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APPLICATION OF BDA SCHEME IN TYPHOON TRACK PREDICTION

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ABSTRACT: The MM5, which is the PSU/NCAR mesoscale nonhydrostatic limited-area model, and its adjoining modeling system are used in this paper. Taking T106 analysis data as background field the authors generate an optimal initial condition of a typhoon by using two bogus data assimilation schemes, and conduct some numerical simulating experiments. The results of No.9608 typhoon (Gloria) show that the optimal initial field have some dramatic improvements, such as inaccurate position of typhoon center, weaker typhoon circulation and incomplete inner structure of the typhoon, which are caused by shortage of data over the sea. Some improvements have been made in the track forecast. Through several comparing experiments, the initialization optimized by BDA scheme is found to be more reasonable than GFDL scheme and its typhoon track forecast is better.

Key words: four-dimensional data assimilation; BDA scheme; GFDL scheme; typhoon numerical simulation; track forecasting

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1 INTRODUCTION

Typhoon is a kind of severe weather that occurs on the sea surface of the tropics. Since it can bring severe disaster to places where it passes, it is of vital importance to make good prediction of it, especially its track, for purposes of preventing and alleviating the disaster it causes. Although there are many methods to predict typhoon track, numerical models are employed in most operational predictions. Due to many unsolved problems, the accuracy of typhoon track predicted by numerical models is still not very high. The low accuracy of typhoon track prediction is mainly caused by scarcity of observation data on the sea, inappropriate choice of parameterization due to inaccurate analysis of physical processes, and so on. Owing to insufficient data available, one of the most difficult problems in numerical weather prediction of typhoons is the initialization of models. In the analyzed large-scale field provided by operational centers, the vortex structure of typhoons is usually very weak or even cannot be discerned. So, a process of initialization is needed to strengthen the initial vortex feature to be close to its real case. Such kind of technique is called typhoon Bogus technique[1]. Many meteorologists from home and abroad have made great contributions to researches on this subject. Kurihara[1] proposed a scheme of typhoon filtering, in which the poorly-discerned tropical cyclone was removed from the analyzed large-scale pattern and then a bogus typhoon vortex was introduced. It was shown from the experiment results that the scheme could improve the quality of initial value of numerical models, enhance the strength of predicted typhoon and reproduce the typhoon track better. Wan et al.[2] suggested a new scheme of bogus typhoon, in which a more realistic typhoon structure was introduced into the initial value, TBB dataset derived from satellite observation was employed to improve the distribution of convective heating and determine the radial circulation was determined that agreed well with TBB data, in the bogus typhoon. It was shown that the scheme could improve the equilibrium between wind and pressure so as to enable the model better coordinate with the bogus typhoon. Practice has shown that the technique can improve the initial typhoon field and increase of accuracy of typhoon track forecast. Some dynamical problems can be solved to some extent with the bogus technique through seeking solutions to equilibrium

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equations, but the equations of vorticity advection and hydrostatics remain unsolved and couplings between different variables are not realized in the true sense. Specially, the atmospheric water vapor is not coupled with other variables but rather they are dealt with separately.

Four-dimensional variational data assimilation (4DVAR) is a new method adopted currently to deal with the initial value problem of numerical prediction and it is suitable for typhoon numerical prediction as well. In 4DVAR, dynamical and thermodynamical equations are used as strong constraints. In the initial fields achieved through 4DVAR, the variables are coordinated and consistent with the numerical model. Here in this work, following and the 4DVAR method to initial the typhoon, a bogus vortex will be incorporated into the analyzed pattern, which is called the technique of Bogus Data Assimilation (BDA)[3]) so as to reconstruct inner typhoon structure and improve prediction efficacy. Experiment results with GFDL (Geophysical Fluid Dynamics Laboratory) typhoon bogus technique and the BDA technique will be compared to analyze the advantage of 4DVAR in typhoon prediction.

2 BRIEF INTRODUCTION TO GFDL SCHEME

Proposed by Kurihara[1], the basic idea of the GFDL scheme is to eliminate the analyzed typhoon from the initial analyzed pattern and then incorporate a bogus typhoon, i.e.

(initial field)=(globally analyzed field)-(analyzed typhoon)+(bogus typhoon)

Based on a large amount of typhoon observations (airplane probing etc.) and structures of mature typhoons, a bogus typhoon is incorporated. The major steps of construction can be summarized as below.

(1) Eliminate the analyzed typhoon to get the smooth background field;

(2) Calculate the wind and humidity in the area of typhoon following empirical formula;

(3) Get the air mass distribution from wind field by solving the equilibrium equation on the σ plane;

(4) Taking distance as weight, merge the bogus typhoon into the background field smoothly and then get the initial field of typhoon.

Employed as typhoon prediction model, the MM5 was integrated for 48 hours from the initial field obtained with the GFDL scheme. The results of 48-h prediction are then analyzed.

3 FUNDAMENTAL OF THE BDA SCHEME

The main idea of BDA（Bogus Data Assimilation）scheme is to introduce a bogus typhoon vortex as "observation data" and incorporate it into the typhoon initial field using the 4DVAR technique and so as to optimize any incorrect or weak typhoon initial field.

The BDA scheme consists of two parts, one is the construction of typhoon bogus vortex, and the other is the minimization process by which the prediction model is forced to yield a typhoon vortex field consistent with the original initial field. There are various ways to construct bogus typhoon vortex though, the one used here only needs quite a few model variables (only sea level pressure and wind field are needed). The minimization process is performed for all model variables here so that they all meet the constraints of atmospheric dynamics and physics well.

3.1 Construction of typhoon vortex

The sea level pressure of typhoon vortex is determined by the formula proposed by Fujita[4], which is

$$p_o(r) = p_c + \Delta p\left\{1-\left[1+\frac{1}{2}(\frac{r}{R_0})^2\right]^{-\frac{1}{2}}\right\} \qquad (1)$$

Here, p_c is the pressure at the typhoon center, Δp is a parameter related to the sea level pressure for the typhoon, R_0 is an estimated value of radius of the maximum sea level pressure gradient and it is adopted as $\sqrt{2}$ times the radius of the maximum wind. The location and center pressure of typhoon can be found in the typhoon yearbooks.

3.2 Construction of tangential wind

The horizontal wind field in the area of typhoon is constructed with the scheme of tangential wind profile proposed by Chan and Williams[5] in 1987, which is

$$V(r) = V_{\max}\left(\frac{r}{r_{\max}}\right)\exp\left\{\frac{1}{b}\left[1-\left(\frac{r}{r_{\max}}\right)^b\right]\right\} \qquad (2)$$

Specifically, $V(r)$ is the tangential wind, $V_{\max}$ is the maximum value of wind speed near the ground, $r_{\max}$ is the radius of the maximum wind speed, b is a factor controlling wind distribution in the periphery of typhoon; the smaller b is, the more slowly the wind in the periphery of typhoon weakens. In general, the wind speed is large and wind shear is strong near the typhoon center. Due to the limitation of model resolution, however, strong wind shear near the typhoon center may cause some form of instabilities and cannot be used in the profile equation directly without modification. Previous researchers[6] set empirical parameters of bogus typhoon as V_{max}= 18 m/s，r_{max}= 180 km, b = 0.46. Following the scheme as presented below, the tangential wind will progressively decrease from ground to model top:

$$V_{pc}=\begin{cases}0 & (s<s_1)\\ 1-\exp(-c_1\times\dfrac{s-s_1}{1.0-s_1}) & (s_1\le s\le 1)\end{cases} \qquad (3)$$

Here, c_1 is an empirical coefficient and taken at 7.0, σ_1 is related to the height of typhoon warm core and taken at 0.17. It is equivalent of setting the warm core at 250 hPa. Hence the wind distribution of typhoon at all levels can be calculated from $V(r)\cdot V_{pc}$.

3.3 Process of minimization

Variational data assimilation is a method, based on the concept of least square method, to fit the observation data with model results which are on regular, evenly distributed grids. The fitting is represented by distance function for evaluation. Thus, objective function which is used to express the distance is defined by

$$J(X)=J_b+J_p+J_v \qquad (4)$$

Here,

$$J_b=\frac{1}{2}(X-X_b)^T B^{-1}(X-X_b) \qquad (4a)$$

$$J_p=\sum_{t_i}\sum_{\Omega}\left[p(r)-p_o(r)\right]^T W_p\left[p(r)-p_o(r)\right] \qquad (4b)$$

$$J_v=\sum_{t_i}\sum_{\Omega}\sum_{k}\{\left[u(r,k)-u^{\text{bogus}}(r,k)\right]^T W_u\left[u(r,k)-u^{\text{bogus}}(r,k)\right]+\left[v(r,k)-v^{\text{bogus}}(r,k)\right]^T W_v\left[v(r,k)-v^{\text{bogus}}(r,k)\right]\} \qquad (4c)$$

and $X=(u,v,w,p',T,q)^T$. It represents the model variables at initial time (the first guess field) and will be adjusted gradually by time integration. The standard analyzed field of MM5 is taken as the background filed X_b and $p(r)$ is the sea level pressure of model atmosphere. Ω is about 2.5-3.5 times of R. B is the covariance matrix of background field error, which contains diagonal elements only and can be estimated by differences between MM5 prediction results and analyzed fields for the same moment. u^{bogus} and v^{bogus} are wind components in the zonal and meridional direction respectively. W_p, W_u and W_v are all constants and are taken as W_p = 1.60 hPa^{-2}, W_u = 0.185 s^2/m^2 and W_v = 0.185 s^2/m^2 (for a range of errors) [3].

In the work, with the MM5 used as the forward model and the adjoint code of MM5 (Zou et al.) [7] used as a tool to minimize the target functional J, the optimized initial field of typhoon is achieved. In the experiment of 4DVAR, the assimilation window is taken as 30 minutes, within which "observation" data (the bogus typhoon) is read every 6 minutes, and 30 iterations are performed. This is equivalent of supposing that the temporal tendency of sea level pressure in the typhoon area is close to 0 in the interval of 30 minutes, with 30 iterative steps.

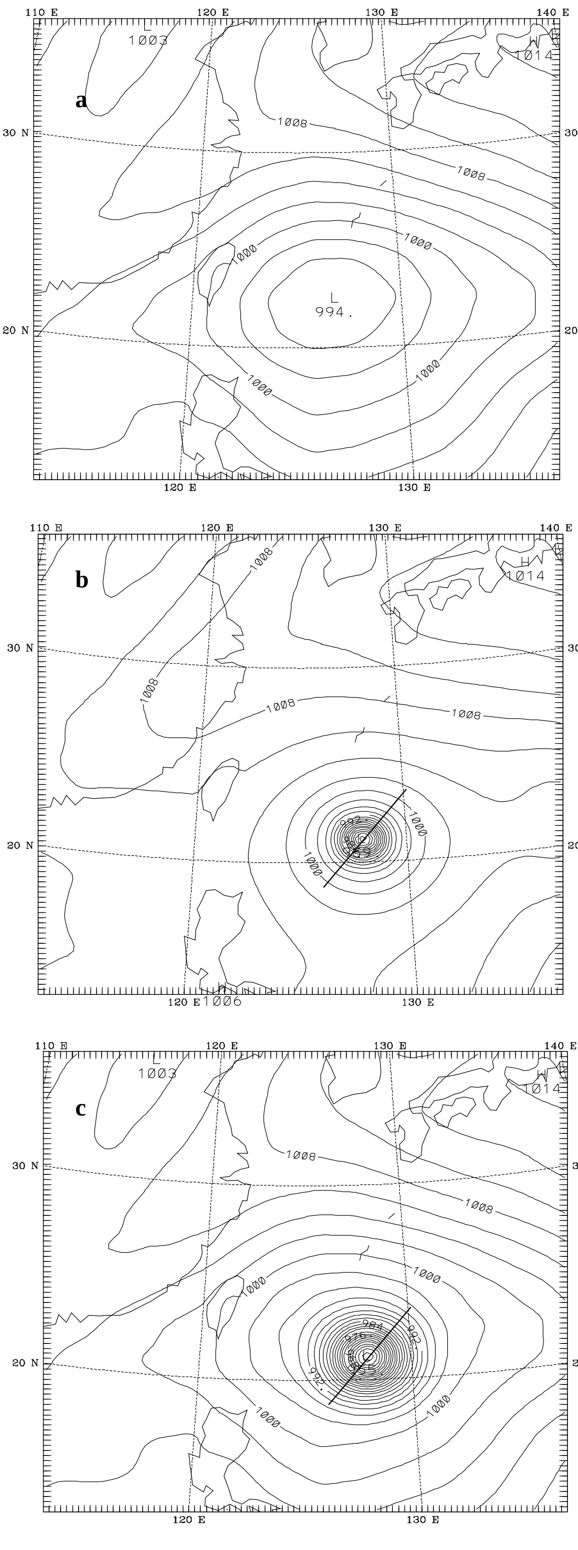

Fig.1 Initial sea surface pressure for Gloria. Intervals of contours: 4 hPa. a. Analyzed field with T_{106}; b. GFDL scheme; c. BDA scheme.

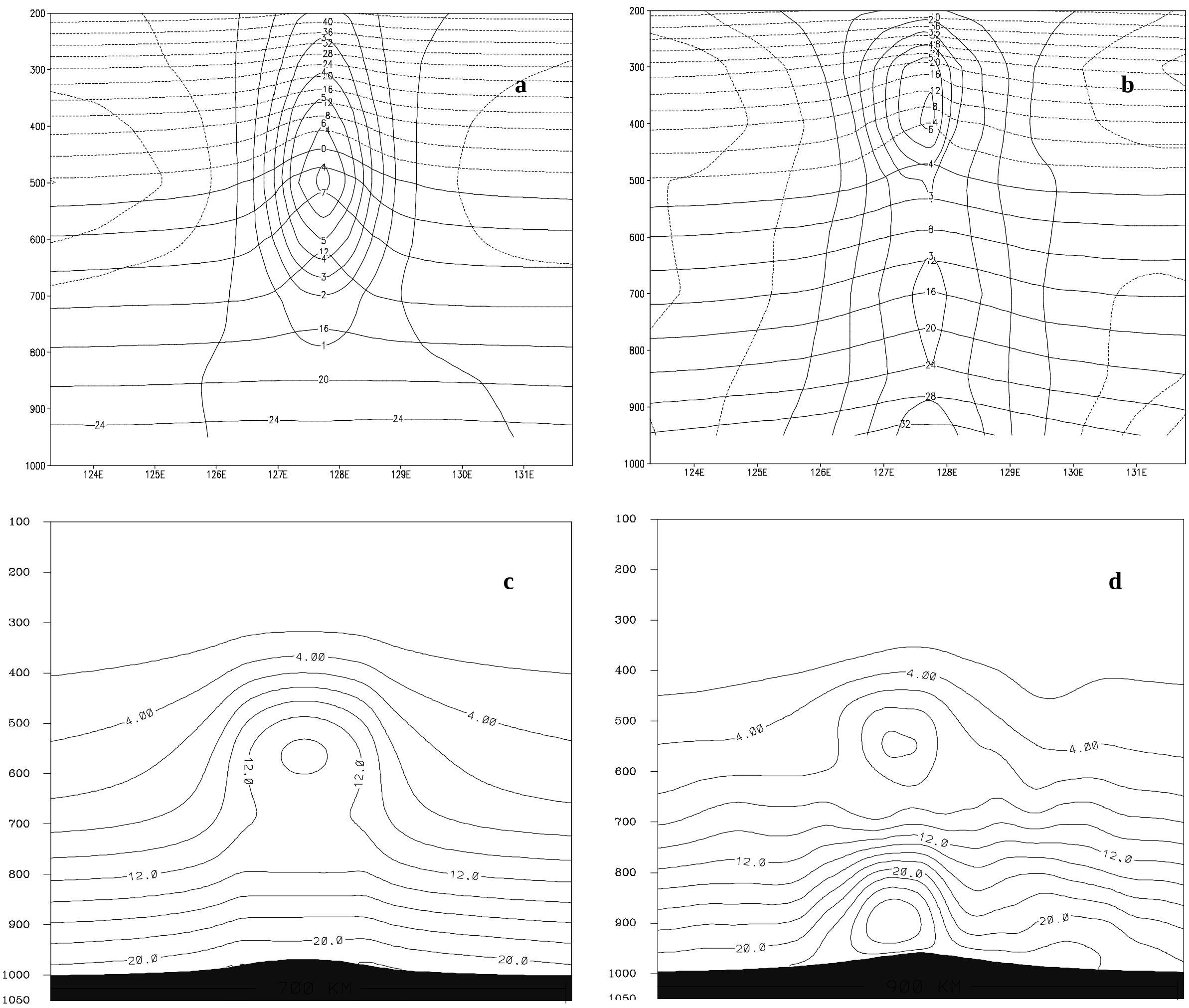

Fig.2 Vertical sections of temperature (contour interval: 4°C) and humidity (contour interval: 2 g/kg) along the line AB in Fig.1. (a) Temperature with GFDL scheme; (b) Temperature with BDA scheme; (c) Humidity with GFDL scheme; (d) Humidity with BDA scheme.

4 DESIGN OF EXPERIMENTS

In the work, three experiments are designed for comparison and the non-hydrostatic mesoscale model MM5V2 from PSU/NCAR is used as the numerical prediction model of typhoons. In Scheme 1, data from a global reanalysis dataset with T106 resolution is used as the initial field directly. In Scheme 2, the GFDL formula is introduced into the bogus typhoon directly to improve the quality of initial value for numerical prediction of typhoons. In Scheme 3, the BDA scheme is used to assimilate the bogus typhoon into typhoon initial field to optimize the quality of initial values. The case of Typhoon 9608 (Gloria) will be simulated with the aforementioned 3 schemes and results will be analyzed.

In all the experiments with the 3 schemes, model parameters and physical parameterization schemes remain the same. The details are as follows: 91×91 horizontal mesh points with a horizontal resolution of 30 km and 10 layers in the vertical, which are σ values of 0.025, 0.075, 0.175, 0.300, 0.400, 0.500, 0.625, 0.775, 0.920 and 0.995 respectively; GRELL is the scheme for cumulus parameterization, the precipitation scheme is implicit, BLACKADAR high resolution scheme is used for the planetary boundary layer, with relaxation lateral boundary condition and radiance upper boundary condition.

5 ANALYSIS OF RESULTS

5.1 Initial field of typhoon

First, the differences between initial fields improved by the GFDL formula and BDA scheme and the initial field from T_{106} reanalysis dataset are analyzed comparatively to illustrated the advantage of BDA scheme in the generation of initial fields.

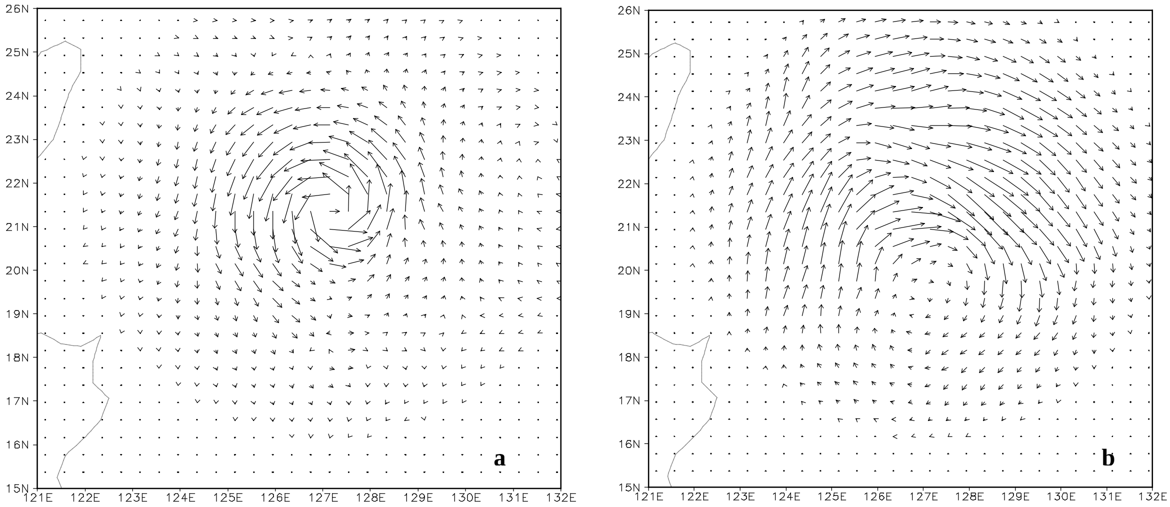

Fig.3 Differences of composite wind fields before and after assimilation at 850 hPa (a) and 200 hPa (b).

It is shown from Fig.1 that, the initial minimum pressure at the centre of Gloria is 994 hPa from the scheme with global reanalysis dataset and it is 44 hPa larger than that of the real case, which is 950 hPa; the initial minimum pressure at the centre of Gloria is 994 hPa from the scheme with GFDL formula, showing a great improvement; and the initial minimum pressure at the centre of Gloria has decreased to 955 hPa, which is closer to that of the real case with scheme of BDA. It is also shown from Fig.1 that, the deficiency of incorrect position of typhoon centre due to scarcity of observation over the sea has been corrected greatly by use of the GFDL formula and BDA scheme.

Compared with the traditional scheme of bogus typhoon(GFDL formula), the BDA scheme possesses an obvious advantage, i.e. it can adjust extra variables of model initial field with small amount of variables. The vertical sections of temperature and specific humidity across the centre of typhoon (drawn along the line AB in Fig.1) are illustrated in Fig.2. It can be seen that, through modification of sea level pressure, temperature and humidity are all adjusted although they are not variables involved in the assimilation process. Due to the scarcity of observations over open sea, the vertical structure of initial temperature from T_{106} dataset is more homogeneous and the feature of warm core is not obvious (figure omitted). Whereas the features of warm core are all well distinguished in the two initialization scheme of typhoon bogus from the anomalies of temperature (figure not shown), it is clear that the maximum anomalies of temperature appear within 500-600 hPa in the result with GFDL formula and within 300-400 hPa in the result with BDA scheme. The latter is more rational, as the maximum anomaly of temperature should appear within 250-300 hPa, according to the classic theory of typhoon structure. The vertical cross sections of humidity are shown in Fig.2c and Fig.2d. From Fig.2d, it can be seen that, through the adjustment of the BDA scheme, the feature of humidity field in the planetary boundary layer is more rational and a wet center at low model levels near the typhoon center emerges. In 4DVAR, with numerical model serving as constraints and hence under the forcing of dynamics and thermodynamics, the warm and wet structure of typhoon are reconstructed as they are, fields are more consistent with variables and coupled with the model. This is a key advantageous point of the BDA scheme over the GFDL scheme.

The difference between initial wind field from BDA scheme and that from T_{106} reanalysis dataset (first guess field) is illustrated in Fig.3. It can be seen that, after the modification by the BDA scheme, anticyclonic circulation at the high levels, and cyclonic circulation at the low levels, of typhoon, have increased (Fig.3a). That is to say, after the modification by the BDA scheme, the outflow at high levels and inflow at low levels are intensified, which is essential for the prediction of typhoon strength and track.

As illustrated in Fig.4, which is the vertical section of horizontal wind across the center of typhoon (drawn along the line AB in Fig.1c), the modified wind field is asymmetric, although the input wind field is symmetric after the optimization process. This shows that the BDA scheme can produce initial vortexes with asymmetric structure through the assimilation of information from typhoon telegram. Under dynamic constraints by the prediction model, through the advection process of the background field and other

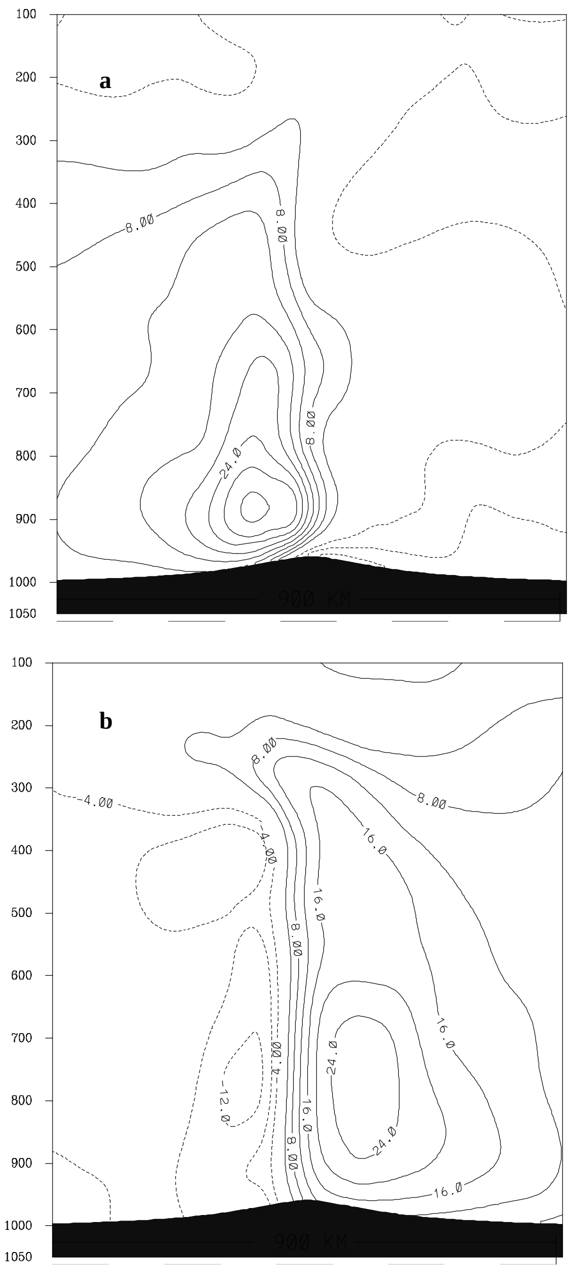

Fig 4. Vertical sections of horizontal winds with the BDA scheme along the line AB in Fig.1 (contour intervals:4m/s) (a) for zonal wind, (b) for meridional wind.

mechanisms (the Coriolis force, for example), asymmetric wind can be produced. By contrast, the asymmetric structure cannot be produced by the traditional bogus scheme. This just shows the advantages of 4DVAR.

5.2 Prediction of typhoon track

Generally speaking, there are three factors affecting the numerical prediction of typhoon track. They are: (1) steering current in large-scale environment; (2) initial intensity of typhoon; (3) accuracy of observed initial position of typhoon. Since atmospheric dynamic equations are employed as strong constraints in the process of 4DVAR, the interactions between typhoon and large-scale environment taken into account.

The results of typhoon track from control experiment and those from the two experiments with different bogus schemes are compared. It can be seen from the results that, due to excessively large error, which is a bias of 150 km in the position of typhoon centre in the initial field of the control experiment (shown in Fig.5), the error in track prediction is very large with two loops within the prediction period. After the introduction of the bogus typhoon, the inaccurate initial position is much corrected and prediction errors in subsequent time are much smaller than those of the control experiment (shown in Fig.5). The 48-h prediction error of typhoon centre position in the experiment with GFDL scheme is 189.08 km and that in the experiment with BDA scheme is 145.36 km, which is smaller. It can also be seen from Fig.5 that, large improvements have been made in the direction of movement in the 48-h forecast results with both the GFDL and BDA schemes and keep in parallel directions with the observed track, though with some biases.

From the former analysis, it is clear that the optimized initial field with the BDA scheme can greatly improve the three factors affecting the numerical prediction of typhoon track. This is because that, the technique of 4DVAR can incorporate observations in an effective and coordinated manner

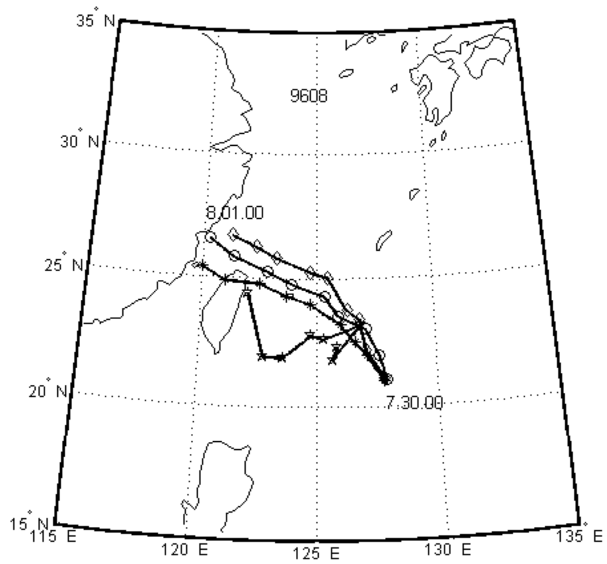

Fig.5 Prediction of track of typhoon 9608. "＊" is for positions from observation; "☆" for positions from control experiment; "◊" for positions from experiment with GFDL scheme; "○" for positions from experiment with BDA scheme.

without regard to their time, type, region and accuracy and extract maximum amount of useful information. Therefore, compared with the initial field with traditional typhoon bogus scheme, the initial field with the BDA scheme is closer to that of real case and can improve the prediction of typhoon track.

6 CONCLUSIONS

It can be known from the above analysis that, the adoption of typhoon bogus is very necessary in numerical prediction of typhoons. In the results from large-scale analysis, there are deficiencies, such as inaccurate center position, weak strength and irrational structure in the analyzed typhoon, and hence it is necessary to introduce a bogus typhoon vortex in which much relevant information of typhoon is used to improve the initial field. The BDA scheme is an effective method to produce the initial field of typhoon. It minimizes the use of typhoon data (only the sea level pressure at the typhoon centre, position of typhoon centre and the radius of maximum wind speed near the typhoon center are used) and can construct an initial vortex with dynamic and thermodynamic structure. So it is an effective way to deal with the problem of observation scarcity over the sea. The BDA scheme can construct an initial vortex coordinated with the large scale background field and make it possess the main characteristics of inner structure of typhoon, such as warm and wet centre, asymmetric wind field and so on. In addition, from the results of comparing the GFDL scheme with the BDA scheme, it can be seen that, although the GFDL scheme is very mature and the structure of typhoon vortex constructed with it is better than with the BDA scheme (with only the sea surface pressure and wind field assimilated), the typhoon structure in the initial field assimilated with the BDA scheme is quite rational and the prediction results of typhoon track with it is better than that with the GFDL scheme.

Although the work performed here has improved the prediction of typhoons to some extent, there still exist many problems unsolved, such as how to construct the bogus properly to represent the typhoon vortex as close to the observation as possible and to be in coordination with the large-scale background field. In addition, the choice of weight coefficients is empirical. How to choose it properly and what rules should be followed for choosing it is still a thing deserving study. And, in the work, only the assimilation of typhoon bogus is tested and the advantages of 4DVAR are not sufficiently used. As mentioned before, 4DVAR is an effective method to merge as much information into the initial field as possible[8-9]. For example, many unconventional data from data sources such as the satellite and radar can be assimilated into the initial filed to make it to be closer to the real case.

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