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AN ENSEMBLE FORECAST EXPERIMENT OF A LANDING TYPHOON

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Abstract: Based on the Global Regional Assimilation and Prediction System-Tropical Cyclone Model (GRAPES-TCM), an ensemble forecast experiment was performed, in which Typhoon Wipha during the period immediately prior to landfall was selected for the study and the breeding of growing mode (BGM) method was used to perturb the initial conditions of the vortex field and the environment field. The results of the experiment indicate that each member had a different initial status in BGM processing and they show a reasonable spread among members along with the forecast phase. Changes in the large-scale field, thermodynamic structure, and spread among members took place when Wipha made landfall. The steering effect of the large-scale field and the interaction between the thermodynamics and the dynamics resulted in different tracks of the members. Meanwhile, the forecast uncertainty increased. In summary, the ensemble mean did not perform as well as the control forecast, but the cluster mean provided some useful information, and performed better than the control in some instances. The position error was 34 km for 24 h forecast, 153 km for 48 h forecast, and 191 km for 66 h forecast. The strike probability chart qualitatively described the forecast uncertainty.

Key words: landing typhoon; ensemble forecast; GRAPES-TCM; breeding of growing mode method; cluster analysis

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1 INTRODUCTION

Ensemble forecasting is a numerical prediction method used to generate a representative sample of the possible future states of a dynamic system. Its application has been extended from the original global medium-range (5–15 days) ensemble forecast to various temporal and spatial scales, including storm scale, cloud scale, and even seasonal or climate scales. Significant progress has been made in short-range ensemble forecast, especially for tropical cyclones (TCs). Since the mid-1990s, the development of ensemble perturbation methodologies for TC has been mainly focused on its track. Generally, for a system with relatively small temporal and spatial scales, its predictability is low. Together with the interaction of large-scale environment, a particularly small perturbation is not fit for other synoptic systems, so it is difficult to generate optimal perturbations. Chan[1] pointed out that ensemble forecast of TC track and intensity is still in its infancy. Prediction of possible future states of TCs by new methodologies other than traditional deterministic forecasts will require more studies. Aberson et al.[2-4] used ensemble members of the National Centers for Environment Prediction (NCEP) as initial conditions for the Vic Ooyama's Barotropic model (VICBAR) to forecast Atlantic hurricanes and examined the feasibility of ensemble forecast. The results show very limited improvement in the track forecast, indicating that perturbation from one model may not be applicable to another. Zhang et al.[5, 6] and Mackey et al.[7] analyzed the differences between control runs and ensemble members using Empirical Orthogonal Function (EOF) method, and identified the most rapidly growing modes. With perturbation on the initial modes, both the track forecast and the intensity forecast of TCs were improved. Cheung[8, 9] tested three methods to generate perturbations for the environment flow using a barotropic model applied to the motion prediction of TCs. These methods were Monte Carlo forecast (MCF), lagged-average forecast (LAF), and breeding

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of growing mode (BGM) method. The BGM technique led to an improvement on environment perturbation in >40% of all cases, and the LAF technique improved one third. However, the barotropic model restricts improvement in ensemble technique for TC forecasts due to its simplified dynamic process. Therefore, further study (Cheung[10]) was carried out with the MM5 model to compare the performance of MCF and BGM. The results show that dynamically constrained perturbations, such as the BGM, are superior for improving the skill of TC track predictions. Puri et al.[11] used the targeted diabatic singular vector, which was derived from linearized physics, to generate initial perturbations for TC forecast in the European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble prediction system. A significant spread in the tracks was obtained. A high level of sensitivity to the background state was noted, which was used in deriving the singular vectors. However, the singular-vector technique demands a large amount of computing resources. Few studies have been done on this method, and it has few applications in the tropics. Chan[1] indicated that the cases studied above are quite limited, and much work has to be done to make the best use of ensemble forecast with baroclinic models in the tropics. Not only are more case studies needed, but more studies and experiments on the Numerical Weather Prediction model are necessary. Issues addressed in such studies may include the effect of boundary conditions, the balance between dynamic and thermodynamic variables, and the perturbation of parameters.

Research on the ensemble forecast of TC in China is still in its early stages. It mainly uses the MM5 model. In order to find the most effective ways to produce initial perturbation, Zhou[12, 13] tested different techniques to perturb the initial location and structure of the TC vortex. For strong interactions between the TC vortex and the environment, better results are obtained by perturbing the whole flow based on the LAF method than by perturbing the vortex and environment separately based on BGM. The importance of perturbation of the lateral boundary conditions was discussed. Huang[14] proposed the use of the BDA method combined with initial position and intensity perturbations. Yuan[15] suggested that an ensemble system, constructed using different initial conditions from different models, has a certain capability to forecast TC in the South China Sea. Wang[16] compared initial perturbation and model physics ensemble approaches, and showed that combining two types of ensemble is better than just using a single type in TC forecasting. However, the ensemble spread is still not sufficiently large. Huang[17] applied the ensemble Kalman filter technique to TC forecasting. The result of the ensemble mean with data assimilation is better than that without data assimilation, and the ensemble mean is better than the control run. At present, operational ensemble forecast of TC has not been fully implemented, although the National Meteorological Center of China has provided products of TC ensemble forecast since 2007. In conclusion, though TC forecast covers various scales such as large, vortex, and convective scales, the key to TC ensemble forecast is still the initial perturbation method.

In operational public weather service, the official track of the landfall process of Whipa was forecast more to the east than observation, which overestimated the impact and damage induced from Whipa in the Yangtze River Delta region, especially for Shanghai. In this study, an ensemble experiment with 72-h forecast is performed during which Typhoon Wipha was about to make landfall. A method to generate optimal perturbations for TC ensemble forecast is sought. The Global/Regional Assimilation and Prediction System-Tropical Cyclone Model (GRAPES-TCM), which is an operational model for TC forecast from the Shanghai Typhoon Institute, is used. The BGM method is used to perturb the initial conditions of the vortex flow and the environment flow.

This paper continues with a description of the model and data in section 2, which is followed by a description of the experiment design in section 3. In section 4 the results are presented and the paper finishes with discussions and conclusions in section 5.

2 MODEL AND DATA

2.1 *Model*

The simulation (controlled to a 0.5° resolution) employed a horizontal domain of 141×101 grid points with 31 vertical layers covering the West Pacific (100°E to 160°E, 0°N to 45°N). The Kain-Fritsch cumulus parameterization scheme, the MRF planetary boundary layer scheme, the NCEP 3-class microphysics scheme, the Duhia shortwave radiation and the RRTM long-wave radiation scheme are selected for the model physics in the control experiment.

2.2 *Data and initialization*

The 12-h forecast data supplied by the aviation run of the global spectral model (AVN) are used to create the initial and lateral boundary conditions. The relocation technique is used for the initial vortex configuration to modify the location of the TC on the background, according to the TC real time information. The results from the operational practices indicated that the 24-h and 48-h position error were decreased by as much as 50 km due to the relocation scheme unitized[18].

3 ENSEMBLE EXPERIMENT

3.1 *Wipha (2007)*

Wipha (2007) originated from a tropical disturbance that developed in the northeast of Luzon Island on September 15. On September 16, the storm gained enough strength to be designated as a tropical storm. On September 17, the storm underwent a rapid intensification and strengthened into a typhoon. It continued to strengthen rapidly and was upgraded to a super typhoon early on September 18 with maximum wind speed of 55 m/s. In the early hours (0230 UTC, Coordinated Universal Time) of September 19, Wipha made landfall in Cangnan county, Zhejiang province. Before its landfall the storm slightly weakened and became a Category 3-equivalent typhoon with minimum central pressure of 950 hPa and maximum wind speed of 45 m/s recorded. After its landfall, the cyclone weakened rapidly into a severe tropical storm in only 4 hours. As Wipha accelerated towards the northeast, it began to undergo extratropical transition early on September 20.

3.2 *Experiment design*

Figure 1 shows the procedure of ensemble forecast for TC based on BGM. The breeding cycles start 36 hours before the initial forecast time with a rescaling of bred error every 12 hours. In the beginning, two forecasts are made, one from the 12-h forecast from AVN (A) with the vortex relocation technique, and the other with random perturbations (R) with the pattern of Gauss distribution. After each breeding cycle, the bred vector is rescaled nearly the same as the initial perturbation in terms of magnitude. The new perturbations of environmental flow and vortex component are obtained based on Eqs. (1) and (2), respectively. Then these new perturbations are added to the new analysis of the next cycle. The cycle is repeated until the process is finished.

$$f_i = C \times \Delta P_i, \quad (1)$$

where f_i and ΔP_i are rescaling factor and standard deviation of some element i, respectively; C is weighting.

For environmental fields, the standard deviation (ΔP_i) is computed after a breeding cycle for variables at 850 hPa including geopotential height (H), temperature (T), wind (u, v), humidity (Q), and sea level pressure (SLP). Here 850 hPa is selected as the reference level to better reflect the error structure. In addition, a weighting (C) is defined to tune error in the downscaling factor (f_i) in Eq. (1).

$$f_i = C\times(X_{\mathrm{pi}}-X_{\mathrm{ni}})\times\|X_{\mathrm{c}}\|/\|X_{\mathrm{p\ i}}-X_{\mathrm{ni}}\| \quad (2)$$

Similar to Geophysical Fluid Dynamics Laboratory (GFDL), the rescaling factor for the vortex component is shown in Eq. (2), where $C = 0.05$, X is 3D or 2D variables such as H, T, wind (u, v), Q, and SLP of an ensemble member, Subscripts pi, ni and c indicate "positively perturbed", "negatively perturbed" and "control" member, respectively; $\|X\|$ is the square root of the summation of X^2 over the whole vortex area.

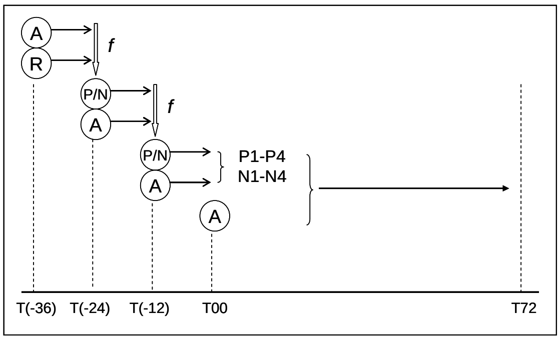


Figure 1. The procedure of ensemble forecast for the tropical cyclone based on BGM. "A" represents the 12-h forecast from AVN, "R" represents the random perturbations. "f" represents the rescaling factor. "P(N)" represents the rescaled positively (or negatively) perturbed. "P1-P4" and "N1-N4" represent ensemble members.

4 RESULTS

4.1 *Initial time*

The vortex component of SLP is shown in Figure 2 in which the environmental field is filtered out. It can be seen that the vortex structure and intensity are well captured. After the 36-h breeding cycle, there are distinct differences in the scale, structure, and intensity among the members. In terms of vortex structure, member 1 and member 5 are quite similar; namely, both show a smaller scale and a larger gradient in the southwest part than in the northeast, and become elongated in the NE-SW direction. The structure of the other vortex tends to be approximately axisymmetric; the eye of member 4 is somewhat loose; the scales of member 3 and member 7 are much larger than others. Among the members, the intensity range is from –12 hPa to 2 hPa, member 3 and member 7 have the strongest intensity of –12 hPa, and member 5 is the weakest one with an anomaly of –6.5 hPa. The largest disparity is between members 5 and 7 with a pressure difference of 8 hPa.

At the initial time, the intensity of Whipa is 992 hPa for each member, and the perturbation field of SLP was totally different. The pattern of perturbations did not have the regular feature of positive and negative centers, and instead showed irregularity. This reflects the nonlinear effect of the inherent atmosphere and the sensitivity of the pattern to the effect of the initial conditions. The perturbation field with the spread maximum value is centered on the vortex itself. But for other elements, such as temperature, wind field etc, the perturbed high area and low area are distributed over the whole domain, and the centralized pattern of the perturbation field is less obvious than SLP. Therefore it can be noticed that different elements and members have different perturbation fields.

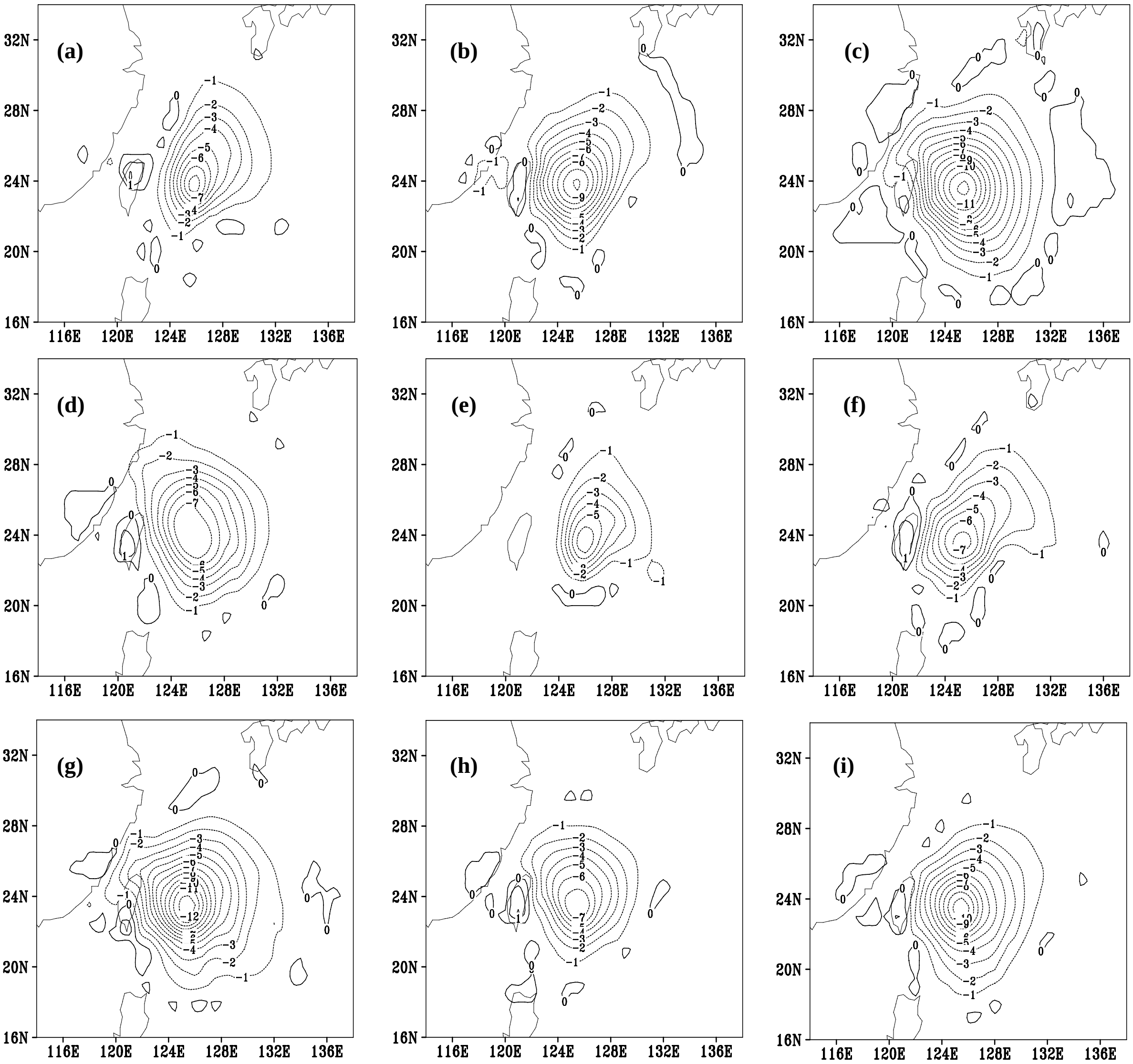


Figure 2. The vortex components of sea level pressure from nine ensemble members at initial time. Units: hPa; interval: 1 hPa; Members 1 to 8 (a to h), control run (i).

Being able to show the difference among members and the magnitude and distribution of spread, the ensemble spread, to some extent, could reflect the uncertainty of forecast. Ensemble mean and spread of the geopotential height at the initial time is shown in Figures 3a, 3b, and 3c for levels of 1000, 850, and 500 hPa, respectively, and the results indicate that the largest spread occurred around the central area of the vortex with a magnitude within 40 gpm for all three levels indicating a good vertical consistency. What is more, the spread of other elements (including meridional and zonal winds and temperature) does not have such distinct feature as that in the geopotential height.

4.2 *Average flow*

Two kinds of synoptic systems could influence the movement of Whipa. The first is the subtropical high over the Western North Pacific, and the other is a trough in the mid-high latitudes. The typhoon was located on the southwest of the trough at the initial time, with the impacts from the southeast flow of the subtropical high. When it moved constantly northwestward and approached the coastal regions of eastern China, with the interaction effects related to the northward movement of the subtropical high and the eastward movement of the trough, the northward component of the TC movement was gradually increased.

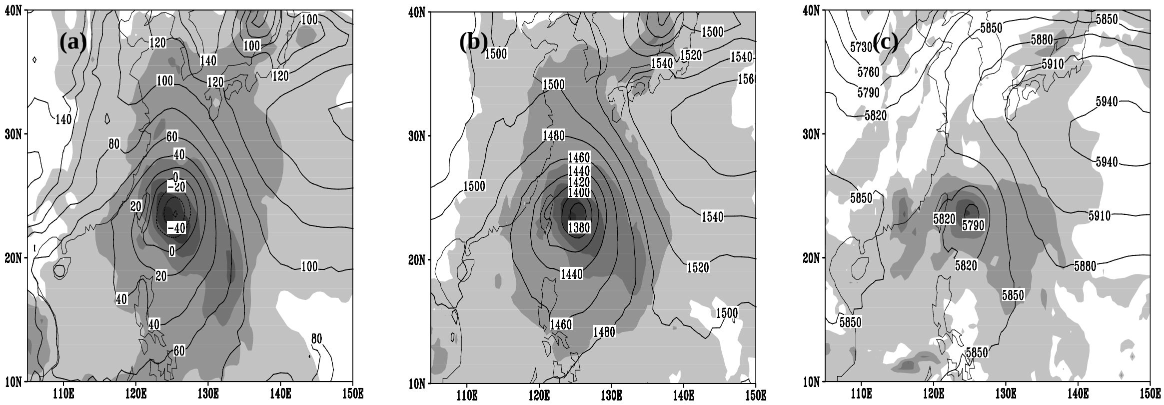
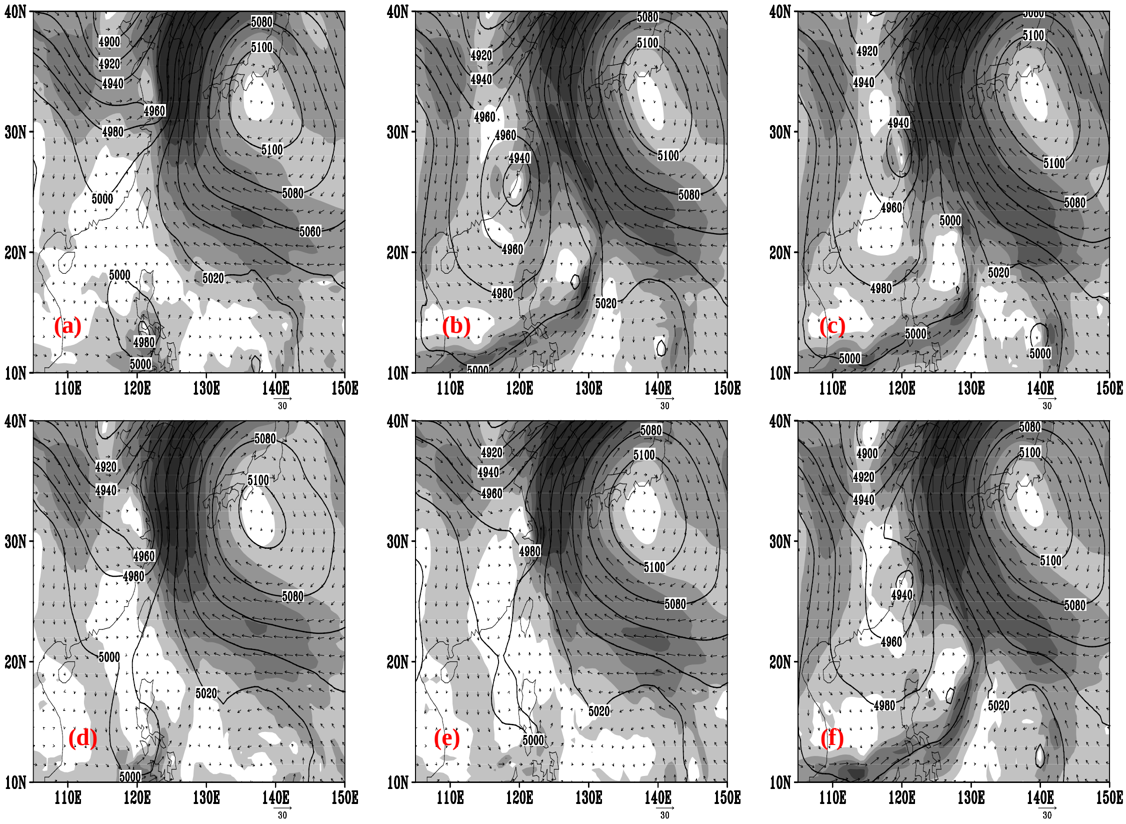


Figure 3. The ensemble means (contours) and spreads (shaded areas) of geopotential heights at different levels. 1000 hPa (a), 850 hPa (b), and 500 hPa (c). Units: gpm.

The average flow of geopotential height and wind (300 to 850 hPa) was used for analyzing the effect of the evolution of large-scale flow on the movement of Whipa. Figure 4 shows the average flow when the typhoon made landfall. According to the results, the members were divided into two classes. The first consisted of 5 members, namely, members 1, 4, 5, 7, and the control run. Due to the friction functions of the topography and the filling effects from the front of the upper-level trough, the circulation of low-pressure was not very clear. The second class consisted of four members, namely, members 2, 3, 6, and 8. In contrast, the circulation of low-pressure was very clear, which was due to the large height gradient of the west side of the subtropical high. Due to the different features derived from the average flow of members, movements of the TC varied more clearly.



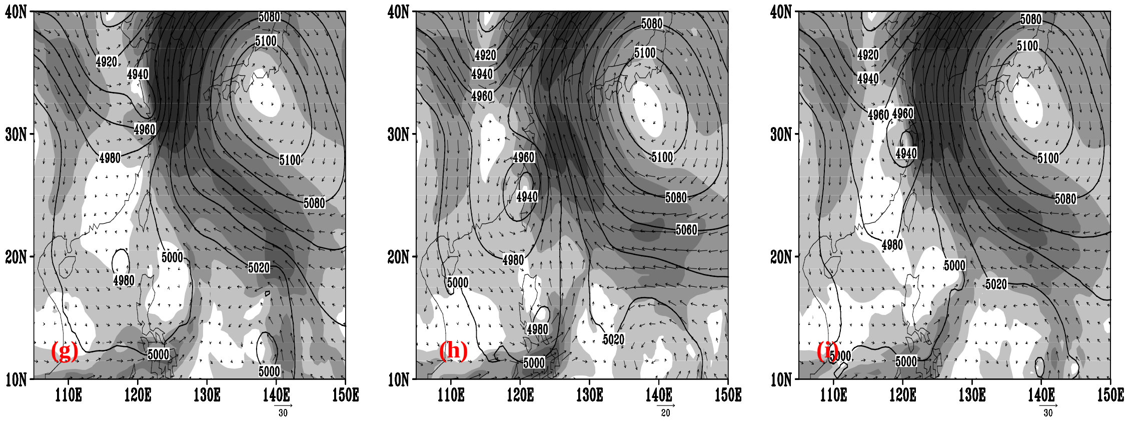


Figure 4. The average flow of geopotential height (contour, units: gpm) and wind field (shaded area, units: m/s) from 300 to 850 hPa. Other descriptions are the same as in Figure 2.

Geopotential height filed of 1000, 850, and 500 hPa represented the different levels of the troposphere, which could be used for analyzing the time series of the spread in the whole layer. During the restriction effect with the BGM process, the differences among members were apparent at the initial time (Figure 5a). The differences at 500 hPa were much more obvious than that at the mid-low troposphere. The spread increased with time. Moreover, the growth ratio of spread from the lower layer was faster than that from the upper layer. Figure 5b shows the results from the geopotential height. The spread from the low level of the troposphere was larger than others at the initial time. When the typhoon was making landfall at 0000 UTC September 19, 2007, a change of spread occurred in the vertical direction. The slope of the spread is an important factor to judging the degree of change. The differences among members after its landing were much larger than that before landing. To some extent, this suggests that the forecast uncertainty increases with differences.

4.3 *Track forecast*

The track forecast is shown in Figure 6. In this graph, the red line represents the best track, the black line represents the control run, and the blue lines represent the ensemble members. Whipa continued to move further inland after its landing on the central coastal region of Fujian province. Thereafter, it turned northeastward in its later stage, and moved toward the Yellow Sea again at the central coastal region of Jiangsu province. Compared with the best track, the landing site of the control run was more northward than the best track. The typhoon would land on the central to northern part of Zhejiang province, and the related impact on Shanghai should not be ignored as well.

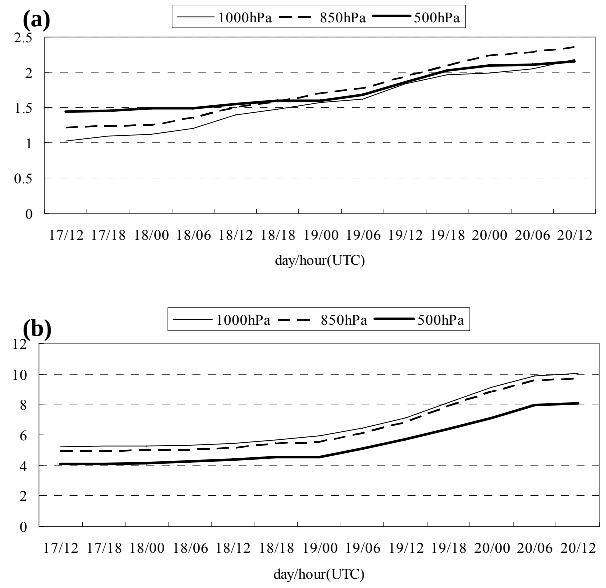


Figure 5. The time series of ensemble spread of zonal wind (a, units: m/s) and geopotential height (b, units: gpm).

The track forecast was different among members. In general, it could be divided into two kinds. The first involved Whipa landing at the region from southern Zhejiang to the boundary area between Zhejiang and Fujian. After its landfall, the typhoon keeps moving slowly inland and finally disappears due to the effects of filling. The second kind of forecast involved Whipa landing at the central-to-north part of Zhejiang province to cause a serious impact on eastern China, as well as the northern part of the East China Sea. It was expected to curve into the Yellow Sea between the mainland of China and the Korean Peninsula, and then begin an extratropical transition process.

Based on the strike probability results in the 72 hours to come (Figure 6b), the difference among the members was not too large before Whipa approached Taiwan Island. A probability of 70% indicates that the typhoon will move toward the northern part of the island, and approach Zhejiang and Fujian coasts later. Nearly 50% of the probability indicates that the landing site will be located at the central mid-southern coast of Zhejiang province. However, the difference among the members after its landing was much more obvious than that before its landing. The strike probability of such related impact area decreased sharply to <15%. Meanwhile, there was no significant signal to show which area might be struck by the TC after its landing. The affected regions cover a large part of eastern China. Therefore, the strike probability could provide some effective information, especially for the landfall forecast, and quantitatively describe the forecast probability.

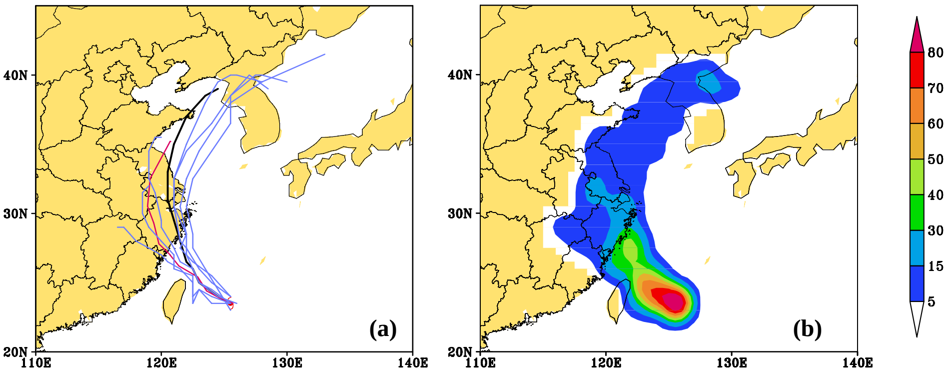


Figure 6. Tack forecast (a; red line, best track; black line, control run; blue lines, members) and ensemble strike probability in 72 hours (b).

The position error of Whipa is shown in Figure 7, with 6-h interval and 60-h valid time. The average error was calculated until 0000 UTC September 20, 2007.

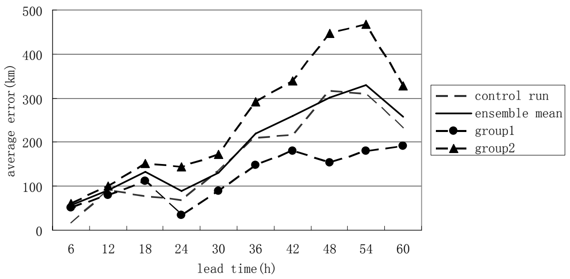


Figure 7. Average position error with 6-h intervals.

The time series of different types of forecast error based on Ward cluster analysis are shown in Figure 7. All members were divided into two classes. The first one consisted of members 2, 3, 6, and 8. The forecast involved the typhoon moving inland and then disappearing. The other class consisted of members 1, 4, 5, and 7, for which the forecast was recurvature.

The errors of the control run of 24, 48, and 60 h were 68, 316, and 230 km, respectively. Compared with the control run, the ensemble mean forecast was worse, with a forecast error of 89 km in 24 h and 250 km in 60 h. However, the mean forecast was better at hour 48, with an error of 300 km. In general, differences between the ensemble forecast of all members and the control were small. However, the two totally different forecasts were made using the cluster analysis. The forecast error of group 1 was smaller than that of the control run during the forecast period, and much smaller than that of group 2, with errors of 34 km (24 h), 153 km (48 h), and 191 km (60 h). Clearly, the members from group 2 played a “negative” role in the calculation of the ensemble mean.

The west side of Whipa in the mainland of China was 118.9°E at 1200 UTC September 19, 2007. The previous speed with the northwestward movement was about 20–25 m/s. However, when the typhoon passed the west side, it quickly turned northeastward and the speed increased to 30–40 m/s. In group 1, the situation was different with the two scenarios, although the forecast of members could be summarized as landing and disappearing. The first scenario was that the typhoon kept moving northwestward and made landfall and moved inland to disappear finally. By contrast, the second scenario was that the typhoon made a recurvature and disappeared thereafter. In this scenario, although the forecast of the vortex itself was not as good as that of group 2, the forecast of the movement tendency and speed were close to the best track

In group 2, the forecast of the recurvature process of typhoon was good, but the west-side inland part of the TC was more eastward than in the observation, which caused the recurvature to appear earlier at faster speed. Some insights on how to use a large amount of information from ensemble forecast can be drawn from the case study, and it also could be safely concluded that the cluster analysis is definitely a practical and effective way for the post-processing of ensemble forecasts.

5 CONCLUSIONS AND DISCUSSIONS

(1) The ensemble forecast system based on GRAPES-TCM, which is different from the deterministic forecast, could provide some information of forecast uncertainty, and was found to be a useful method of typhoon forecasting.

(2) The initial condition could reflect the character of the environment and the vortex after the dynamic process of BGM. The pattern of perturbations did not have the regular features of positive and negative centers. Instead, it showed irregularity, and reflects the nonlinear effect of the inherent atmosphere. This pattern caused an ensemble spread in the latter phase.

(3) During the landing process of the TC, the different features derived from the average flow of members and the movements of TC varied significantly.

(4) In general, differences between the ensemble mean forecast among all members and the control were small. However, the two totally different forecasts were both made by the cluster analysis. Insights on how to use a large amount of information from ensemble forecasts can be drawn from the case study. Carefully elaborated in this thesis, cluster analysis is definitely proven to be a practical and effective way for the post-processing of ensemble forecasts.

(5) Strike probability could provide some effective information, especially for the landfall forecasts, on forecast probability of a quantitative description.

In the future, more case studies should be done to enhance the understanding about the forecast ability of the ensemble system based on GRAPES-TCM. Besides, considerations on initial uncertainty, the balance of dynamic and thermodynamics variables, the uncertainties from model parameterization, and lateral boundary conditions should be taken into account as well. The extraction and utilization of information from ensemble forecast will become a significant area of future research.

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