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THE ENSEMBLE FORECASTING OF TROPICAL CYCLONE MOTION I: USING A PRIMITIVE EQUATION BAROTROPIC MODEL

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ABSTRACT: Ensemble forecasting of tropical cyclone (TC) motion was studied using a primitive equation barotropic model by perturbing initial position and structure for 1979 – 1993 TC. The results show that TC initial position perturbation affects its track, but the ensemble mean is close to control forecast. Experiments was also performed by perturbing TC initial parameters which were used to generate TC initial field, and more improvement can be obtained by taking ensemble mean of selective member than selecting members randomly. The skill of 60 % – 70 % of all cases is improved in selective ensemble mean. When the ambient steering current is weak, more improvement can be obtained over the control forecast.

Key words: tropical cyclone motion; ensemble forecast; typhoon numerical forecast

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1 INTRODUCTION

Errors of numerical forecasting comprise those in the initial value, model and computation and the first kind of error becomes more and more outstanding with the on-going development of computers and numerical models. Subject to available observation means, the real atmosphere is anything but approximately measured. Meanwhile, one should pay attention to the possibility, as suggested by Lorenz[1], that any slight differences during the initial state may lead to results that turn out to be totally dissimilar from what would be expected otherwise, as far as definitive non-linear dynamic systems are concerned. It may indicate that any two initial fields, however minute their difference seems at the first place, would allow it to grow at increasing magnitude over the growth of the integration, even to a point when they just show huge contrast. Being a synoptic system over the tropical ocean that is not monitored sufficiently, the tropical cyclone (to be simplified as TC hereafter) has to be estimated in terms of characteristic quantities like location and intensity with errors, and the initial structure embedded into the objective analysis field is only empirically reconstructed, which may differ more greatly from reality. In Niu's opinion[2], errors caused by inaccurate measurement of the initial location and speed of the TC takes up 41% of the total in the 24-hour track forecast, which in some way reflects how important it is for the location error to play in the forecasting. Forecast errors that may result from idealized TC structure are at the farther end of our allowance. For the ensemble forecast technique, it is both an efficient way of addressing the problem of forecast results from the viewpoint of location errors and a path forward for the present numerical prediction.

Epstein[3] and Leith[4] are the first to note that the ensemble forecast is superior over any single forecast techniques in that it yields forecast results by constructing a series of initial fields that somewhat differ from the initial data and yet are able to describe the initial errors and forming individual members for the ensemble in temporal integration. The key is for the

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ensemble members to be sampled for a density distribution of error probability in the initial data and to generate members for the ensemble whenever computational conditions are available to achieve the best possible statistical results.

So far, the successful application of the ensemble forecast in medium- and short- term numerical weather forecast has justified the ideas of Epstein and Leith. The TC ensemble forecast is a new area of interest relative to that for medium-term synoptic ensemble forecast[5-8]. As there has not been a clear concept of perturbations in the tropical atmosphere, the research on the TC ensemble forecast is still in the early stage outside China but to be unfolded in China. In view of the enormous computation required in the ensemble forecast in which experiments have to be run in the dozens for each case, a barotropic model is selected here for its relatively mild demand on computation. Based on possible errors in the initial NWP field for TC, the work will construct ensemble members, conduct ensemble forecast experiments and make preliminary attempts to develop relevant techniques for track forecasting so as to offer basis and reference of some degree for the application of ensemble forecast technique in complicated TC models.

2 BRIEF ACCOUNT OF THE MODEL

For the basic equation of the experimental model, the barotropic primitive equation is used, which adopts the flux form of spherical coordinates. The initial condition is determined from interpolations of the objective analysis field of the ECMWF, apart from introducing an idealized TC model with configurations referring to references [9], i.e. setting the TC geopotential distribution satisfying that

$$\Phi_{(r)} = \Phi_e - \Delta\Phi_0 \exp[-a(\frac{r}{R_b})^2] / \sqrt{1 + b(\frac{r}{R_m})^2} \quad (1)$$

Here, Φ_e is the height of the ambient environmental geopotential, r is the distance from gridpoints to the TC center, $\Delta\Phi_0$ is the difference of geopotential height between Φ_e and the vortex center, R_m is the radius of maximum wind speed of the TC, R_b is the mean radius of TC circulation and both a and b are dimensionless parameters. The gradient wind equilibrium is satisfied in the initial wind field; the lateral boundary of the model is time-dependant with variables on it available by temporal interpolation in the day-to-day ECMWF objective analysis fields; the interval of the gridpoints is 1.25° × 1.25°, the model domain of forecast is 95°E–160°E, 0 – 55°N, the time step is 360 s long, and difference format as put forward by Grimmer et al. [10] for ensuring the conservation of total mass and total energy; the time integration starts with the Eular backward difference but changes to the central difference format for the remainder.

3 CONTROLS AND RESULTS

The daily objective analysis data for 1200 UTC from 1979 to 1993 and optimum TC track data presented in the *Yearly Books on Typhoons* are used to make 576 72-hr track forecasts (called controls hereafter) with respect to 230 TCs during the time, following the above methods for generating initial fields. The forecast errors are listed in Tab.1. Integration stops whenever the TC circulation is too weak to be fairly resolvable, resulting in different times of forecasting for different periods of forecast. In the table, R is the skill score of forecast results in contrast to that for the CLIPER technique and has the following algorithm of

$$R = \frac{E_{\mathrm{CLIPER}} - E_{\mathrm{control}}}{E_{\mathrm{control}}} \times 100\% \quad (2)$$

where E_{control} and E_{CLIPER} are distance errors respectively for the controls and the CLIPER in relation to optimized TC locating. It is known from the table that the 12- to 72- hr forecasts are positive skills relative to the CLIPER, suggesting that the use of the barotropic model is capable of forecasting TC track with some degree of assurance. Numerical predictions of TC track are expected to improve, for the barotropic model is based on the current work.

Tab.1 Mean distance errors in the forecasts of the controls and skills relative to the CLIPER

forecast duration	12 h	24 h	48 h	72 h
forecasts / times	729	729	673	576
Mean errors / km	48.9	117.3	325.8	615.7
Skills / %	34.3	26.9	16.1	10.7

4 SENSITIVITY EXPERIMENTS ON TC STRUCTURE EIGENVECTORS' ERRORS

From Eq.(1), we know that an ideal TC model for the control depends on R_m, R_b and V_m (they all govern the size of Δf_0), as well as the location of the TC center. The quantities are with errors in actual estimation. The structure of TC does have some effect on the motion, as shown in many research results reported since the 1980's. An example of this is Chan et al.[11] who use the barotropic vorticity equation model to study the TC motion free of any ambient airflows in relation to R_m, R_b and V_m.

To investigate the effect of the errors of the characteristic quantities of TC structure in the observed ambient field on the track, the following sensitivity experiments have been designed (Tab.2). Specifically, the quantities (R_m, R_b and V_m) are added or subtracted with corresponding error values to form initial fields and comparisons between their integration results and those of the controls are presented in Tab.2. It shows that the initial field perturbation affects the motion with varying degree, for example, an error of 5 m/s in the maximum wind speed of TC can cause a mean error of 14 – 22 km in 48-hr track forecast, with the maximum error of 379 km, and even 503 km for the maximum error in 72-hr track forecast. It is due to the fact that TC motion is resulted from the interactions between inner and outer factors so that even the same initial perturbation can have location deviations different from case to case. Similar results are also observed in the maximum wind speed radius and mean TC radius. The characteristic quantities for constructing TC models are indefinite in operational observation. It is shown in the above sensitivity experiments that the indefinite nature of the quantities can affect the results of the forecasts. It is by attempting to add perturbations to these quantities that the ensemble forecast technique generates a large number of samples to improve the forecast accuracy.

Tab.2 Forecast TC location in the sensitivity experiments relative to the controls

perturbation quantity	perturbation value	forecast times	48 h mean dis. dev./ km	48 h max. dis. dev. / km	72 h mean dis. dev./ km	72 h max. dis dev. / km
ΔV_m	+5 m/s	167	22.3	379.7	46.1	503.4
	-5 m/s	165	14.8	81.4	42.8	429.2
ΔR_m	+50 km	166	107.5	404.9	255.4	882.2
	-50 km	128	88.3	278.2	220.7	800.9
ΔR_b	+150 km	166	57.1	312.1	145.3	653.0
	-150 km	139	82.1	339.5	209.6	1060.7

5 ENSEMBLE FORECAST EXPERIMENTS WITH DIFFERENT PERTURBATION TECHNIQUES

Subject to observational means, the initial structure of TC may not be precisely determined and can have substantial influence on the track forecast, which has been confirmed in previous analysis. The current section will give separate discussions of location errors of perturbation TC in the barotropic model and ensemble with characteristic TC parameters.

5.1 *Initial location perturbations*

In the design of initial location perturbation of TC, the longitudinal and latitudinal positions relative to the initial location are randomly given with the maximum not exceeding 70 km. The randomizing technique is used chiefly because of the concern that operational location of TC has randomized errors. Fifty-four perturbations for TC location are generated for each of the cases, which are presented in Fig.1. It is assumed that the 54 members are sampled to determine the probability distribution of the perturbations for ensemble member formation. The members are then respectively integrated to conduct ensemble mean for ensemble forecast of the TC track. As shown in relevant analysis (results not given), the location perturbation can be large enough to cause forecast errors in the hundreds of kilometer in the 72-hr location forecast; the mean errors of 12 – 72 hr location forecasts are comparable for ensemble mean and controls, no less than 5 km. In other words, ensemble forecast skill is close to that of the controls for initial perturbation location, indicating that the perturbation technique is incapable of improving the accuracy of track forecasting, which agrees with the conclusion of Cheung[6].

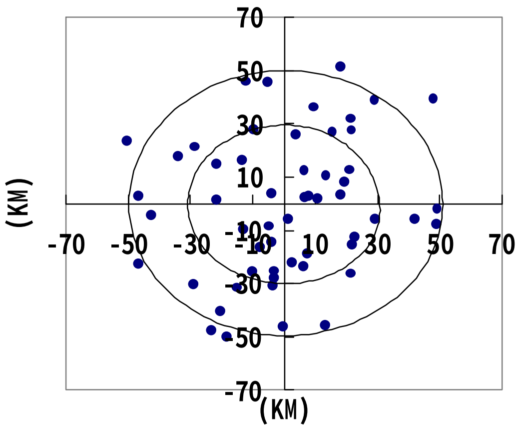

Fig.1 Perturbation relative to optimized TC location.

5.2 *Initial perturbations of TC structure*

The alteration of TC circulation distribution by the perturbations of R_m, R_b and V_m is symmetric while a real TC is asymmetrically structured, as shown in much research. The latter affects the track of TC to the extent that should not be overlooked. Using a barotorpic vorticity equation that includes divergence, Li et al.[12] have derived a diagnostic equation for the motion of TC by incorporating asymmetric Rankie vortexes and assuming that the TC moves in the direction that has the maximum changes in vorticity and have claimed that asymmetric TC structures are one of the causes for abrupt changes in TC motion. Following the diagnostic equation, asymmetric TC structures are introduced when the TC model is being constructed and the initial symmetric vortex in the control is modified to a wave-asymmetric one, i.e. the initial R_m and R_b are taken as the function of the azimuth angle θ, indicating the asymmetry between the inner and outer sections of the TC.

$$R_b(q) = R_{b0}[1 + b_0 \cos(q - q_0)] \tag{3}$$

$$R_m(q) = R_{m0}[1 + b_1 \cos(q - q_1)] \tag{4}$$

where b_0 and b_1 are the intensity of asymmetry and q_0 and q_1 are azimuth angles, respectively.

Assuming that the errors of the characteristic quantities of the TC structure occur randomly, members for the ensemble can be formed by simultaneously adding a randomized perturbation to V_m, R_m, R_b, b_0, q_0, b_1 and q_1 and to the initial values like the effective radius R_E superposed by the ambient field and typhoon vortex. Taking reference to [12], the maximum intensity of the inner and outer sectors of the TC is less than 0.2, with the perturbation radii, V_m less than 5 m/s, R_m less than 50 km, R_b and R_E both less than 150 km. The perturbation technique is to make the perturbation of ensemble members reflective of the indefinite nature of the initial TC structure to the highest extent possible and sample them for all possible errors for this stage. Following the technique, a total of 434 ensemble forecast experiments have been done for the years 1979 – 1993, in which fifty-four members have been generated for each case.

Ensemble mean is applied to the forecasts of the 54 ensemble forecast members and the skill level *R* relative to the controls are computed as in

$$R = \frac{E_{\text{control}} - E_{\text{ensemble}}}{E_{\text{control}}} \times 100\% \tag{5}$$

where E_{ensemble} and E_{control} are the errors of forecast locations respectively for the TC ensemble mean forecasts and controls.

Tab.3 gives the skill levels of the ensemble mean forecasts relative to the controls in terms of mean distance errors. It shows that it is of negative skill in the 42-hr and 48-hr forecasts as compared to the controls, but the former is slightly better than the latter. Specifically, cases in which the former approach is of positive skill comparing to the latter have taken up 55% – 60% and mean errors have reduced by 23.0 km in the 72-hr forecast.

Tab.3 Mean location errors of the ensemble mean forecasts and skill levels relative to the controls (%)

time duration / h	12	18	24	30	36	42	48	60	72
R / %	3.4	1.6	1.0	1.2	1.2	-2.0	-1.4	1.0	3.7
E_{ensemble} / km	43.3	77.6	112.8	156.1	201.3	263.5	313.3	440.6	568.8
positive skill percentage / %	60.7	58.5	53.5	56.9	53.2	57.7	55.2	59.5	63.6
$E_{\text{ensemble}} - E_{\text{ontrol}}$ / km	1.5	1.2	1.0	2.0	2.4	-5.1	-4.8	4.7	23.0

During the study, it is found that the forecast by some ensemble members is deviated obviously from the total forecast and with much larger errors. In other words, the members in question are playing a negative role in the ensemble mean and need to be eliminated. For the purpose, members that are the closest to the ensemble mean, such as 12, 18, 24, 30, etc, are selected to run ensemble mean again, also known as the quadratic ensemble mean, and the results are presented in Tab.4.

Tab.4 Skill levels of quadratic ensemble mean compared to the controls

number of members	12	18	24	30	36	42	48	TC-EOF
12 h	0.4	0.5	0.5	1.6	2.1	2.9	3.6 (73 %)	-0.1
18 h	0.2	0.3	0.3	0.6	0.9	1.5	1.7 (70 %)	-2.5
24 h	0.2	0.3	0.3	0.3	0.4	0.8	1.2 (64 %)	-0.5
30 h	0.2	0.5	0.5	0.5	0.3	1.0	1.7 (63 %)	0.2
36 h	-0.1	0.3	0.3	0.3	0.2	0.7	1.4 (58 %)	0.8
42 h	0.2	0.7	0.7	0.7	0.8	1.1	1.2 (60 %)	0.8
48 h	0.6	0.8	0.8	0.8	0.8	1.1	1.2 (58 %)	2.2
60 h	1.6	1.7	1.7	1.5	1.6	1.9	2.1 (60 %)	2.9
72 h	2.0	2.0	2.0	2.0	2.1	2.2	2.8 (60 %)	2.8

Note: The percentage in the "48" column is that of the TC cases with positive skill in the particular ensemble forecast in the total forecast cases.

It is known from Tab.4 that the skill levels tend to increase with the number of ensemble members. It is also known from a comparison with Tab.3 that the skill turns from negative to positive over the 42 – 48 hr periods and the TC cases with positive skills increase the percentage in the total number of forecasts to 60% – 70%, i.e. the forecast is better in most of the cases than that in the control.

Additionally, the selective ensemble technique proposed by Zhang et al.[7] is also used in trial. The methods allows for an ensemble mean for 12-hr forecast TC location and ensemble members that are the closest to observed TC location. The result shows that the ensemble forecast shows great improvement over the control in the first 30 hours. After it, the skill score is dramatically reduced as compared to the control and even turns to negative after 42 hours. It shows that the number of ensemble members affects the result of the ensemble forecast and different ensemble techniques yield different forecast results, indicating that it really counts with regard to the method for conducting the ensemble forecast.

5.3 *EOF perturbations of tropical cyclones*

As shown in the analysis above, the perturbation approach needs quite a number of ensemble members. Dividing initial errors into fast-growing and non-growing types, Toth and Kalnay[13, 14] find that errors growing fast during the model integration rapidly make the forecast deviate from real atmospheric conditions and their estimation and construction of ensemble perturbation based on them will not only reduce the size of the sample but also increase the accuracy of the forecast and prolong efficient length of it. In this work, the EOF technique suggested by Zhang and Krishnamurth[7, 8] is used only in TC area to determine the fast-growing mode as the initial perturbation of TC structure.

The computation is conducted in the following steps: (1) The initial structure perturbation technique for TC is used to generate the initial field of perturbation experiment; (2) the perturbation experiment and the control are integrated for 72 hours to give 3-hourly output of forecast wind fields 0 – 7 latitudes from the TC center (u and v fields); (3) the difference is sought between two experimental forecast wind fields to have the time series of the forecast difference fields for the u and v circulation within the TC range; (4) the eigenvectors are EOF-expanded and the characteristic vectors fast-growing with time are chosen from the primary components and taken as the fastest-growing modes; it is found in the computation that the time coefficient of the EOF-1 is generally increasing with time at a fast pace, which can then be viewed as the fastest-growing mode; (5) the mode is added to or subtracted from the initial field, which is then used as the initial TC field for the ensemble members. Given various perturbation values of the initial TC structure and repetition of the aforementioned processes, eight EOF computations have been done to form 16 members of the ensemble forecast, following the same technique as used in Zhang and Krishnamurti. Then, ensemble mean is conducted, with the level of skill listed in the column of TC-EOF in Tab.4. Comparisons have shown that using the method, the 36 – 72 hour forecasts have comparable levels with the quadratic ensemble mean for all of the 48 members, though the former is a little poorer than the latter concerning forecasts within 36 hours. Anyhow, the technique has less load of computation as it employs much fewer ensemble members over 36-hr – 72-hr periods.

6 EFFECTS OF THE AMBIENT FIELDS

For the tropical cyclone, the structure itself varies when it comes to its effect on the motion under different ambient conditions. To investigate the result of ensemble mean forecasting given different ambient steering air currents, the steering current is divided into three types based on the intensity of the initial ambient steering flow (the flow speed being less than 2 m/s, 2 – 4 m/s and larger than 4 m/s, respectively), in which the ambient steering flow is determined by the ambient wind speed within 3 – 7 latitudes from the TC center after the TC circulation is filtered for the ambient component. The number of cases in various types is 113, 220 and 101, respectively. Fig.2 gives the result of categorization of the forecasts with the quadratic ensemble of the 48 members by the intensity of the steering current. It shows that the ambient flows are relatively weak over the periods 24 – 72 hours, associating with relatively high levels of skill in the forecast of TC location. The trend is more obvious with the increase of forecast duration. With a weak ambient environment, the skill of TC location forecast is lower than with a strong one, for the 24-hr period.

Likewise, the same technique is used to run a statistical study of the forecasts with TC-EOF by the intensity of ambient steering airflows and the result is presented in Fig.3. It is concluded from it that with a weak ambient steering current, the ensemble forecast has a higher skill than with a strong one.

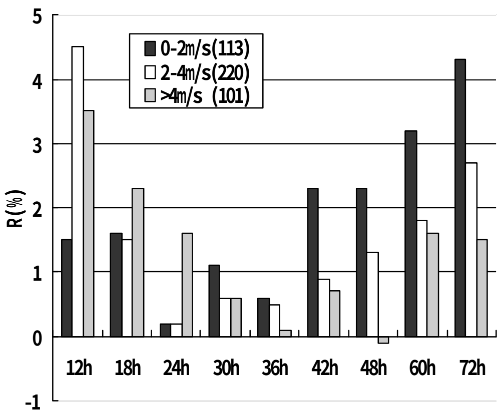

Fig.2 Skill of the quadratic ensemble mean forecast relative to the control, under ambient steering current of varying intensity.

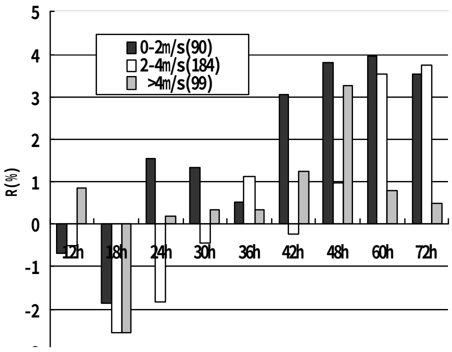

Fig.3 Same as Fig.2 but for the TC-EOF technique versus the control.

7 RESULTS AND DISCUSSIONS

a. The initial location of TC can have some effect on the track forecast. The reduction of mean errors is not significant for an ensemble mean forecast employing only the perturbation method for initial location.

b. Based on errors possibly existing in the initial structure of TC, the initial TC structure is perturbed to generate ensemble members. The location forecast is better with the quadratic ensemble mean (specially in weak ambient steering current) than with a single control experiment. The ambient conditions of TC affect the result of ensemble forecasts using the perturbation technique.

c. The ways in which the ensemble is carried out in ensemble forecasting is very important as difference in the technique leads to difference in the forecast result. The number of ensemble members also affects it.

The ensemble forecast technique for TC track has been discussed and the results are tentative only. As we know, the TC motion is resulted from interactions between the vortex and the ambient flows. The errors of the initial structure do not singly lead to deviation of TC track form observation, which may be one of the reasons for less satisfactory ensemble forecasts in this work. It is therefore quite important to take into account collectively the initial ambient field and initial structure of TC, which needs more in-depth study.

Of course, the implication of the ensemble forecast lies beyond the provision of ensemble mean forecasting. Various possible tracks can be roughly demonstrated and indefinite degree of the control forecast estimated from the forecasts of a number of ensemble members. As the degree of discrete of the forecast track reflects to some extent the reliability of the forecast, the relationship between the divergence of the ensemble members and the forecast skill is also our next subject of interest.

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REFERENCES:

[1] LORENZ E N. Deterministic nonperiodic flow [J]. *Journal of Atmospheric Sciences*, 1963, **20**: 130-141.

[2] NIU Xue-xin, Dynamics of Tropical Cyclones [M]. Beijing: Meteorological Press, 1992. 147-148.

[3] EPSTEIN E S. Stochastic dynamic prediction [J]. *Tellus*, 1969, **21**: 739-759.

[4] LEITH C E. Theoretical skill of Monte Carlo forecasts [J]. *Monthly Weather Review*, 1974, **102**: 409-418.

[5] CHEUNG K K W, CHAN J C L. Ensemble forecasting of tropic cyclone motion using a barotropic model. Part I: perturbation of the environment [J]. *Monthly Weather Review*, 1999a, **127**: 1229-1243.

[6] CHEUNG K K W, CHAN J C L. Ensemble forecasting of tropic cyclone motion using a barotropic model. Part II: perturbation of the vortex [J]. *Monthly Weather Review*, 1999b, **127**: 2617-2640.

[7] ZHANG Z, KRISHNAMURTI T N. Ensemble forecasting of hurricane tracks [J]. *Bulletin of American Meteorological Society*, 1997, **78**: 2785-2795.

[8] ZHANG Z, KRISHNAMURTI T N. A perturbation method for hurricane ensemble predictions [J]. *Monthly Weather Review*, 1999, **127**: 447- 469.

[9] WANG Yu-qing, ZHU Yong-ti. Analysis of mechanisms for twin tropical cyclones and numerical study II: Numerical simulation [J]. *Chinese Journal of Atmospheric Sciences*, 1992, **16**: 659-668.

[10] GRIMMER, SHAW. Energy-preserving integration of primitive equation on sphere [J]. *Quarterly Journal of Royal Meteorological Society*, 1967, **93**: 337-349.

[11] CHAN J C L, WILLIAMS R T. Analytical and numerical studies of the beta-effect in tropical cyclone motion. Part I: zero mean flow [J]. *Journal of Atmospheric Sciences*, 1987, **44**: 1257-1265.

[12] LI Tian-ming, ZHU Yong-ti. Analysis and simulation of tropical cyclone motion —I: asymmetric structure and abrupt changes of track [J]. *Scientia Sinica* (*Series B*), 1990, **1**: 104-112.

[13] TOTH Z, KALNAY E. Ensemble forecasting at NMC: the generation of perturbation [J]. *Bulletin of American Meteorological Society*, 1993, **74**: 2317-2330.

[14] TOTH Z, KALNAY E. Ensemble forecasting at NCEP and the breeding method [J]. *Monthly Weather Review*, 1997, **125**: 3297-3319.