta_1 = \arcsin(\delta \sin \beta_0)$. According to Hu et al.[12] and Niu[16], under normal circumstances, f_i is usually in a north-northwest direction and $\delta = 1/8$.

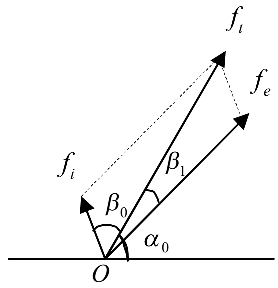

Fig. 2. Relationship among moving direction, internal force, external force of a typhoon

In order to calculate p_a, based on the previous work[17, 18] and with the method of Kuihara et al.[3], the center location o' of the analyzed typhoon is first identified with the 850-hPa wind. Analysis wind is divided into a reference field and a disturbance field and then the averaged wind of the disturbance field along the angle is calculated. When the averaged wind speed reaches the maximum and then drops to 3 m/s for the first time, this distance is marked as r_a, and the difference between the maximum and minimum pressure along r_a is regarded as p_a. With an improved filtering scheme of MM5, regarding o' as the center within the scope of r_a, and considering the sea-level wind field of the analysis typhoon as a superposition between the stream function and potential function, stream function and potential function from the background wind field are estimated to obtain the divergence-free motion and irrotational motion of the background wind field. The basic wind field is obtained by subtracting these two values from the background field and then the analysis typhoon is eliminated.

Comparing Eq. (7) with Eq. (17), we have

$$\lambda(\theta) = r_0(\theta),$$

$$\omega(\theta) = p_m(\theta),$$

and $F = \sqrt[b]{(((\Delta p/(p_m - p))^2 - 1)/a}$.

Then, the typhoon wind field can be derived according to the above theoretical analysis. Then, subtract the moving speed from the basic field and superimpose it to the derived wind to obtain a final wind field, so that the asymmetrical components in the basic wind field can be partially preserved.

Finally, the characteristics of parameters a and b will be analyzed. According to the conditional Eq. (10), suppose $y(r,a) = \partial V / \partial r |_{\theta=\theta_0}$, θ_0 can be in any direction. Take for example Typhoon Matsa (0509) at 1800 UTC (Coordinated Universal Time) on August

4, 2005. Given $b=2$, regardless of the surface non-linear dissipation, $k=1.7\times10^{-4}$ [12], $\varphi=38^{\circ}$ [19], $p_c=969$ hPa, and $p_a=5$ hPa, and search the root of equation $y(r,a)=0$ within the regional range of $0<r<L(\theta_0)$, $0<a<5$. This root is equivalent to $R(\theta_0)$, the value of MWR, when a is given a specific value. Since $r_0(\theta_0)$ is a constant, the change of $R(\theta_0)$ can be expressed as $R(\theta_0)/r_0(\theta_0)$. After calculating, the relationship between a and R/r_0 is shown in Fig. 3a. The result is greatly different from the calculation in axisymmetric cases and thus this paper takes a =1.2). Then, with other parameters unchanged, the parameter b is adjusted to obtain the relation among b, maximum wind, and the MWR, as shown in Fig. 3b. When $b>1.5$, the variation of b will only change the maximum wind but not the MWR. Thus, it will be all right to select a specific value of b based on the conditional Eq. (11). For this paper, it meets the need of study if the maximum bogus wind in the typhoon area is equal to the sea-level maximum wind available from observation or derived empirically from the centre pressure.

Figure 4 is a corresponding constructed sea-level asymmetric bogus typhoon model. The typhoon center pressure and maximum wind are obtained from the observation, being 969 hPa and 39 m/s, respectively. It can be shown that the asymmetrical structure of the typhoon pressure field reflects the effects of environmental pressure, while a maximum wind speed zone appears in the area near the Subtropical High with larger pressure gradients.

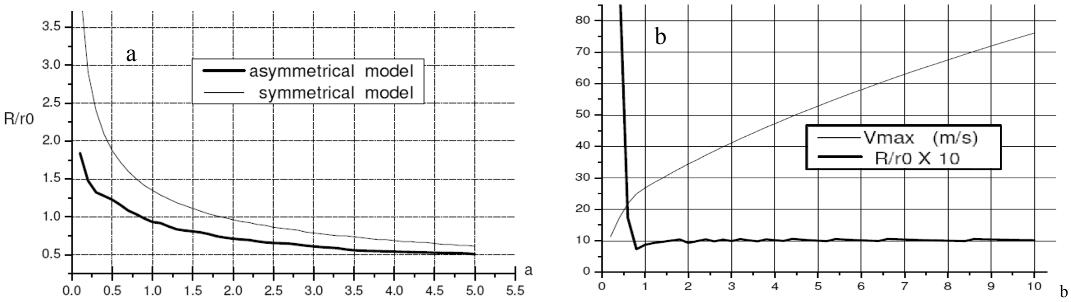

Fig. 3. Variation curves of R/r_0 (ratio of MWR to r_0) and V_{max} (max. wind) due to parameter a (a) and parameter b (b) in the bogus typhoon model

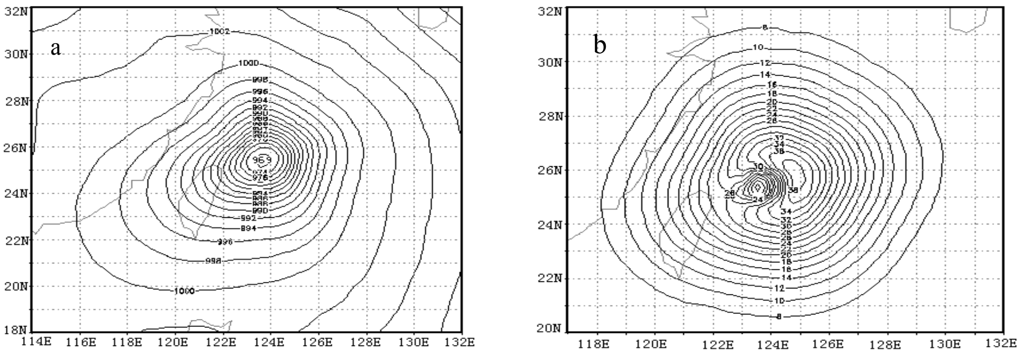

Fig. 4. The bogus data of Typhoon Matsa at 1200 UTC on August 4, 2005. a: Sea level pressure (center pressure at 969 hPa); b: Sea level wind (max. wind at 39 m/s)

3 DYNAMIC ASYMMETRIC BDA SCHEME

The technique of four-dimensional variational assimilation is employed in this paper. Considering the trend of typhoons moving with time, bogus vortexes constructed at multiple moments of time are assimilated into numerical models to build a dynamic asymmetric BDA scheme. The typhoon is intensified and relocated by the dual restriction of the numerical model and bogus data. Due to the absorption of large amount of basic field information in constructing the bogus data, and as the change of analysis data at different time directly influences the quality of the bogus data, such an assimilation scheme changes a "static" typhoon to a "dynamic" typhoon and makes the assimilation information more complete.

As the time interval is too large for both the global analysis fields and observational data of typhoons, the technique of linear interpolation is used to obtain the analysis fields in middle time levels to construct multi-time bogus typhoons. Suppose the initial analysis field is $X_{0\text{h}}$, the analysis field 6 hours later is $X_{6\text{h}}$, then the analysis field X_n at the *n*th minute within the 6 hours is to be interpolated, following the interpolation formula below:

$$X_n = [(360-n)X_{0\text{h}} + nX_{6\text{h}}]/360. \quad (19)$$

Similarly, the observational data are also obtained with this interpolation method. Experiment analysis shows that this approach is feasible.

So far, it is indicated that "dynamic" means two things: First, the impact of typhoon moving speed is considered in constructing an asymmetric typhoon. Second, multiple bogus vortexes containing different information at different time are assimilated within an assimilation window.

The objective function of four-dimensional variational assimilation is defined as follows:

$$J = J_B + J_{Bogus}, \quad (20)$$

$$J_B = \frac{1}{2}\left[X(t_0) - X_B\right]^T B^{-1}\left[X(t_0) - X_B\right], \quad (21)$$

$$J_{\text{Bogus}} = \frac{1}{2}\sum_t \sum_i \left[X(t_i) - \hat{X}(t_i)\right]^T W_i(t_i)\left[X(t_i) - \hat{X}(t_i)\right], \quad (22)$$

where J_B indicates the deviation of model initial control variables $X(t_0)$ from the background field X_B, J_{Bogus} indicates the deviation of model control variables $X(t_i)$ from bogus data $\hat{X}(t_i)$. The superscript "*t*" means to transpose, *B* is the covariance matrix of background error, "-1" means to inverse. $W_i(t_i)$ is the weight coefficient reflecting the quality and credibility of the bogus data.

4 DESIGNS OF NUMERICAL EXPERIMENTS SCHEMES

The MM5 model and its adjoint model are used in the numerical experiments. The length of the assimilation window is 30 minutes. The optimizing algorithm is the limited memory (variable storage) quasi-Newton method (LBFGS). See Liu et al.[20]. The center of the simulated area is (124.5°E, 25.5°N). The domains use double basic nesting with two-way feedback. The coarse grid is 75×91, with grid distance of 54 km. The nesting grid is 136×130, with grid distance of 18 km. In the vertical direction it is 23 layers in non-uniform distribution. Six-hourly, 1°×1° U.S. National Centers for Environmental Protection (NCEP) reanalysis data are used. The cumulus parameterization scheme is GRELL, and the boundary scheme is MRF. Three experimental schemes are shown in Table 2. Axisymmetric typhoon bogus data are the same as those in Zou and Xiao[8]. Bogus data only include sea-level wind and pressure fields. The observational data are from the China Meteorological Administration.

Table 2. Designs of numerical experiment schemes

Serial No.	Initial Schemes
Scheme 1	NCEP data directly used as the initial field (control experiment)
Scheme 2	asymmetric Bogus vortex assimilated every 5 minutes and then simulated
Scheme 3	asymmetric Bogus vortex assimilated every 5 minutes and then simulated

Six summer typhoons impacted by the Subtropical High are shown in Table 3. During the simulation period, three typhoons, Matsa, Khanun (0515) and Wipha (0713), landed and then moved over land for a long time; typhoons Shanshan (0613) and Man-yi (0704) shifted in moving direction from the northwest to the northeast and moved along the edge of the Subtropical High, while typhoon Ewiniar (0603) neither landed nor obviously turned its direction, but moved along north-west. Since Khanun and Wipha disappeared soon after landing, 48-hour simulation is employed for the two typhoons.

Table 3. Details of the six typhoon cases

Names	Simulation periods
Matsa	2005080418 UTC—2005080718 UTC
Khanun	2005091012 UTC—2005091212 UTC
Ewiniar	2006070700 UTC—2006071000 UTC
Shanshan	2006091412 UTC—2006091712 UTC
Man-yi	2007071118 UTC—2007071418 UTC
Wipha	2007091718 UTC—2007091918 UTC

5 ANALYSES OF SIMULATION RESULTS

The histogram of distance error of the six typhoons' track simulation is shown in Fig. 5. It indicates that the simulation results using the initial fields of the BDA method are generally superior to those of the control experiments, while the overall effect of Scheme 3 is better than that of Scheme 2. As to the landing typhoons Matsa, Khanun, and Wipha, larger errors appear after 36 hours of simulation in Scheme 2, such as the maximum 700-km error after 48 hours with Wipha, and the maximum 470-km error after 54 hours with Matsa. In Scheme 3, the maximum error is reduced to 500 km with Wipha and 300 km with Matsa. As to Shanshan and Man-yi which neither landed nor obviously turned their direction, the track simulations are greatly improved in each scheme, as compared with the three landing typhoons. In Scheme 2, however, there is great error after 54 hours with

Shanshan and after 36 hours with Man-yi during the simulation, particularly in the case of Shanshan where the error is much larger than that in Scheme 3. For Ewiniar, both the assimilation schemes have improved the track simulation. Particularly, for the period for which no improvement is made on track simulation in Scheme 2, such as the 18th to 42nd hour for Matsa, the 60th to 66th hour for Man-yi, Scheme 3 can still improve its track simulation, because the bogus data it used take into account the information of background fields and the dynamic characteristics of typhoons are also considered in assimilation.

Table 4 shows the averaged distance error of 6 (or 4) typhoons at each time of observation (at 6-hour intervals) of 72-hour (or 48-hour) simulation. The average errors of Scheme 3 are all smaller than those of Scheme 2, and such a result is quite encouraging, which reflects the value and significance of the research on dynamic and asymmetric BDA.

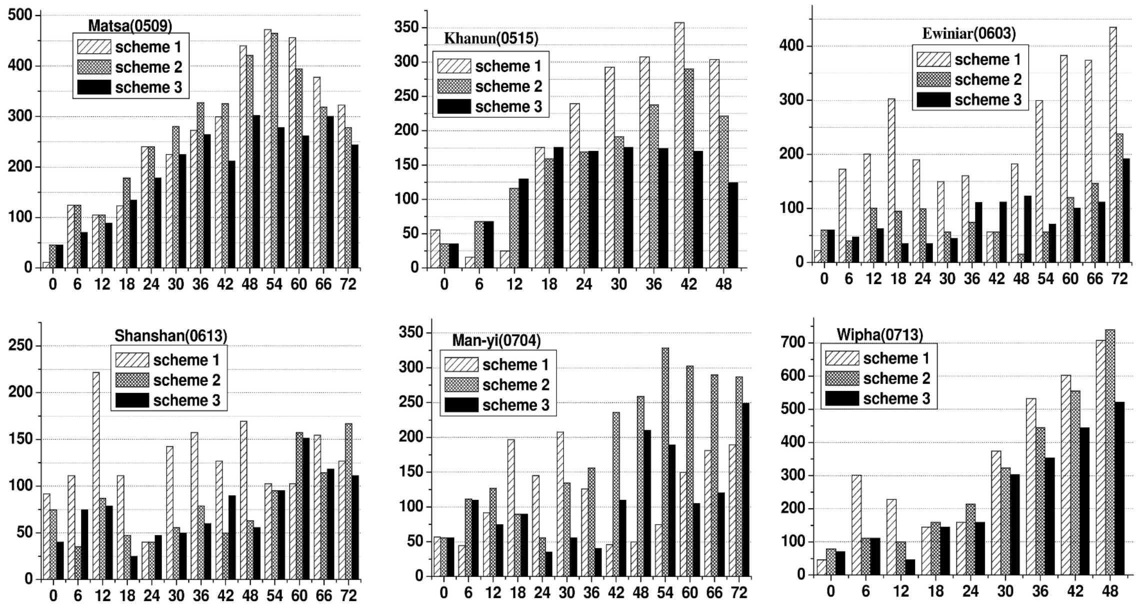

Fig. 5. The track forecast distance error of the six typhoons. The bscissa axis is time (hour); the vertical axis is the distance error (km).

Table 4. Average distance error in each time of observation

Scheme	6h	12h	18h	24h	30h	36h	42h	48h	54h	60h	66h	72h
1	128.2	145.3	175.6	169.0	231.8	259.3	248.2	308.8	237.1	272.8	271.8	268.4
2	81.6	106.0	121.4	136.4	173.5	219.8	252.2	286.6	236.2	243.5	217.3	242.4
3	80.1	80.1	100.7	104.2	142.2	167.1	189.4	222.6	158.4	154.7	162.6	199.0

Figure 6 shows the change of simulated center surface pressure of typhoons during the simulation. The intensity of both assimilation schemes is stronger than that of the control experiment. The typhoon center pressure in Scheme 2 is lower than in Scheme 3. The reason may be that the asymmetry affected and generated by the environment is taken account in the bogus typhoon, and this non-axisymmetric character is more favorable than the symmetric character for the weakening of typhoons after landing or after a period of simulation. In fact, this trend makes the typhoon center pressure in Scheme 3 closer to the observation than that in Scheme 2 at the later period of simulation. However, at this point, when the actual typhoon has been greatly weakened, the simulated typhoons in the BDA experiment remain strong, resulting in excessive development of cyclones. The restrictions it imposes on the simulation improvement of the BDA scheme need to be further studied.

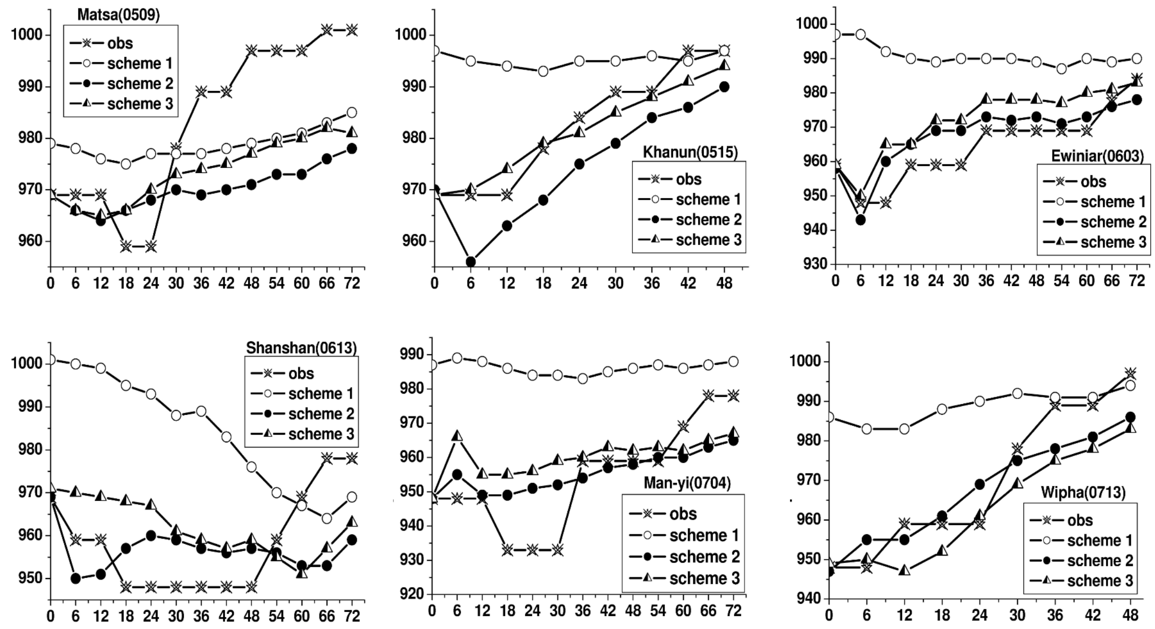

Fig. 6. Variation curves of center surface pressure of the six typhoons. The abscissa axis is time (hour); the vertical axis is center pressure (hPa).

6 CONCLUSIONS

The asymmetric bogus methods presented in this paper include (1) the deduction of the wind speed equation in the Cardan form from the horizontal motional equations which take friction into account and then the equation is solved, the execution of Fourier series fitting on closed isobars in the periphery of typhoons, and the calculation of environmental pressure impacted by the Subtropical High at all directions; (2) the extension of the Fujita formula to be asymmetric and controling of the wind profiles; and (3) the acquisition of the basic field from which the analysis typhoon is filtered and the moving speed is deducted for information to be absorbed into the Bogus typhoon. This method does not divide the typhoon into two parts, one being symmetric and the other asymmetric, but calculates it asymmetrically all along, thus avoiding the problem of importing asymmetric components when the typhoon is assumed to be symmetric. It also avoids the difficulty of determining the direction of the major axis and minor axis of the wind field when the typhoon is assumed to be oval. It further avoids the uncertainty in setting the MWR.

Through numerical simulations on the six typhoons, it is found that the track simulation of a dynamic BDA scheme based on assimilating asymmetric bogus data is better than that of the classical BDA scheme based on simple assumptions that the typhoon is symmetric and quasi-stationary. This improvement is particularly obvious in the landing or a turning typhoon. Moreover, in the period of simulation for which the classic BDA scheme fails to bring any improvement, the simulation in the new scheme can still be improved, because the bogus data used in the new scheme considers the information of background fields and the dynamic character of typhoons. For intensity, the simulation in the new scheme is generally weaker than that of the classic scheme. This trend makes the central typhoon pressure in the new scheme closer to observation than that of the classic scheme in the middle and late period of the simulation. However, when the actual typhoon has been greatly weakened, the simulated typhoons in the BDA experiment remain strong, resulting in excessive development of the cyclones. The restrictions it imposes on the simulation improvement of the BDA scheme need to be further studied.

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