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ENSEMBLE PREDICTION EXPERIMENTS OF TYPHOON TRACK BASED ON THE STOCHASTIC TOTAL TENDENCY PERTURBATION

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Abstract: The GRAPES-TCM is used to make ensemble prediction experiments for typhoon track. Three kinds of ensemble schemes are designed for the experiments. A total of 109 experiments are made for the nine typhoons in 2011 and the integral time is 72 h. The experiment results are shown as follows. In the three ensemble schemes, on the whole, scheme 1 has the best track prediction. Its average absolute track error and overall deviations of typhoon moving speed and moving direction are all the smallest in the three schemes. For both scheme 1 and scheme 2, they are all smaller than those of their control predictions. Both of their ensemble predictions show superiority to their deterministic predictions. Overall, compared with the observations, the typhoon moving directions of the three schemes mainly skew to the right, and in the late integration they mainly tend to be relatively slow. In the three schemes, the track dispersion of scheme 1 is the largest and that of scheme 3 the smallest. In scheme 1 it is much larger than in schemes 2 and 3. The difference of dispersion between scheme 2 and scheme 3 is small. The track dispersions of the three schemes are all much smaller than their rational dispersions. Compared with the eight domestic and overseas operational numerical weather prediction (NWP) models, scheme 1 has better predictions than the other seven operational models except ECMWF NWP model. Scheme 1 has the value of operational application.

Key words: typhoon; track; ensemble; scheme; stochastic total tendency perturbation
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1 INTRODUCTION

Typhoon is one of the main natural hazards of our country. At present, typhoon prediction mainly depends on numerical weather prediction (NWP). With the development of NWP, NWP is more and more accurate and valid prediction time is longer and longer. In our country, typhoon operational prediction has experienced large improvement and track error decreases from year to year. At present, compared with that in the early 1990s, the 24 h and 48 h track errors reduce nearly 50%. The 72 h track error is almost the same as the 48 h track error in the early 1990s (Duan et al.[1]; Xu et al.[2]; Qian et al. [3]). However, our country's typhoon prediction is still behind the overseas advanced typhoon predictions. Among the domestic and overseas operational NWP models' predictions for the fourteen typhoons in 2010, ECMWF model's predictions are the best for 24, 48 and 72 h. Its average distance errors are 50.7, 87.0 and 126.1 km smaller than Beijing model's respectively. Japan model's average distance errors are all smaller than the domestic models' (Tang et al. [4]). The predictions for the twenty-one typhoons in 2011 are similar to those in 2010. Among the domestic models', Guangzhou model's average distance errors are the smallest for 24, 48 and 72 h. However, they are still 36.1, 76.1 and 160.9 km larger than ECMWF model's respectively (Chen et al.[5]).

NWP error comes from the uncertainties of initial condition and model. On the basis of the current NWP technique and observation mean, ensemble prediction is a new way to reflect the NWP uncertainty objectively and decrease the effect of various kinds of uncertainties to NWP effectively. It started in the middle 1990s to apply the ensemble prediction technique to typhoon prediction. Most works applied the technique to typhoon track prediction and included the initial condition uncertainty (Zhang and Krishnamurti [6]; Zhang and Krishnamurti[7]; Cheung and Chan[8]; Cheung and Chan[9]; Puri et al.[10]; Cheung [11]; Chan and Li [12]; Yamaguchi et al. [13]; Buckingham et al. [14]). In our country, similar works have also been done (Zhou et al.[15]; Zhou et al.[16]; Yuan et al.[17]; Huang et al.[18]; Zhang et al.[19]; Wang and Liang[20]; Huang et al.[21]; Tan and Liang[22]; Tu et al.[23]).

According to Richardson et al. [24], Buizza et al. [25], Harrison et al. [26], and Zhang and Zhi [27], the model uncertainty should be included preferentially in the precipitation ensemble prediction. Similarly, the model uncertainty should not be excluded in the typhoon ensemble prediction. Using the method of Multiple

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Model (MM), Goerss [28] and Kumar et al.[29] made the prediction experiments of typhoon track and intensity. Their results show that ensemble prediction is far superior to each model's prediction. Using the method of Multiple Physics (MP), Zhang et al.[19], Wang and Liang [20] and Hou et al. [30] made the typhoon track ensemble prediction experiments. In Wang et al.[20], the MP ensemble prediction of strong typhoon is better than that of weak typhoon. In Zhang et al. [19], the uncertainties of initial condition and model are both important to typhoon simulation. The initial condition uncertainty mainly affects the simulation previous 12 h. The MP model uncertainty exists throughout the whole simulation process.

At present, in the ensemble prediction based upon the model uncertainty, besides the methods of MM and MP, the frequently used methods of forming the perturbation members include the methods of Stochastic Total Tendency Perturbation (STTP), Stochastic Perturbed Parameterization Tendencies (SPPT) and Stochastic Kinetic Energy Backscatter (SKEB). In February 2010, the model uncertainty was included in the NCEP Global Ensemble Forecast System (GEFS). The STTP method is used to form the model perturbation members (Hou et al.[31-32]). In the ECMWF GEFS, the methods of SPPT (Buizza et al. [25]) and SKEB (Shutts [33]; Berner et al.[34]) are used to form the model perturbation members. In the MSC GEFS, the methods of MP, SPPT and SKEB have been used to form the model perturbation members since July 2007 (Charron et al.[35]).

This study will apply the STTP method to the typhoon track ensemble prediction to investigate this method's effect. Section 2 describes the model and data used in this study. Section 3 and section 4 introduce the ensemble schemes and cases used to make the ensemble prediction experiments, respectively. Results are presented in section 5 and the summary and discussion are provided in section 6.

2 MODEL AND DATA

GRAPES-TCM is a typhoon track prediction system which is set up based upon GRAPES (Huang et al.[36]). GRAPES-TCM is used as the prediction model in this study. The model's grid spacing, domain, physics configurations, used data, method of creating the initial fields and renew of the lateral boundary conditions are all consistent with those used in Wang [37]. The model domain covers the area of 5～50°N and 100～148°E with 0.15° ×0.15° horizontal grid spacing and 321 ×301 horizontal grid points. The model has 41 vertical levels and its top is set at 25000m. Its physics configurations include Kain-Fritsch (KF) cumulus parameterization scheme, MRF and YSU planetary boundary layer parameterization schemes, NCEP3-class single ice-phase microphysics parameterization scheme, Duhia shortwave radiation scheme and RRTM longwave radiation scheme.

The data used in this study are obtained from the initial fields of NCEP Global Forecast System (GFS). Using the GRAPES-TCM initialization module, the 1°× 1° fields of NCEP GFS are initialized to create the preparing fields. Typhoon vortexes are removed from the preparing fields to create the background fields. According to the real-time typhoon data, bogus are formed and added to the background fields to create the model initial fields. The lateral boundary conditions are renewed once every 12 h.

The observed typhoon tracks used to evaluate the ensemble predictions and calculate the track errors and the real-time typhoon data used to form the bogus are both obtained from the operational reports which are issued by the China Meteorological Administration (CMA) and named with 'BABJ'.

3 ENSEMBLE SCHEMES

In this study, three kinds of ensemble schemes are designed to make the experiments. Each scheme contains six ensemble members and the STTP method is used to form the perturbation members. The STTP method is as follows. During the model integral process, stochastic small perturbations are added to the physics tendency items to form the perturbation members every certain time interval. The perturbation members reflect the model uncertainty. In this study, stochastic small perturbations are added to the tendency items of horizontal wind and potential temperature every one hour interval. The stochastic number generator is used to create the stochastic small perturbations. The stochastic small perturbations meet the normal distribution and their amplitudes are one or two magnitudes smaller than the tendency items. Perturbing the tendency items of horizontal wind and potential temperature can lead to perturbing all the physics tendency items.

Typhoon track prediction is sensitive to the planetary boundary layer process. In this study, two kinds of planetary boundary layer parameterization schemes MRF and YSU are chosen. The MRF scheme stems from the improvement of the TM nonlocal K diffusion model. The YSU scheme is the improved MRF scheme. The experiment results of Muifa typhoon [37] show that the track predictions with the MRF and YSU schemes have their own characteristics. For weak typhoon, between the MRF and YSU schemes, the YSU scheme's prediction is better. For strong typhoon, the MRF scheme's prediction is better. Overall, the track predictions of the two schemes are both well.

In this study, in ensemble scheme 1, the MRF and YSU planetary boundary layer parameterization schemes are chosen simultaneously, and using the STTP method, two perturbation members are formed based upon the MRF and YSU schemes, respectively. So, scheme 1 contains two non-perturbation members and four perturbation members. In ensemble scheme 2 and ensemble scheme 3, the MRF and YSU schemes are chosen respectively, and using the STTP method, five perturbation members are formed based upon the MRF scheme or YSU scheme. So, scheme 2 and scheme 3 both contain one non-perturbation member and five perturbation members. In the ensemble schemes, the method of arithmetic average is used to produce the ensemble tracks.

4 CASES

A total of 109 experiments are made for the nine typhoons in 2011. Summary of the nine typhoons is shown in Table 1. In this table, 'Start date' and 'End date' indicate the start date and end date when a tropical cyclone (TC) strengthens into a tropical storm or a stronger TC. 'Intensity' indicates a TC's strongest intensity during its lifetime. 'Landfall' indicates the landfall in our country.

Table 1. The number of samples on different TC Intensity Grade

Typhoon number	Typhoon name	Start date-End date	Intensity	Track trend	Landfall	Experiment times
1101	Aere	May 7 - May 11	Tropical storm	Westward and turning	No	6
1102	Songda	May 22 - May 29	Super typhoon	Westward and turning	No	12
1104	Haima	Jun. 21 - Jun. 24	Tropical storm	Northwest-ward	Yes	5
1105	Meari	Jun. 22 - Jun. 27	Severe tropical storm	Northward, landing and turning	Yes	8
1108	Nock-ten	Jul. 26 - Jul. 30	Severe tropical storm	Westward	Yes	6
1109	Muifa	Jul. 28 - Aug. 9	Super typhoon	Westward and turning	No	36
1111	Nanmadol	Aug. 23 - Aug. 31	Super typhoon	Northwest-ward	Yes	15
1117	Nesat	Sept. 24 - Sept. 30	Severe typhoon	Westward	Yes	10
1119	Nalgae	Sept. 28 - Oct. 4	Severe typhoon	Westward	Yes	11

In 2011, twenty-one TCs which are at least tropical storms or stronger TCs, occurred in the western North Pacific and South China Sea. The twenty-one TCs consist of five super typhoons, two severe typhoons, one typhoon, five severe tropical storms and eight tropical storms. In these TCs, seven made landfall in our country. Three super typhoons, two severe typhoons, two severe tropical storms and two tropical storms are chosen from these TCs to comprise the nine experiment typhoons which include six landing TCs. Sarika (1103), the one other landing TC, is not included in the experiment typhoons because its lifetime is shorter than 72 h. Muifa (1109), one of the experiment typhoons, had major impacts on the coastal area and offshore sea of our country, although it didn't make landfall in our country. Nesat (1117), another experiment typhoon, is the TC which led to the most severe disaster and the greatest economic loss in our country in 2011. The nine experiment typhoons all originated in the western North Pacific and of the nine typhoons, Haima (1104), Nock-ten (1108), Nesat (1117) and Nalgae (1119) moved to the South China Sea from the western North Pacific.

Several experiments are made for every experiment typhoon and the total experiment times is 109. Thirty-six experiments are made for Muifa whose lifetime is as long as 12 d. For every experiment, the integral time is 72 h and the integral time step is 120 s.

5 EXPERIMENT RESULTS

5.1 *Errors of track predictions*

At first, let's pay attention to the average absolute errors of track predictions. Fig.1a ~Fig.1i show the average absolute errors of each typhoon's several track predictions by the three ensemble schemes and the two non-perturbation members of scheme 1. The track errors of most typhoons increase gradually with increasing the integral time. However, the errors of 1104, 1105 and 1108 show the feature of first increasing, then decreasing and last increasing again. Except the errors of 1101 and 1117 are large (72 h maximum errors are near 400 km), for other typhoons, 72 h maximum errors are all smaller than 250 km on the whole.

Comparing the three scheme's track prediction effects, it could be found that each scheme's performance is related to the experiment typhoon and the integral time. From Fig. 1, for the predictions of 1108, 1111 and 1119 and the early predictions or early and middle predictions of 1101, 1104 and 1105, scheme 3's error is the smallest and scheme 2's the largest. For the middle and late predictions or late predictions of 1101, 1102, 1104, 1105 and 1109, scheme 2's error is the smallest and scheme 3's the largest. Different from the other eight typhoons, the prediction tracks of 1117 are not sensitive to the STTP model uncertainty at all. For 1117, the three schemes' errors are roughly the same, and only at 72 h scheme 3's average absolute errors are a little smaller than scheme 1 and 2's.

In scheme 1, the perturbation members are formed based on the two non-perturbation members. The two non-perturbation members of scheme 1 are also the non-perturbation members of scheme 2 and 3 respectively, which make scheme 1's predictions have the features of scheme 2 and 3's. So scheme 1's average errors are always between scheme 2's and 3's, and in the three schemes, scheme 2 and 3's errors are

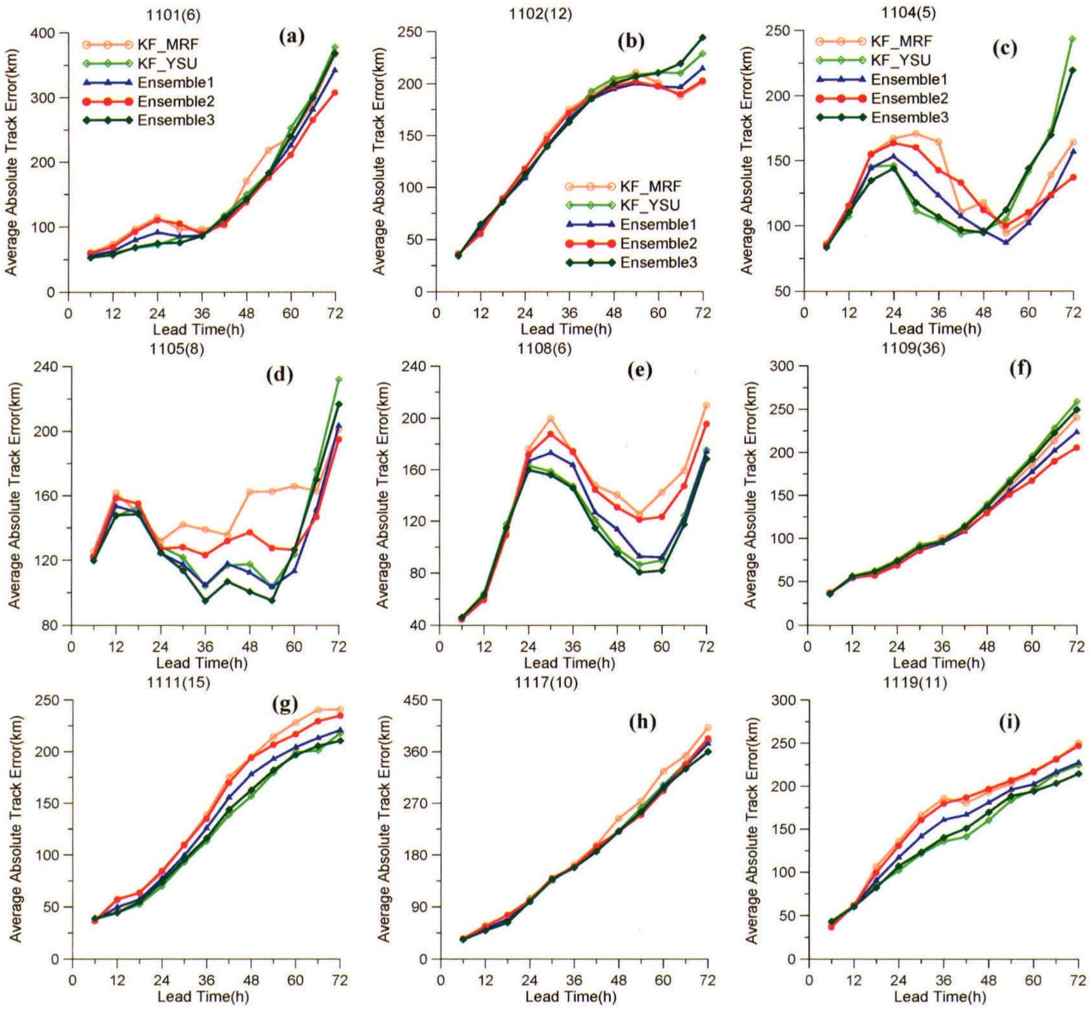

Figure 1. The average absolute errors of each typhoon's several track predictions (a to i) by the three ensemble schemes and the two non-perturbation members of scheme 1 (unit: km, the same below). Abscissa is the integral time, unit: h, the same below. The digit above the figure is the typhoon number (prediction times), the same below.

always the smallest or largest, which could be found in the above results. Obviously, in the three schemes, scheme 1's track predictions are the most stable and also the best overall.

Comparing each scheme's track ensemble predictions with its control predictions, it could be found that for the total 109 experiments (Fig.2), scheme 2's ensemble predictions are better than its control predictions and scheme 3's are roughly the same as its control predictions. In scheme 1, on the whole, ensemble predictions are better than its two non-perturbation members' predictions. For each typhoon, ensemble predictions sometimes are better than its two non-perturbation members' predictions and sometimes are between them.

In summary, track predictions of the three ensemble schemes show different features with different typhoon and different integral time. On the whole, the average prediction errors of scheme 1 and 2 are smaller than their control predictions' and the ensemble predictions are superior to the deterministic predictions. Scheme 3's average prediction errors are roughly the same as its control predictions'. In the three schemes, scheme 1's track predictions are the most stable and also the best overall.

Track error contains the deviations of moving speed and moving direction. In order to understand the feature of each scheme's track prediction better, track error is decomposed into along-track error and cross-track error which reveal the deviations of moving speed and moving direction respectively. As shown in Fig.3, through the prediction point P, a straight line perpendicular to observed track is drawn. This line intersects observed track at the point Q. If typhoon is observed to locate at the point C this moment, the distance between point C and Q is the along-track error and the distance between point P and Q is the cross-track error. If point Q lies ahead of (behind) point C, along-track error is positive (negative). If point P lies right (left) of point Q, cross-track error is positive (negative). In this study, the average magnitudes of along-track and cross-track errors and the average along-track and cross-track errors are calculated respectively.

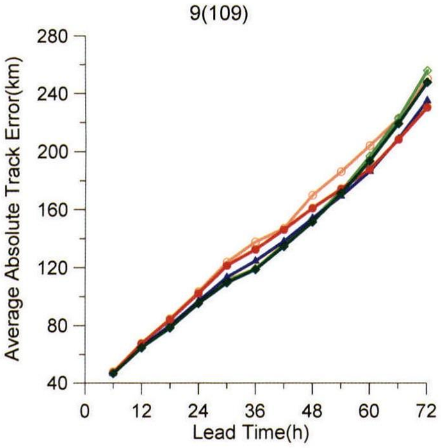

Figure 2. The average absolute errors of the total typhoons' 109 track predictions. The explanation of line colors is the same as in Fig.1a.

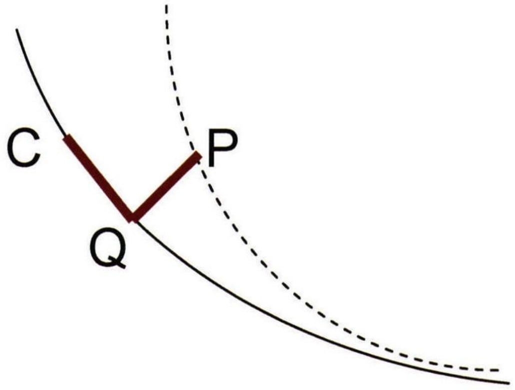

Figure 3. The schematic diagram of along-track error and cross-track error. The solid line is observed track and the dashed line is prediction track.

Figure 4 shows the average magnitudes of a long-track errors and the average along-track errors of each typhoon tracks predicted by the three ensemble schemes and the two non-perturbation members of scheme 1. From the average magnitudes of along-track errors, it could be found that no matter for each typhoon's predictions or for total typhoons' (Fig.5), the three schemes' along-track errors show roughly the same features as their average absolute errors. On the whole, scheme 1's average magnitudes of along-track errors are the smallest in the three schemes. Scheme 1 and 2's average magnitudes of along-track errors are both smaller than their control predictions' and scheme 3's is roughly the same as its control predictions'.

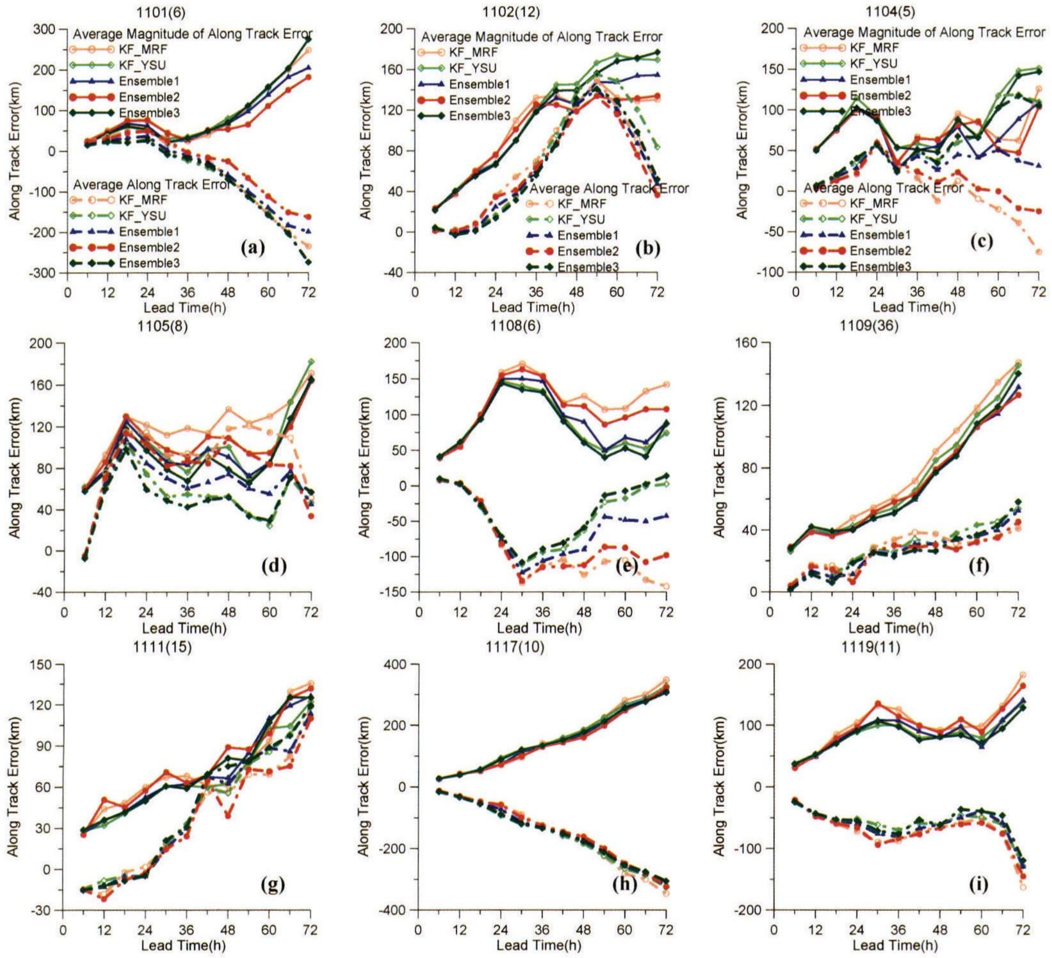

Figure 4. The average magnitudes of along-track errors (solid) and the average along-track errors (dotted) of each typhoon tracks (a~i) predicted by the three ensemble schemes and the two non-perturbation members of scheme 1.

The average magnitude of along-track error reveals the overall deviation of typhoon moving speed and the average along-track error reveals the overall fast or slow deviation of typhoon moving speed. From the average along-track errors of total typhoons (Fig.5), it could be found that in the early and middle integration, typhoon moving speeds predicted by the three schemes are near observed speeds and their average along-track errors are all near zero. In the late integration, each scheme's moving speed has a slightly slow deviation overall and scheme 2's slow deviation is the largest and scheme 3's the smallest in the three schemes. For each typhoon, one typhoon's average along-track error may be completely different from one other's. For 1101, 1108, 1117 and 1119, most of the three schemes' moving speeds have a slow deviation, and for 1102, 1105, 1109 and 1111, most have a fast deviation. For 1104, 1105 and 1108, different scheme has obviously different average along-track error.

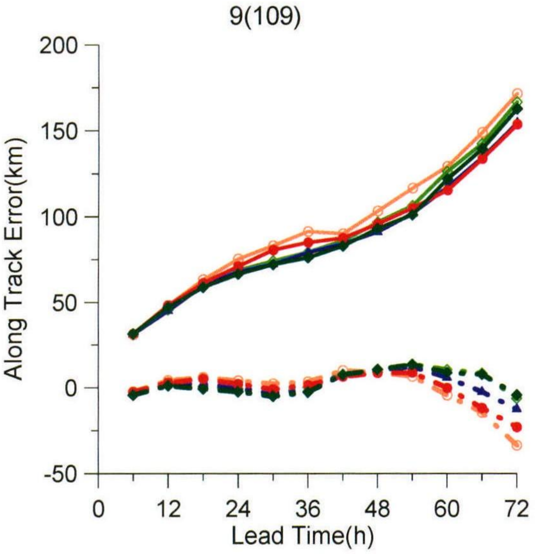

Figure 5. The average magnitudes of along-track errors (solid) and the average along-track errors (dotted) of the total typhoons' 109 track predictions. The explanation of line colors is the same as in figure 1a.

Figure 6 shows the average magnitudes of cross-track errors and the average cross-track errors of each typhoon tracks predicted by the three ensemble schemes and the two non-perturbation members of scheme 1. From the average magnitudes of cross-track errors of total typhoons (Fig.7), it could be found that the overall deviation of typhoon moving direction of scheme 1 is the smallest in the three schemes. On the whole, the deviations of scheme 1 and 2's moving direction are both smaller than the deviations of their control predictions'. The deviation of scheme 3's moving direction is smaller than the deviation of its control predictions' in the late integration and is roughly the same as that of its control predictions' in other integral time. These results are basically the same as each scheme's overall deviation of typhoon moving speed and track average absolute error.

The average magnitudes of cross-track errors of Fig. 6a~6i show that the relative magnitudes of deviations of three schemes' typhoon moving direction vary with the experiment typhoon and they are different from those of three schemes' typhoon moving speed. Even so, it could be found from Fig.6 that for each typhoon, scheme 2 and 3's overall deviations of moving direction are the smallest or largest in the three schemes and scheme 1's is between scheme 2's and scheme 3's, which is the same as the deviation of each scheme's typhoon moving speed and track average absolute error.

The average cross-track error reveals the overall right or left deviation of typhoon moving direction. From Fig.7, it could be found that the three schemes' average cross-track errors are all between 0 and 40 km and scheme 2's is the largest and scheme 3's the smallest, which reveal that for total typhoons, each scheme's moving direction has a right deviation overall and scheme 2's right deviation is the largest and scheme 3's the smallest. From Fig.6a ~6i, it could be found that each scheme's average cross-track error varies with the experiment typhoon and integral time. For 1105, 1111, 1117 and 1119, most of the three schemes' moving directions have a right deviation and for 1101 and 1109, most have a left deviation. For 1102, 1104 and 1108, each scheme's overall deviation of typhoon moving direction varies with the integral time.

In summary, no matter for track average absolute error or for the deviations of typhoon moving speed and moving direction, scheme 1's error and deviation are both the smallest and scheme 1 and 2's predictions are both better than their control predictions. The three schemes' typhoon moving directions mainly skew to the right, and in the late integration their moving speeds mainly tend to be relatively slow. In the three schemes, scheme 2's right deviation and slow deviation are both the largest and scheme 3's are both the smallest.

5.2 *Ensemble dispersion*

An ideal ensemble forecast system needs not only predictions near observations but also appropriate dispersion which is neither too small nor too large and is near prediction error on the whole.

In the following text, M is the prediction times 109 and N is the number of ensemble members 6. The m refers to the m-th prediction and i refers to the i-th member. The mean squared error of ensemble mean (MSE) (Ziehmann[38]) is estimated as

$$\mathrm{MSE}=\frac{1}{M}\sum_{m=1}^{M}S_m^2 \qquad (1)$$

where S_m is the distance between ensemble mean track and observed track. The average ensemble variance (VAR)[38] is estimated as

$$\mathrm{VAR}=\frac{1}{M}\sum_{m=1}^{M}\sigma_m^2 \qquad (2)$$

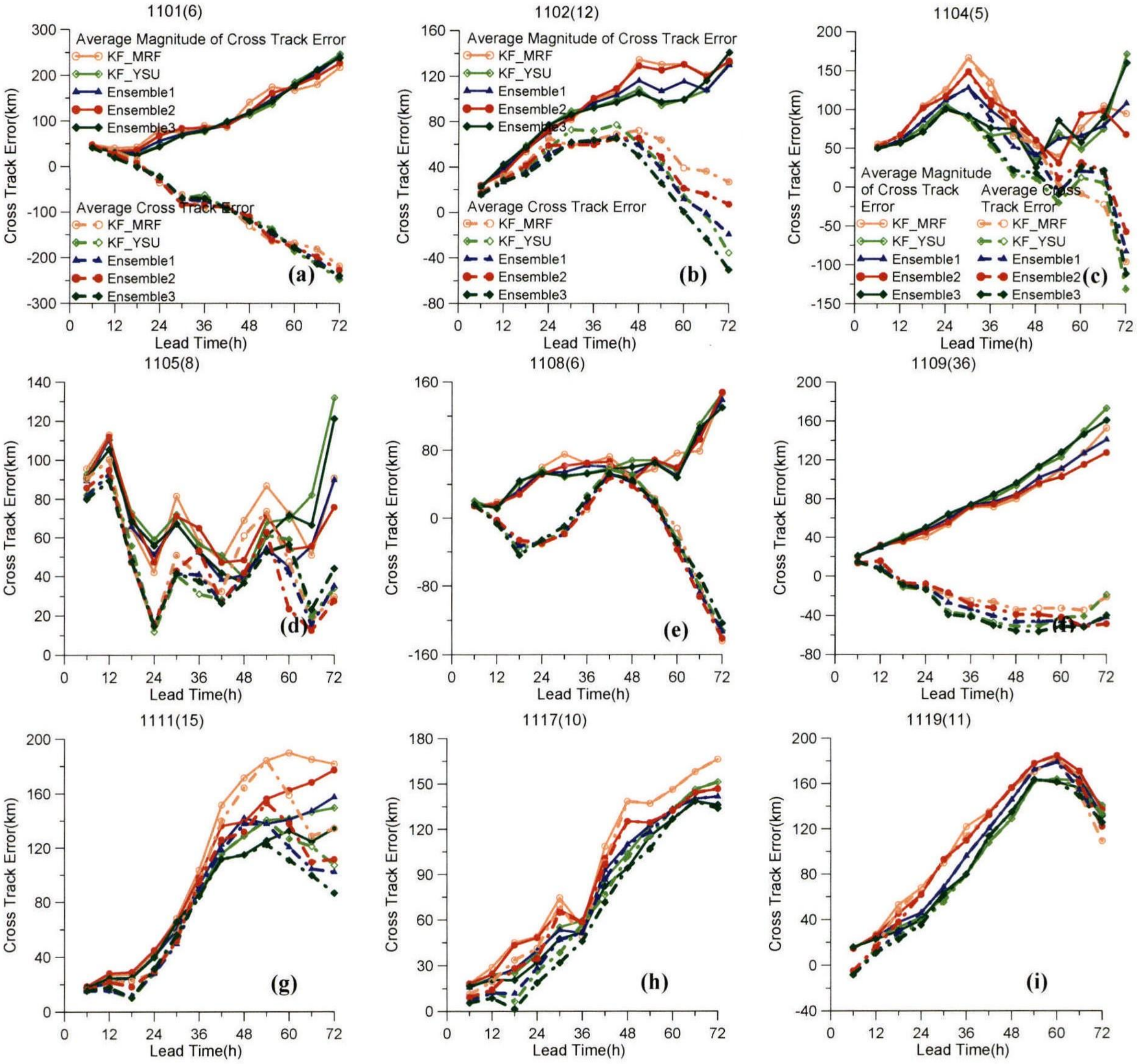

Figure 6. The average magnitudes of cross-track errors (solid) and the average cross-track errors (dotted) of each typhoon tracks (a～i) predicted by the three ensemble schemes and the two non-perturbation members of scheme 1.

In Eq. (2), σ_m^2 is given by Eq. (3).

$$\sigma_m^2=\frac{1}{N}\sum_{i=1}^{N}S_i^2 \tag{3}$$

Here, S_i is the distance between each member track and ensemble mean track. In an ideal ensemble forecast system, the ratio of MSE to VAR is expected to be (Eckel and Mass[39]; Buckingham et al.[40]).

$$\left(\frac{\mathrm{MSE}}{\mathrm{VAR}}\right)_{\mathrm{exp}}\approx 1+\frac{2}{N-1}=\frac{N+1}{N-1} \tag{4}$$

So the expected VAR ($\mathrm{VAR}_{\mathrm{exp}}$) is estimated to be

$$\mathrm{VAR}_{\mathrm{exp}}\approx \mathrm{MSE}\frac{N-1}{N+1} \tag{5}$$

The reason that $\mathrm{VAR}_{\mathrm{exp}}$ is not exactly equal to $\mathrm{MSE}\frac{N-1}{N+1}$ is that MSE comprises both prediction and observation errors. Observation error refers to the error in observed typhoon position. Supposing the error in observed position is 20 km, then the observation variance ($\mathrm{VAR}_{\mathrm{obs}}$) is

$$\mathrm{VAR}_{\mathrm{obs}}=20^2=400 \tag{6}$$

Thus,

$$\mathrm{VAR}_{\mathrm{exp}}=\mathrm{MSE}\frac{N-1}{N+1}-\mathrm{VAR}_{\mathrm{obs}}=\mathrm{MSE}\frac{N-1}{N+1}-400 \tag{7}$$

Obviously, when VAR is equal to $\mathrm{VAR}_{\mathrm{exp}}$, the ensemble dispersion is appropriate and the ensemble has the ensemble consistency. When VAR is smaller (larger) than $\mathrm{VAR}_{\mathrm{exp}}$, the ensemble is underdispersed (overdispersed). Since values of MSE and VAR are very large in the late integration, in order to avoid too large values, the square roots of these quantities $\sqrt{\mathrm{MSE}}$ (RMSE), $\sqrt{\mathrm{VAR}}$ (RVAR) and $\sqrt{\mathrm{VAR}_{\mathrm{exp}}}$ (ERVAR) are calculated. Ensemble consistency is measured by RMSE, RVAR and ERVAR.

Besides above techniques, whether the ensemble dispersion is appropriate could be examined by the percentage of observed track falling closer to or farther from ensemble mean track than all member tracks. For an ensemble forecast system with N members, this percentage is expected to be $\frac{200}{N+1}\%$. The deviation from the expected percentage is termed the missing rate error (MRE) (Buckingham et al.[40]) and is defined as

$$\mathrm{MRE}=100\left|\frac{1}{M}\sum_{m=1}^{M}\begin{Bmatrix}0: S_{\min}\le S_{\mathrm{obs}}\le S_{\max}\\ 1: S_{\mathrm{obs}}<S_{\min}\\ 1: S_{\mathrm{obs}}>S_{\max}\end{Bmatrix}-\frac{2}{N+1}\right| \tag{8}$$

where S_{obs} is the distance between observed track and ensemble mean track and $S_{\min}$ and $S_{\max}$ are the minimum and maximum distances of all member tracks from ensemble mean track. A positive (negative) MRE suggests underdispersion (overdispersion) of ensemble.

In addition, the ensemble consistency could be measured by using the probability within spread (PWS)[38]. Similar to MRE, PWS estimates the likelihood of observed track falling within the dispersion of ensemble. PWS differs from MRE in that it considers the varying distance from ensemble mean track. PWS is defined as

$$\mathrm{PWS}=\frac{1}{M}\sum_{m=1}^{M}\begin{Bmatrix}0: S_{\mathrm{obs}}>k\sigma_m\\ 1: S_{\mathrm{obs}}\le k\sigma_m\end{Bmatrix} \tag{9}$$

where k=1,2,3K, σ_m and S_{obs} are the same as those in Eq.(3) and Eq. (8) respectively. σ reflects the ensemble variance or ensemble dispersion. When $k \ge 2$, the dispersion is enlarged to k times the original and PWS increases with enlarging the dispersion. Corresponding to 1σ, 2σ and 3σ, PWS of an ideal ensemble forecast system is expected to have values near 0.68, 0.95 and 0.99 respectively. If PWS is smaller (larger) than its expected value, the ensemble is underdispersed (overdispersed).

The above three methods are used to determine and compare the three ensemble schemes' ensemble consistency. Fig.8 shows the evolutions of RMSE, RVAR and ERVAR of three schemes' prediction tracks with the integral time. Fig.9 and Fig.10 show the evolutions of MRE and PWS with the integral time respectively.

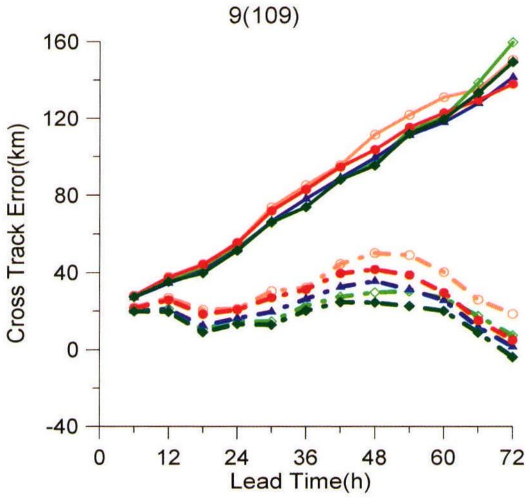

Figure 7. The average magnitudes of cross-track errors (solid) and the average cross-track errors (dotted) of the total typhoons' 109 track predictions. The explanation of line colors is the same as in Fig. 6a.

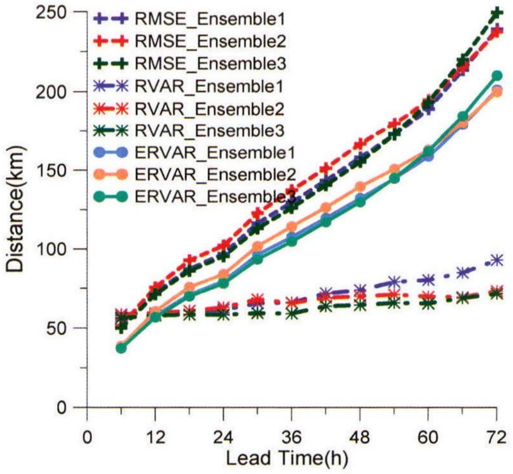

Figure 8. The evolutions of RMSE (dashed), RVAR (dotted) and ERVAR (solid) of the three ensemble schemes' prediction tracks (unit: km) with the integral time.

From Fig.8, it could be found that the three schemes' RMSE, ERVAR, and RVAR all increase with the increasing of the integral time, however RVAR increases very slowly which make it be smaller than ERVAR after 16 h and the difference between RVAR and ERVAR increase constantly. These results indicate that the track dispersions of three schemes are all much smaller than their rational dispersions. In addition, during the entire integral process, scheme 1's RMSE and ERVAR are both the smallest and RVAR the largest in the three schemes, which show scheme 1's track error is the smallest, but its track dispersion is the largest.

Figure 9 shows that the three schemes' MRE are all over the zero line, scheme 1's MRE is the smallest and is much smaller than scheme 2 and 3's, and scheme 2's is near scheme 3's and is smaller than scheme 3's in the late integration. From these results, it could be known that in the three schemes, scheme 1's track dispersion is the largest but is still small on the whole, scheme 2 and 3's are much smaller, and scheme 3's is the smallest.

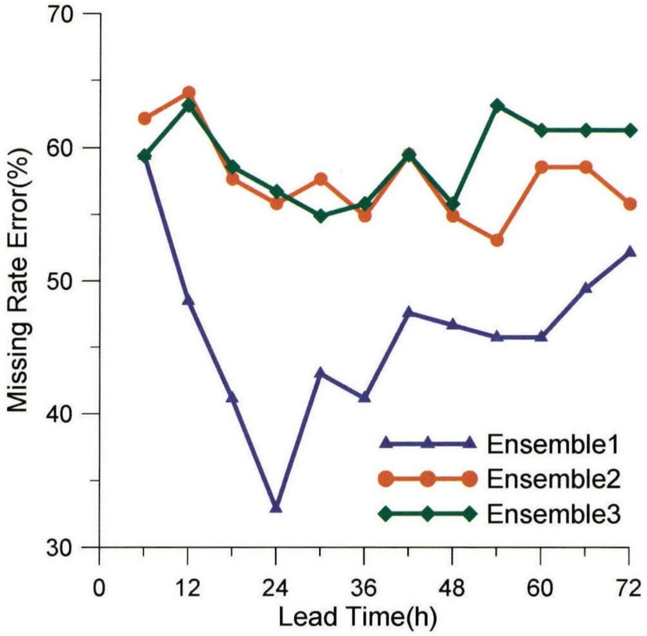

Figure 9. The evolutions of MRE (unit: %) of the three ensemble schemes' prediction tracks with the integral time.

From Fig. 10, it could be found that no matter the dispersion is the original (1σ) or is enlarged to 2 (2σ) and 3 (3σ) times the original, scheme 1's PWS is the largest and scheme 3's the smallest in the three schemes. The difference between different scheme's PWS, especially between scheme 1's and scheme 2 and 3's, is the largest when 3σ and the smallest when 1σ. Comparing each scheme's PWS with its expected value, it could be found that on the whole, the three schemes' PWS are all smaller than their expected values and decrease with increasing the integral time, which make the difference between PWS and its expected value increase constantly. What Fig.10 shows is identical to what Fig.8 and Fig.9 show. Scheme 1's track dispersion is the largest and scheme 3's the smallest in the three schemes, and the track dispersions of three schemes are all much smaller than their rational dispersions.

5.3 *Comparison of predictions with the predictions of each operational NWP model*

In order to understand the three schemes' track prediction effects better, each scheme's predictions are compared with the predictions of each main prediction centre's operational NWP model.

The operational NWP models used for comparison contain four domestic and four overseas models. The four domestic models include the typhoon model of China Meteorological Administration (CMA), Shanghai Typhoon Model (Shanghai), Shanghai GRAPES-TCM model (G-TCM) and Guangzhou Typhoon Model (Guangzhou). The four overseas models include the NWP models of European Centre for Medium-Range Weather Forecasts (ECMWF), United Kingdom Met Office (UKMO) and Japan Meteorological Agency (JMA) and the Typhoon Ensemble Prediction System of Japan Meteorological Agency (J_EPS). The four overseas models and CMA model are all global models and the rest are regional models. ECMWF, UKMO and JMA model are not the models developed only for typhoon.

CMA, Shanghai, G-TCM, JMA and J_EPS model make predictions four times and the rest two times each day. Corresponding to 109 experiments, each model should make predictions 109 or 54 times. However, due to various reasons, some models may not make predic tions at certain time, so each model's prediction time

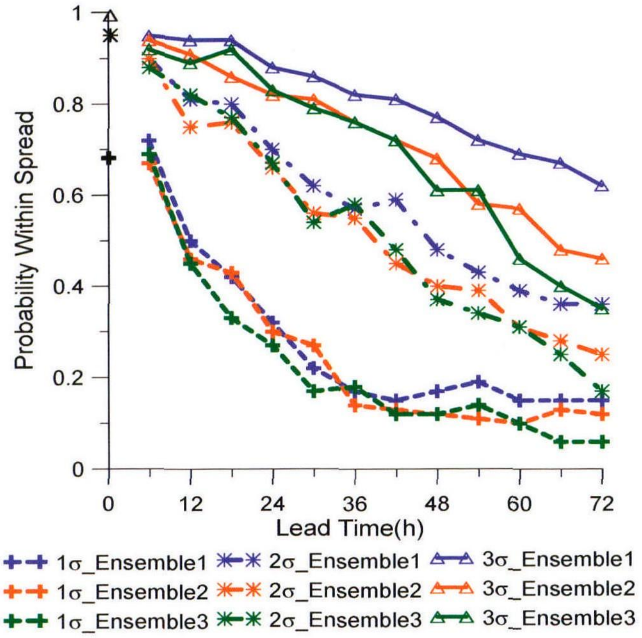

Figure 10. Corresponding to 1σ(dashed), 2σ (dotted) and 3σ (solid), the evolutions of PWS of the three ensemble schemes' prediction tracks with the integral time. The cross, asterisk and triangle on the ordinate are the expected PWS corresponding to 1σ, 2σ and 3σ respectively.

and times may not be exactly same as others'. In order to make the comparison objective and just, the operational models' predictions are compared with the ensemble schemes' for same samples. Based on the comparison, the skill score (R) of ensemble prediction compared with operational model's prediction is calculated by

$$R=\frac{E_{op}-E_{en}}{E_{op}}\times 100\% \qquad (10)$$

where E_{op} and E_{en} are the track average absolute errors of operational and ensemble prediction. It is obvious that the larger R the higher the skill of ensemble prediction. That R is less than zero means that ensemble prediction is inferior to operational prediction.

Scheme 1 has the best track predictions in the three schemes and its skill scores compared with each operational model's predictions are shown in Fig.11. In the total skill scores, negative skill appears four times and the rest are all positive skills. Two of the four negative skills appear at 24 h and their skill scores are -4.5% and -13.8%, and the other two appear at 48 and 72 h respectively and their skill scores reach very low values which are -50% and -35%. In the four negative skills, one is the skill compared with Guangzhou model and the other three all the skills compared with ECMWF model. In the total positive skills, the overall skill scores increase gradually from 24 to 48 and to 72 h, the skill score greater than 20% appears one, three and four times at 24, 48 and 72 h respectively, and the skill score greater than 40% appears two times at 72 h.

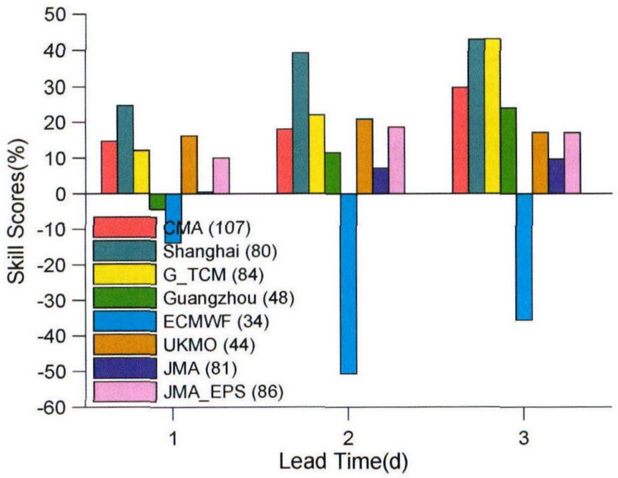

Figure 11. The skill scores of the ensemble scheme 1's track predictions compared with each operational model's predictions. The number in the brackets of legend is the sample number compared.

The above results indicate that scheme 1's track prediction is better than the other seven operational models' except ECMWF model's, and scheme 1 has obvious prediction superiority to CMA, Shanghai and G-TCM model and a little prediction superiority to UKMO and J_EPS model. On the whole, scheme 1 has the value of operational application although it lags behind ECMWF model. It also could be found that ECMWF model's track prediction is much better than other operational models' and overall Guangzhou model's track prediction is the best in the four domestic operational models.

6 SUMMARY AND DISCUSSION

(1) For the predictions of each experiment typhoon, scheme 2 or 3's track average absolute error and overall deviations of typhoon moving speed and moving direction are always the smallest or largest in the three ensemble schemes, and scheme 1's are between scheme 2's and scheme 3's. For the predictions of total experiment typhoons, scheme 1's track average absolute error and overall deviations of typhoon moving speed and moving direction are all the smallest, and scheme 1 has the best track prediction on the whole.

(2) For the predictions of total experiment typhoons, scheme 1 and 2's track average absolute errors and overall deviations of typhoon moving speed and moving direction are both smaller than those of their control predictions, and the ensemble predictions show superiority to their deterministic predictions. Scheme 3's track average absolute error and overall deviation of typhoon moving speed are roughly same as those of its control prediction. Its overall deviation of typhoon moving direction is roughly same as that of its control prediction in the early and middle integration and is smaller than that in the late integration.

(3) The typhoon moving speeds of the three schemes have no obvious fast or slow tendency in the early and middle integration and mainly tend to be relatively slow in the late integration. Scheme 2's slow deviation is the largest and scheme 3's the smallest. The typhoon moving directions of the three schemes mainly skew to the right, and scheme 2's right deviation is the largest and scheme 3's the smallest.

(4) In the three ensemble schemes, scheme 1's track prediction error is the smallest and its track dispersion is the largest. The track dispersion of scheme 1 is much larger than that of scheme 2 and 3. The track dispersion of scheme 2 is near that of scheme 3 which is the smallest. The track dispersions of the three schemes, especially of scheme 2 and 3, are much smaller than their rational dispersions.

(5) The track prediction of scheme 1 is better than that of the other seven operational models except ECMWF model. Scheme 1 has obvious prediction superiority to CMA, Shanghai and G-TCM model and a little prediction superiority to UKMO and J_EPS model. Scheme 1 has the value of operational application.

The above results show that it is practicable and effective to apply the STTP method to the typhoon track ensemble prediction. Scheme 1 and 2's predictions show superiority to the deterministic predictions. The results of scheme 1 prove it has some value of operational application. However, the deficiency of too small dispersion exists in the track ensemble prediction based upon the STTP method, which may be related to the fact that the added stochastic perturbations are too small and the emsemble members are fewer.

In the track ensemble prediction based upon the STTP method, the choice of deterministic prediction member has an important impact on the ensemble prediction. The difference between scheme 2 and 3 is the difference of planetary boundary layer parameterization scheme. On the whole, the ensemble prediction of scheme 2 is better than that of scheme 3 although the deterministic prediction of scheme 2 is not as good as that of scheme 3. Increasing deterministic prediction member can not only increase ensemble dispersion properly, but also get better ensemble prediction effect, just as that of scheme 1.

Of course these conclusions are only for the nine experiment typhoons. More experiments should be made for more typhoons to come to the more universal conclusions. However, through the 109 experiments in this study, the potential of the track ensemble prediction based upon the STTP method has been shown. Experiments for more typhoons will be made in the near future. Through further experiments, we will strive to solve the problem of too small ensemble dispersion. Meanwhile, based upon track ensemble prediction, the experiments of intensity ensemble prediction will also be made.

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