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Ensemble Forecasting of Tropical Cyclone Motion Using a Baroclinic Model

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ABSTRACT

The purpose of this study is to investigate the effectiveness of two different ensemble forecasting (EF) techniques–the lagged-averaged forecast (LAF) and the breeding of growing modes (BGM). In the BGM experiments, the vortex and the environment are perturbed separately (named BGMV and BGME). Tropical cyclone (TC) motions in two difficult situations are studied: a large vortex interacting with its environment, and an apparent binary interaction. The former is Typhoon Yancy and the latter involves Typhoon Ed and super Typhoon Flo, all occurring during the Tropical Cyclone Motion Experiment TCM-90. The model used is the baroclinic model of the University of New South Wales. The lateral boundary tendencies are computed from atmospheric analysis data. Only the relative skill of the ensemble forecast mean over the control run is used to evaluate the effectiveness of the EF methods, although the EF technique is also used to quantify forecast uncertainty in some studies. In the case of Yancy, the ensemble mean forecasts of each of the three methodologies are better than that of the control, with LAF being the best. The mean track of the LAF is close to the best track, and it predicts landfall over Taiwan. The improvements in LAF and the full BGM where both the environment and vortex are perturbed suggest the importance of combining the perturbation of the vortex and environment when the interaction between the two is appreciable. In the binary interaction case of Ed and Flo, the forecasts of Ed appear to be insensitive to perturbations of the environment and/or the vortex, which apparently results from erroneous forecasts by the model of the interaction between the subtropical ridge and Ed, as well as from the interaction between the two typhoons, thus reducing the effectiveness of the EF technique. This conclusion is reached through sensitivity experiments on the domain of the model and by adding or eliminating certain features in the model atmosphere. Nevertheless, the forecast tracks in some of the cases are improved over that of the control. On the other hand, the EF technique has little impact on the forecasts of Flo because the control forecast is already very close to the best track. The study provides a basis for the future development of the EF technique. The limitations of this study are also addressed. For example, the above results are based on a small sample, and the study is actually a simulation, which is different than operational forecasting. Further tests of these EF techniques are proposed.

Key words: ensemble forecasting, tropical cyclone motion

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1. Introduction

As pointed out by Chan (2002), the application of the concept of ensemble forecasting (EF) to the problem of tropical cyclone (TC) motion and intensity predictions is still in its infancy and more research is necessary to establish the viability of the EF technique as an alternative to the traditional deterministic solution in such predictions. Despite such a necessity, only a few groups have carried out studies in this area, beginning with the work of Aberson et al. (1995, 1998). They perturbed the initial conditions using the bred perturbations generated from the global model of the U.S. National Centers for Environmental Prediction. However, only slight improvements in track forecasts were obtained. Zhang and Krishnamurti (1997, 1999) and Mackey and Krishnamurti (2001) subjected the differences in forecasts between the control and per-

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turbed model runs to a complex empirical orthogonal function (EOF) analysis and identified those EOF coefficients with the most rapid growth as the fast-growing modes. These results were then used to perturb the initial conditions of the environmental flow. In these studies, not only were improvements made in track predictions, but the TC structures were also found to be quite reasonable.

Cheung and Chan (1999a, b; hereafter CCa and CCb respectively) applied three EF techniques–the Monte Carlo method, the lagged-averaged forecast (LAF), and the breeding of growing modes (BGM)–to predict TC motion with a barotropic model. Their results showed that over 40% of the forecasts can be improved using the BGM technique by applying perturbations to the environmental flow. Similar improvements were obtained (more than one-third) from the LAF. However, the simplified dynamics of a barotropic model can limit the skill. Therefore, Cheung (2001) used the Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model version 5 (MM5) to evaluate the skill further using random as well as regional BGM perturbations. He pointed out that the skill of this ensemble mean track prediction using the Monte Carlo techniques is almost always lower than that of the control forecast in the cases considered, while the ensemble of regional BGM perturbations did outperform the control forecast after 36 h.

Recently, Puri et al. (2001) studied the utility of the ensemble prediction system of the European Centre for Medium-Range Weather Forecasts in TC prediction by generating the initial perturbations using targeted diabatic singular vectors. They found that the spread in the tracks is highly sensitive to the background state used to derive the singular vectors.

It is obvious from this brief review that only a few studies have been conducted in applying the EF technique to TC predictions. A fundamental issue in all these studies is the method used to generate the initial perturbations. Although the BGM technique has been tested by Cheung (2001), its effectiveness remains to be ascertained, especially when compared with other dynamic techniques such as the LAF. Further, as CCa and CCb have found, in the problem of TC prediction, perturbing the environment and the vortex can yield different results. Since their conclusion is based on a barotropic model, it is essential to investigate the extent to which this statement is true in baroclinic models.

The objective of this paper is therefore to compare the effectiveness of the LAF and BGM in the ensemble forecasting of TC motion using a baroclinic model. In the BGM experiments, the vortex and the environment are perturbed separately (named BGMV and BGME). The focus is on two types of TC motion that led to large forecast errors during the Tropical Cyclone Motion (TCM-30) experiment (Elsberry, 1990): a "stepping motion" that apparently involved the interaction between the environment (including terrain influences) and a large vortex–the case of Typhoon Yancy, and an apparent binary interaction between Typhoon Ed and super Typhoon Flo (CCa, CCb, Joint Typhoon Warning Center, 1990). The aim is to determine whether the EF technique can be effective in such difficult forecast scenarios.

Section 2 gives a brief description of the baroclinic model of the University of New South Wales (Leslie et al., 1985) employed in this study, as well as the data and initial conditions used. How the LAF and BGM perturbation methodologies are applied in the study is explained in section 3. The ensemble forecast results for Yancy are presented in section 4. Section 5 is about the binary typhoon Ed and Flo. Section 6 gives a summary of the results and possible future work.

2. Model and data

2.1 *The model*

The University of New South Wales model (Leslie et al., 1985) is a hydrostatic primitive equation model and has been used in real-time forecasting for a number of years (Leslie and Pureser, 1995; Leslie and Speer, 1998). The integration is carried out on a staggered Arakawa C-grid employing the semi-implicit time differencing scheme. The horizontal grid spacing is 30 km with 24 internal vertical sigma levels σ (0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.89, 0.93, 0.95, 0.975, 0.98, 0.99, 0.995, 0.999), which are proportional to pressure normalized by surface pressure, covering a domain from 5° to 45°N and 90° to 170°E.

The modified Kuo (Kuo, 1965) and Kain-Fritsch (Kain and Fritsch, 1993) cumulus parameterization schemes are used in the present study. The main physical processes in the model include large-scale precipitation, a stability-dependent boundary layer with eddy diffusivities being a function of the bulk Richardson number, vertical diffusion above the boundary layer based on the mixing-length hypothesis, and a surface heat budget prognostic equation for surface temperature. Lateral boundary conditions are updated from the analysis data every 6 h. For more details, the reader is referred to Leslie and Pureser (1995).

2.2 *Data and initial conditions*

The initial fields are taken from the TCM-90 dataset (Rogers et al., 1993), which are on a 0.5° latitude-square grid with a vertical resolution of 50 hPa up to 100 hPa. Cubic-spline interpolation is used to interpolate from the pressure surfaces of the TCM-

90 dataset to the sigma surfaces of the model. Forecast time is up to 72 h.

A bogussing procedure is used in some of the experiments (see sections 4 and 5). When this procedure is carried out, the vortex in the analysis is first filtered using the vortex specification technique of Kurihara et al. (1995). A bogus vortex is then inserted into the filtered analysis, which consists of an axisymmetric vortex used in the bogussing scheme of the Typhoon Model (TYM) of the Japan Meteorological Agency and an asymmetric flow in the form of a persistence vector added at the best-track position. Details of the TYM bogussing scheme can be found in Iwasaki et al. (1987).

3. Perturbation methodologies

Process: The perturbation methods in this study include LAF and regional BGM. The LAF perturbations are generated from the differences between the short-range forecasts. A maximum lag period of 24 h is used with two successive lagged integrations being 6 h apart (as in CCa and CCb). No vortex-environment flow separation is applied and the vortex circulation is treated as part of the large-scale flow, as in Cheung (2001). As a result, the LAF technique has the disadvantage that much larger “perturbations” may occur owing to the larger differences between lagged forecasts, thus the LAF may be less skillful. To solve this problem partly, Ebisuzaki and Kalnay (1991) suggested the scaling back of the larger perturbation to a reasonable amplitude. The perturbations in LAF are scaled down with a uniform factor of 0.3 in this study. Only the differences of the temperature and wind components between two short-range forecasts are added to or subtracted from the initial analysis field. Six pairs of ensemble members can be generated by this method.

The BGM perturbation scheme is similar to that in CCa and CCb. The breeding cycle begins at 24 h before the initial time. Random perturbations are added to (for a positively perturbed field) or subtracted from (for a negatively perturbed field) the analysis. The model is then integrated for 6 h from both the positively and negatively perturbed fields. The differences between these two forecasts are added to or subtracted from the following 6 h analysis after rescaling uniformly by defining the maximum value of the differences to the same value at every sigma level. The process is repeated forward every 6 h until the initial time. After 18 h of breeding, the growth of the perturbation becomes saturated in the root-mean-square sense (not shown). This demonstrates that a 24-h breeding period is reasonable.

When employing the BGM technique, the strategy of separating the TC vortex and its environment is applied. In the experiments in which only the environment is perturbed (BGME), the 6-h predicted vortices are filtered out from the forecast fields. Differences at each level between the filtered predictions are then used, after rescaling, as perturbations in the next breeding cycle.

In perturbing the vortex (BGMV), the vortex area between σ=0.85 and σ=0.3 is perturbed by the differences between the two forecast vortices during the breeding cycles. The breeding perturbations of the

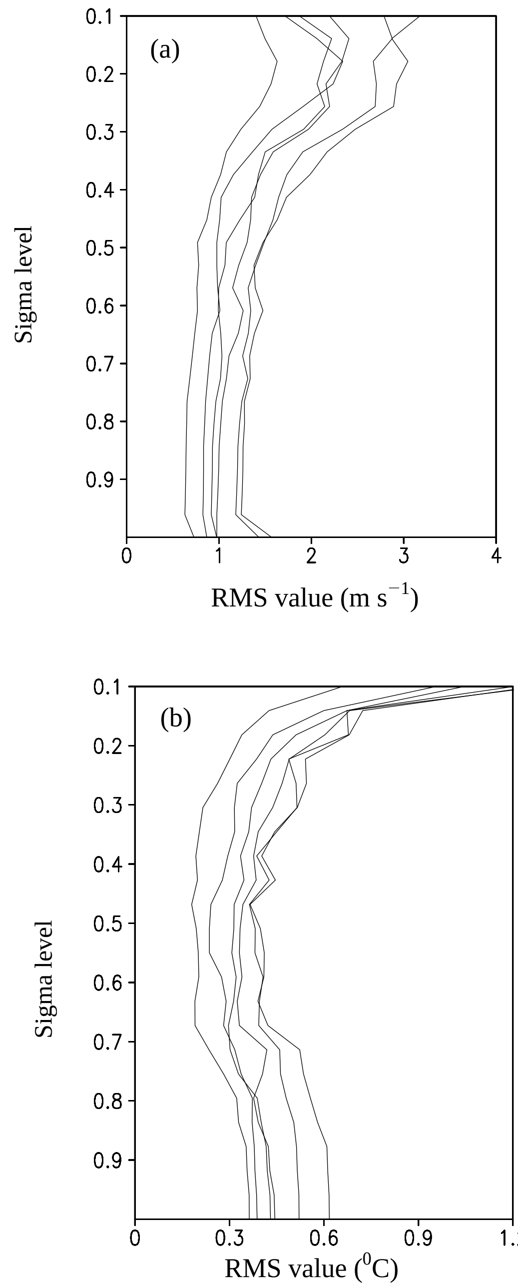

Fig. 1. Vertical variations of the RMS value of the six pairs of LAF perturbations for (a) zonal wind and (b) temperature in the case of Yancy (Y1700).

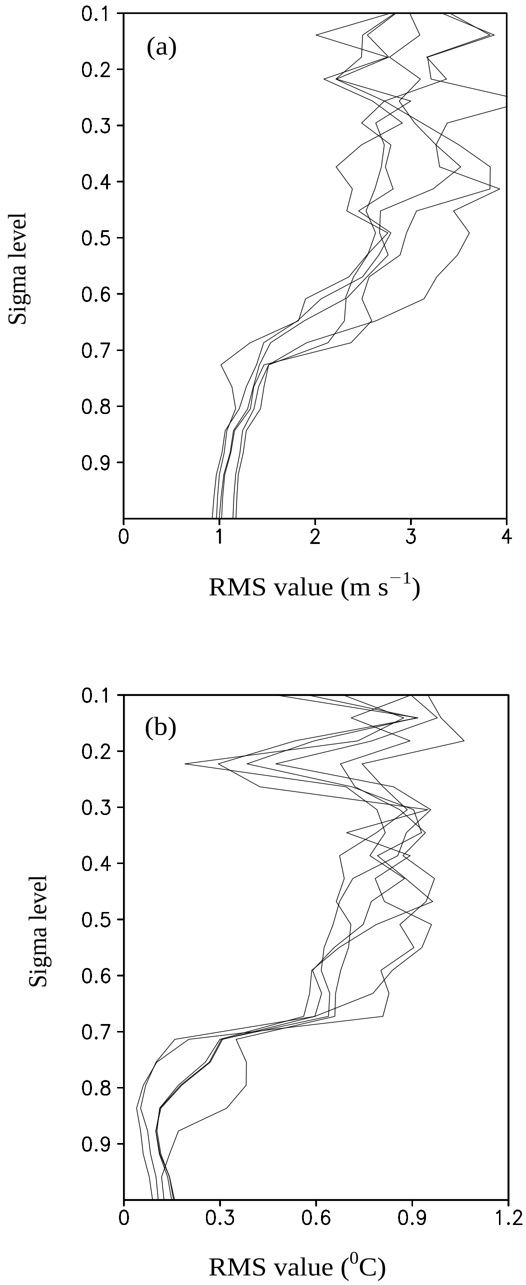

Fig. 2. As in Fig. 1, except for the BGME.

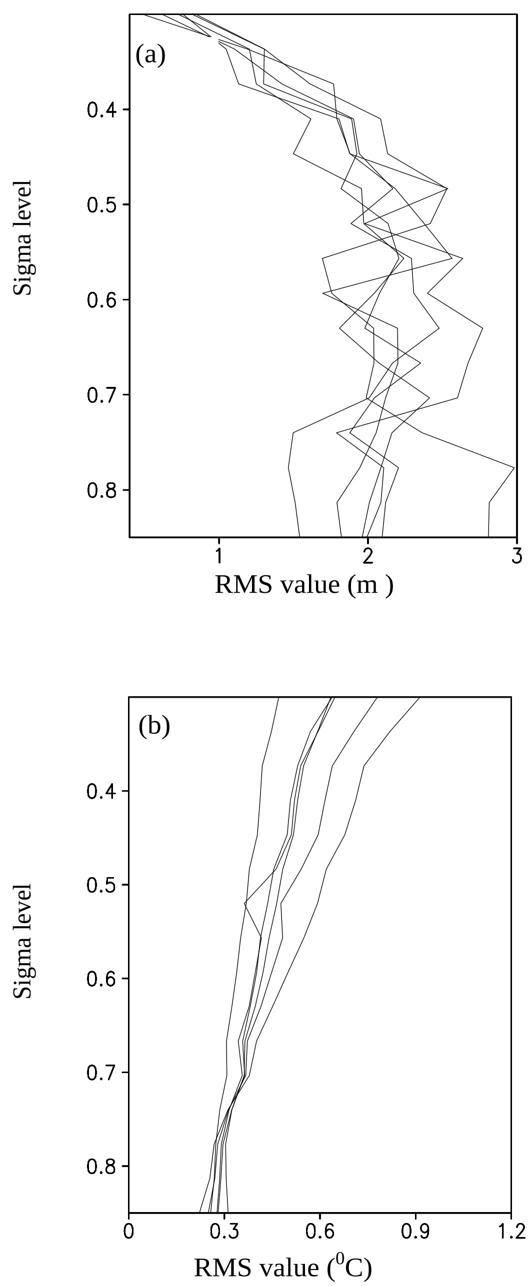

Fig. 3. As in Fig. 1, except for BGMV.

vortex in the breeding cycles are expected to represent the growing errors in the empirical vortex. The perturbed vortex domain in BGMV is determined by the maximum relative vorticity in 24 radial directions from the vortex center in the Kurihara et al. (1995) vortex specification technique.

Amplitude: Ideally, the perturbations should represent the errors in the analysis. The magnitude of the perturbations should therefore be consistent with the possible value of the analysis errors. The size of the perturbations in the vortex needs to be considered differently from that of the environment. The analysis errors in the environment are generally larger in the upper layer than in the lower layer (Leslie and Speer, 1998). In contrast, the mean tangential wind of the TC vortex has a maximum value near the surface and decreases with height (Shea and Gray, 1973). Accordingly, the size of the perturbations of the vortex is larger in the lower layer. To compare the size of the perturbations in the three EF methodologies, the initial root-mean-square (RMS) values of six pairs at every sigma level are calculated.

For the LAF, the RMS values of the six pairs (Figs. 1a, b) are the differences of lagged forecasts rescaled with a uniform factor of 0.3. In the BGME and BGMV experiments, the magnitude of the perturbations is scaled down by defining the maximum value at each sigma level. In the BGME experiments, the RMS values of the initial perturbations (Figs. 2a, b) are larger at the upper levels, which is comparable to the actual statistical results of analysis errors (Leslie and Speer, 1998). The RMS values generally increase with height (Fig. 2b). The values at the lower layers are very small ($\sim$0.2) and there is an apparent discontinuity between sigma levels 0.6 and 0.7. A possible reason for the discontinuity is the large horizontal differences of the temperature perturbations at the lower sigma layers under the influence of the terrain. When the perturbations are scaled with reference to the maximum perturbation value at each level, the RMS value becomes small. The discontinuity of the RMS values in the vertical occurs when the terrain influence decreases rapidly from σ=0.6 to σ=0.7. For BGMV (Figs. 3a, b), the wind perturbations are larger at the lower levels in accordance with the vertical structure of a TC. The perturbations of BGMV are rescaled accordingly by defining the maximum value to be half the mean wind speed between a 1° and 7° latitude radius from the TC center. Compared with Cheung (2001), the RMS values of the initial perturbations in the present study are generally smaller than those in his study.

The number of members: A question often asked in EF studies is the "minimum" number of ensemble members needed to improve the skill of the control forecast through ensemble averaging. The study of Toth and Kalnay (1997) shows that only a minimal improvement of forecast skill is obtained when the number of members is beyond 20, and even in tropical areas the improvement is very limited when this number increases from 10 to 20, whereas the computing time is doubled. Since in LAF, six pairs of ensemble forecasts are produced, six sets of such bred errors are generated in order to have the same number of ensemble members. Further, only the temperature and wind components are perturbed after rescaling because they are the most important factors in TC motion.

The lateral boundary conditions in both the control and ensemble forecasting come from the analysis. Admittedly, same lateral boundary conditions in the ensemble members would reduce the ensemble spread.

4. Forecasts of typhoon

4.1 *Forecasts of Typhoon Yancy*

Typhoon Yancy of 1990 is chosen as an example to examine the extent to which the EF methodology can improve the track forecast accuracy since it is one of the cases with larger forecast errors because of its "stepping motion". The case at the initial time of 0000 UTC 17 August (to be labeled as Y1700) has a position error of 400 km at 72 h from the control forecast.

All three methods, LAF, BGMV and BGME, are tested. None of the experiments includes a bogus scheme because the analysis vortex seems to be well represented by the TCM-90 analysis, with an intensity in the analysis of 984 hPa, which is close to the observational estimate of 980 hPa. Furthermore, the huge vortex circulation of Yancy occupied a large model domain, and it is difficult to filter out such a large vortex from the environment and replace it with synthetic observations depicting the vortex structure.

Most of the LAF members predicted the landfall of Yancy over Taiwan except for one with a predicted track passing north of the island (not shown). Two of the landfall members showed a jump across the Central Mountain Range. The ensemble-mean track is much closer to the best track than the control forecast (Fig. 4). In BGMV (Fig. 4) and BGME (not shown, since it is very close to BGMV), the mean forecast tracks also show an improvement over the control although landfall is not predicted.

It is obvious in this case that the LAF gives better predictions than both the BGMV and the BGME. Toth and Kalnay (1993) noted that the analysis contains fast-growing and non-growing errors. Ensemble perturbation must represent the growing errors in the analysis. In the present study, the LAF perturbations are basically short-forecast errors, i.e., difference fields between two forecasts. The proportion of growing errors in the initial fields is enhanced at the end of the short-term forecasts in a relatively stable northwestward motion. When they are added to or subtracted from the initial field, a more stable northwestward movement is obtained instead of the northward deviations predicted in the control run. Another probable reason is that both environment and vortex perturba-

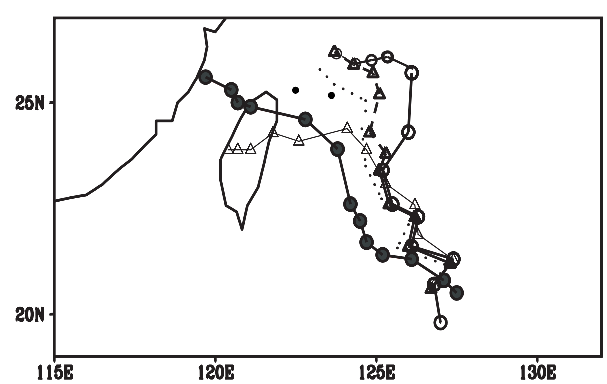

Fig. 4. Ensemble tracks (thin lines) of Yancy (Y1700) using the LAF (triangles with solid line), BGM (dotted line) and BGMV (triangles with dashed line) techniques. Best track is shown with black dots, control run with open circles. Positions are plotted every 6 h.

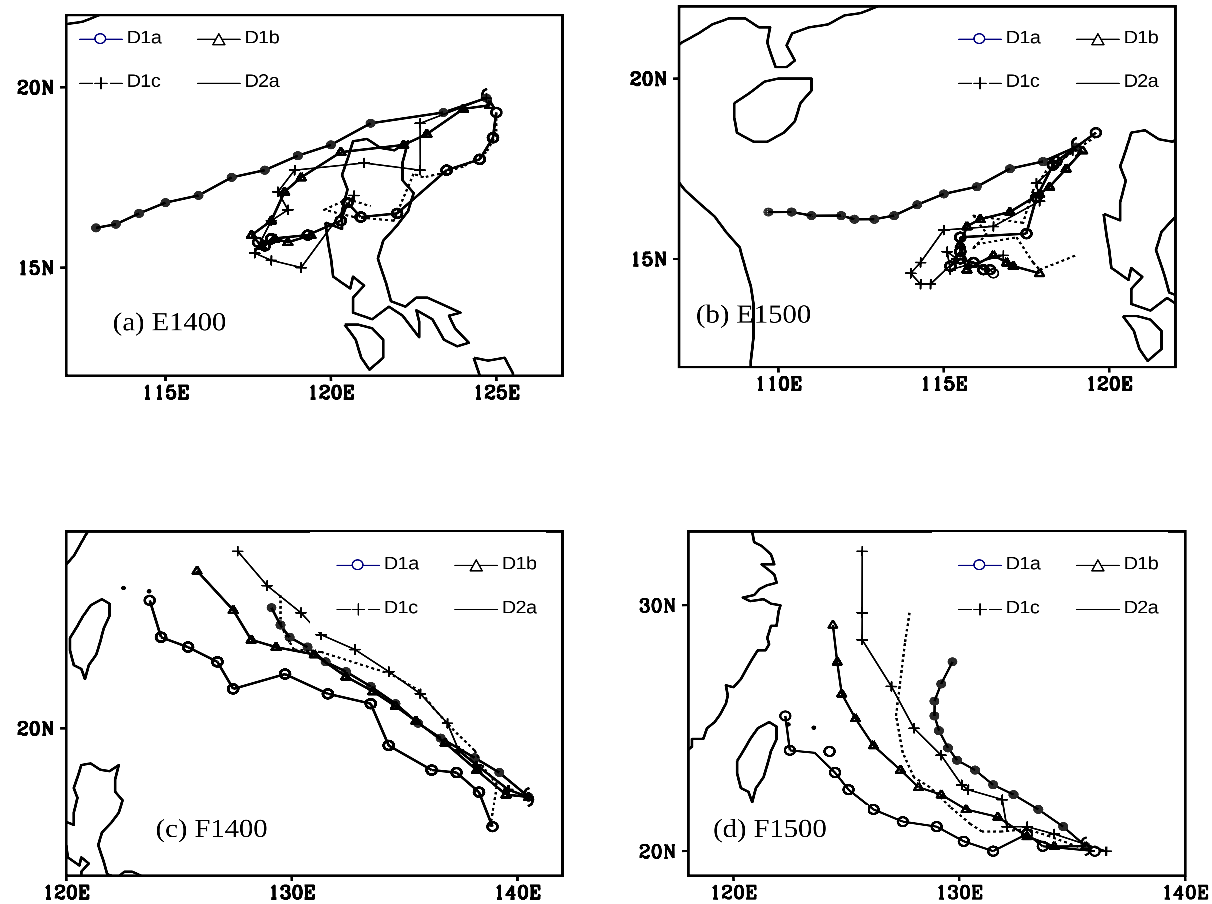

Fig. 5. Forcast tracks of Typhoons Ed and Flo from (a) E1400, (b) E1500, (c) F1400, and (d) F1500. Different symbols represent results from different sensitivity experiments. See Table 1 for a description of each experiment. Best track is shown with closed circles (every 6 h).

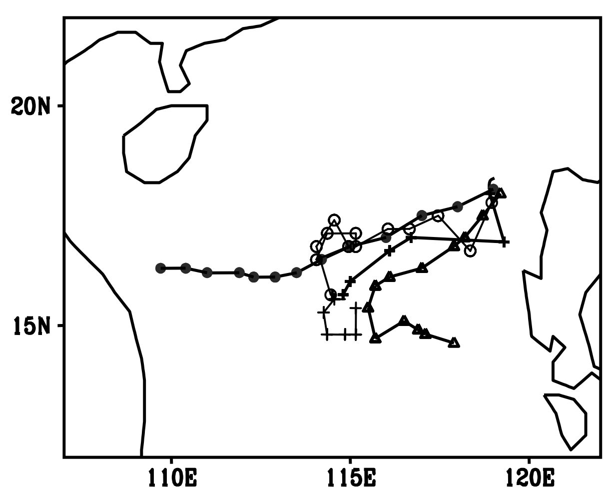

Fig. 6. As in Fig. 5 (b) except for experiments D1b (open triangles), D1e (crosses) and D3a (open circles). Best track with closed circles.

tions are included in the LAF, which is different from the BGMV and BGME. The interaction between the environment and the vortex is considered simultaneously. On the other hand, separating vortex or environmental perturbations (in BGMV or in BGME respectively) probably cannot give a good representation of the interaction because of the difficulty in removing the huge vortex of Yancy from the environment. This therefore results in poorer forecasts. To confirm this speculation, a simple experiment is employed by perturbing both the environment and the vortex with the perturbations from BGMV and BGME. In contrast to BGME and BGMV, the track (dotted line in Fig. 4) shows a little westward movement although it still has larger errors than LAF.

To summarize, for the case of Yancy, it appears that the LAF is superior to either the BGME or BGMV and predicts landfall over Taiwan because the former apparently generate errors in both the environment and the vortex so that these can interact from the beginning of the forecast. It suggests that perhaps in a situation where the vortex is large (indicating a strong interaction between the environment and the

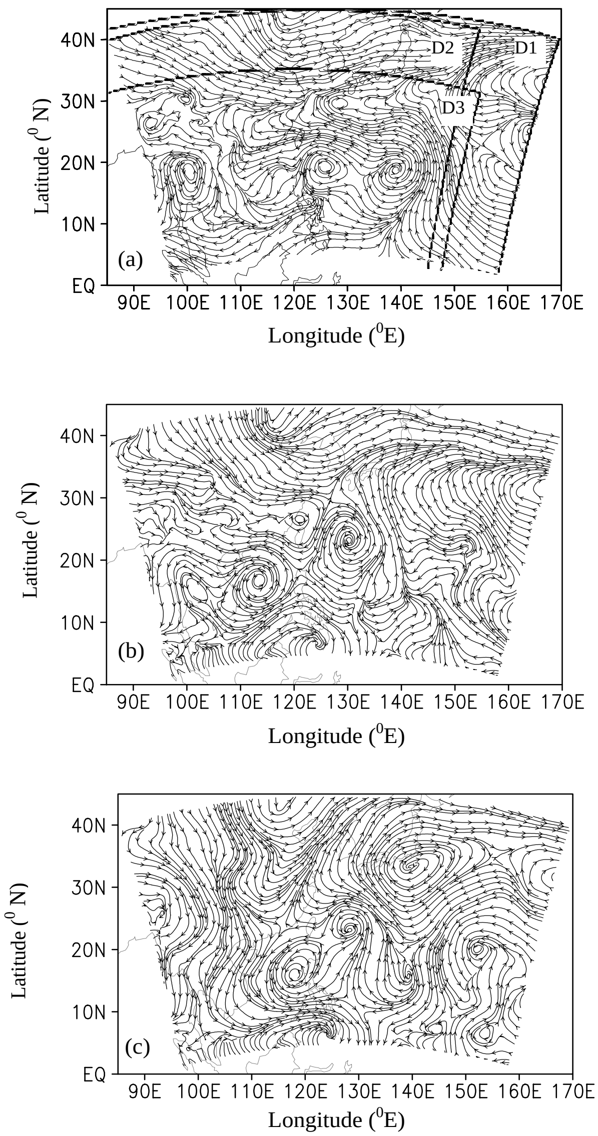

Fig. 7. (a) Streamline analysis at 0000 UTC 14 September. Thick short dashes represent the northern and eastern lateral boundaries of domains D1, D2 and D3 respectively. (b) Streamline analysis at 1200 UTC 16 September, (c) 60-h forecast flow field from 0000 UTC 14 September for D1a. All three plots are on the σ=0.5 surface.

vortex), it might not be appropriate to perturb the two components separately. The track improvement in the full BGM experiments proved our speculation.

4.2 *Forecasts of Ed and Flo*

4.2.1 *Sensitivity experiments*

Similar to the case of Yancy, LAF experiments are applied to the cases of Flo and Ed. The ensemble forecast tracks of Flo are found to be surprisingly insensitive to the perturbations, while those of Ed have the same pattern as that in the control, with all the tracks turning towards the south instead of a steady westward movement (see Figs. 9a, b). The southward deflection in the forecast tracks of Ed leads to large position errors, reaching 1000 km by 72 h. In other words, for this pair of vortices, at least part of the "failure" must lie in the model itself.

To investigate the factors that may have contributed to the failure of these forecasts, a series of sensitivity experiments are carried out (Table 1). Two cases starting from 0000 UTC 14 September 1990 and 0000 UTC 15 September 1990 are studied here (to be labeled as E1400 and E1500 for Ed, and F1400 and F1500 for Flo respectively).

Firstly, the results show that the forecasts are significantly influenced by the lateral boundaries. In the case of F1400 (Fig. 5c), the simulated track of Flo in experiment D2a (smaller domain) is much closer to the observed than in experiment D1a (larger domain) (see Fig. 7a for the actual domain). The 72-h simulated position error of experiment D2a is only 69 km. Because experiment D2a has a smaller domain, a large part of the subtropical ridge is not included in the forecast domain but "specified" through the boundary conditions. Probably because of this, the steering influence of the subtropical ridge to the north and a break in the subtropical ridge are simulated well, which causes Flo to move west-northwestward and finally recurve. In experiment D1a, the subtropical ridge is stronger and the position of the ridge is more westward than that in the analysis (see Figs. 7b, c), which enhances the westward movement of Flo (Fig. 5c). The case starting at 0000 UTC 15 September shows similar improvement in the smaller simulation domain (Fig. 5d) as in F1400. A larger model domain means more weather systems are included in the prediction. It also implies that the larger prediction error of Typhoon Flo in D1a comes from the erroneous prediction of the subtropical ridge strength and position.

In experiment D1b, after the analysis vortices of Ed and Flo have been filtered out, a synthetic vortex is inserted at each best track position. The predicted tracks of Flo from the two initial times become closer to the best track (Figs. 5c, d). For the E1400 case, the deviation to the south before 48 h is removed, but the forecast track still moves towards the south by 72 h so that the forecast errors remain large (Fig. 5a). For the case of E1500, the spread of the forecast tracks of the sensitivity experiments is very small (Fig. 5b).

In experiment D1c, the Kain-Fritsch instead of Kuo cumulus parameterization scheme is used. However, the forecast tracks of Ed are very similar to those in D1b (Figs. 5a, b), which suggests that the large track errors of Ed cannot be attributed to the cumulus parameterization scheme. In the case of Flo, the cumulus parameterization scheme influences the forecast track slightly such that more northeastward movement is obtained in experiment D1c than in D1b (Figs. 5c, d).

Table 1. Sensitivity experiments in studying the Ed and Flo cases. The boundaries of the various domains (illustrated in Fig. 7a) are D1: 5°–45°N, 85°–170°E, D2: 5°–45°N, 85°–155°E and D3: 5°–35°N, 85°–155°E. See text for a detailed description of the different types of TC vortex specification.

Experiment	D1a	D2a	D1b	D1c	D1d	D1e	D3a
Domain	D1	D2	D1	D1	D1	D1	D3
Type of TC vortex	Ed–analysis Flo-analysis	Ed- analysis Flo-analysis	Ed-bogus Flo-bogus	Ed-bogus Flo-bogus	Ed-removed Flo -bogus	Ed-bogus Flo-removed	Ed-bogus Flo-removed
Cumulus parameterization	Kuo	Kuo	Kuo	Kain-Fritsch	Kuo	Kuo	Kuo

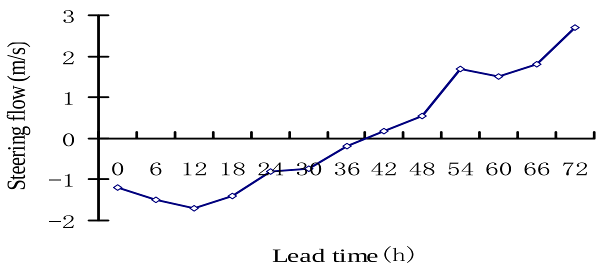

Fig. 8. The mean zonal steering flow during the integration in the D3a experiment for E1500. See text for definition.

It is often observed that when two TCs occur simultaneously in close proximity, they tend to rotate around each other (e.g., Brand, 1970; Chan and Law, 1995). During this process, their outer circulations may also merge. This happens in the case of Ed and Flo. The southeastward turn of Ed appears to result from the steering flow associated with the circulation in the southwest quadrant of Flo. Actually their circulations are separated in the analysis (see Fig. 7b). Two sensitivity experiments (D1d and D1e) are performed by removing Ed and Flo respectively to investigate their interactions and the extent to which they are affected by each other. No significant change is found in the predicted track of Flo when Ed is removed (not shown). In experiment D1e, Flo is removed at the initial time and the point at which Ed turns south is to the west in that in D1b (Fig. 6). However a weak vortex to the northeast of Ed is generated by the model (not shown), which likely influences the movement of Ed as Flo does. The influence of Flo on Ed is apparently not eliminated by removing the initial vortex of Flo in the analysis, but a more westward movement is indeed expected when such an influence is reduced.

Another important consideration is the forecast of the subtropical ridge located to the north of Ed. The model predicts a continuous weakening of the mid-tropospheric ridge over South China while the westerly trough to the north of the subtropical ridge is strengthened significantly. In the analysis, the ridge actually remains to the north of Ed (Fig. 7b), keeping Ed on a westward track. In experiment D3a, the northern lateral boundary is reset at 35°N in order to decrease the influence from the erroneous prediction of the evolution of the westerly trough by using the real boundary condition near the subtropical ridge. During the first 48 h (Fig. 6), Ed moves westward in a manner very close to the best track, but it turns southward later near 114°E. The mean steering flow is found to become westerly at 48 h (Fig. 8). The mean steering flow is calculated by averaging the flow between the 5° and 7° latitude radii from the TC center (following Chan and Gray, 1982) and from σ=0.3 to σ=0.85 after the model vortex is filtered using the vortex specification technique of Kurihara et al. (1995). It is worth noting that the southward turning of Ed is consistent with the change of the steering flow from easterly to westerly. This result suggests that the change in the steering direction contributes to the anticlockwise rotation of Ed's track.

It is also possible that Ed or Flo could affect the evolution of the subtropical ridge in the model. Additional experiments have therefore been performed to study the evolution of the environment by removing both Ed and Flo so that the possible influence from the forecast errors of Ed and Flo can be reduced. It is found that the predicted environment is similar to that with Ed and Flo present in the analysis (not shown).

From these experiments, it may be concluded that the forecast errors of the environment, which includes the subtropical ridge and the outer flow of Flo, largely contribute to the forecast failure of the movement of Ed. The weakening subtropical ridge over South China is replaced by a continuously deepening trough. The northwesterly flow upstream of the westerly trough pushes Ed to the southeast. At the same time, the outer flows of Ed and Flo merge due to the lack of "interference" from the subtropical ridge. When Flo moves to the northeast of Ed, the outer flow of Flo makes Ed move to the southeast.

Stensrud et al. (2000) have highlighted the importance of uncertainties of model physics parameterization in short-range ensemble forecasts. Results of the present sensitivity experiment point out that in addition to initial conditions and physical parameterizations, the configurations of the model, such as model

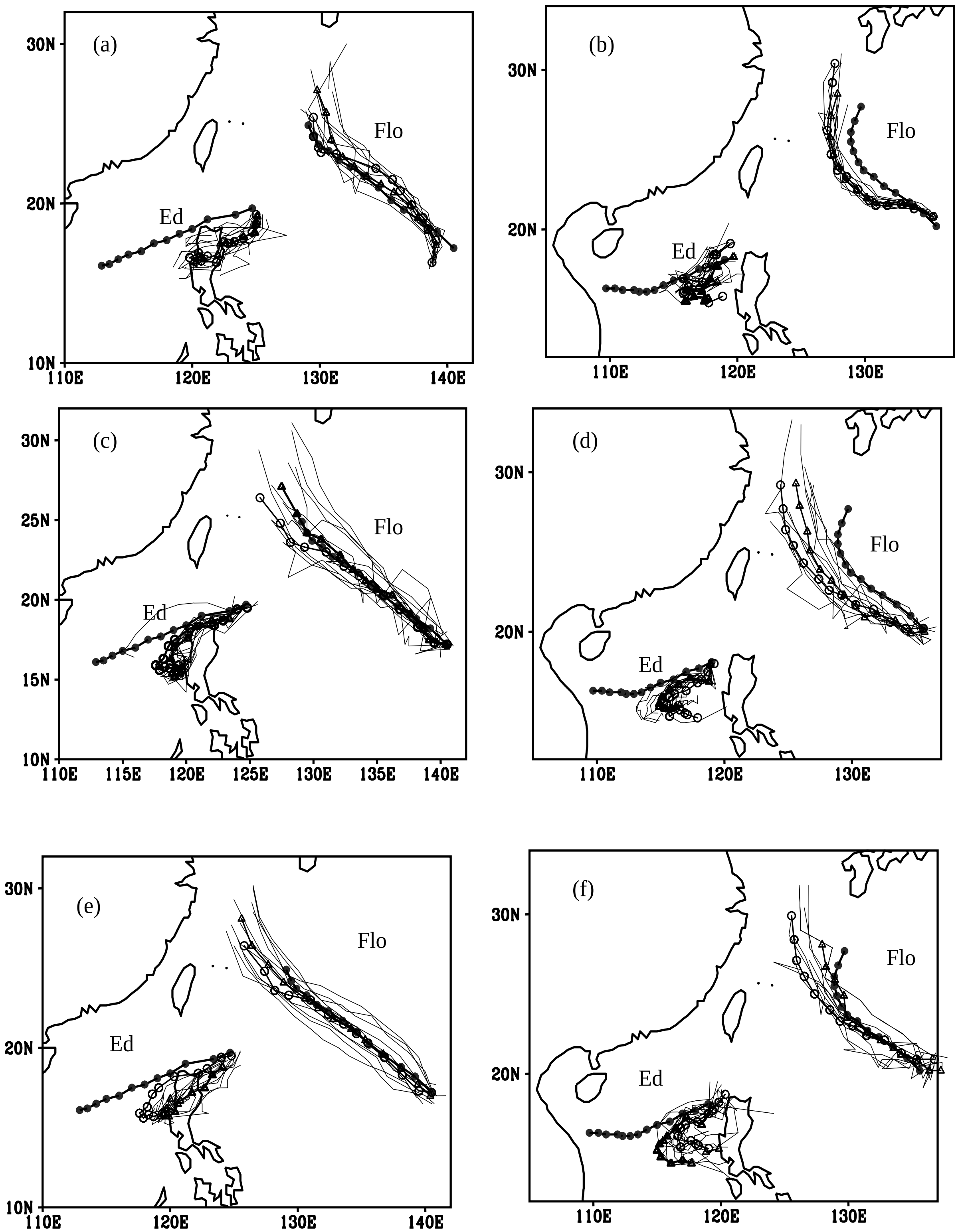

Fig. 9. Ensemble tracks (thin lines) of Ed and FLo from (a) 0000 UTC 14 September (E1400, F1400) in LAF and (b) 0000 UTC 15 September (E1500, F1500) in LAF, (c) E1400 and F1400 in BGME, (d) E1500 and F1500 in BGME, (e) E1400 and F1400 in BGMV, (f) E1500 and F1500 in BGMV. Best track is shown with closed circles, ensemble mean with triangles, control with open circles. Positions are plotted every 6 h.

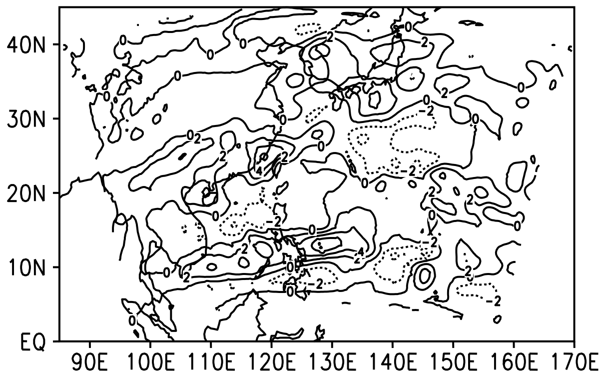

Fig. 10. The zonal component differences at 18 h during a 24-h BGME process on the level σ=0.85.

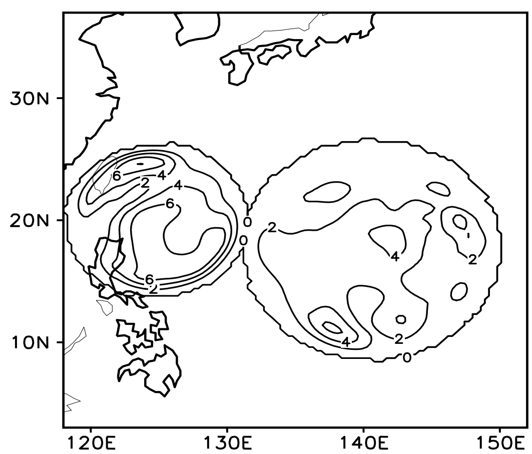

Fig. 11. The total wind velocity differences at the end of a 24-h BGMV process.

domain, can have significant effects on the TC motion due to the forecast ability of the model. It is also one of the important factors that should be considered in ensemble forecasting. Our speculation is based on our simulation results where analysis data are used for lateral boundary conditions. In a regional operational forecasting system, lateral boundary conditions come from the larger domain forecast with inevitable forecast errors. These errors would have a significant effect on forecasts. The effect of lateral boundary errors probably can be reduced by using a different forecast domain in the ensemble members, but obviously this requires further investigation.

4.2.2 *Ensemble forecasts of Flo and Ed*

The three EF techniques are applied to the cases of Ed and Flo to investigate whether such techniques can improve the forecasts of the environmental flow and/or its interaction with the two typhoons, and hence the forecast tracks of Ed and Flo.

The LAF experiments are carried out based on experiment D2a, in which no bogus scheme is included in order to compare with the experiments for Yancy. The spread of tracks is found to be smaller than that in Cheung (2001), apparently because smaller perturbations are used. For E1400 and E1500, the member tracks (Figs. 9a, b) are similar to those of the control. No significant improvement is obtained because the forecast of the western part of the subtropical ridge is not improved when the analysis is perturbed by the errors generated from the LAF technique. For F1400, the control run is quite good, with position errors below 100 km from 48 to 72 h. The mean track is close to the best track except that it has a larger speed. For the F1500 case, the classic recurvature is well simulated by both the control and the EF mean.

For the BGMV and BGME, experiment D1b, in which the bogus scheme is applied to both vortices, is selected as the control run (Figs. 9c–f). Despite the magnitudes of the perturbations (similar to those in Figs. 2 and 3), the initial positions of the members do not differ much from one another. To understand this more, the growth of the perturbations is examined. The magnitudes of the wind difference between the positive and negative forecasts (i.e., the perturbation) become stable after 18 h, which justifies a 24-h period for growing the perturbations even in the tropical regions. An example of this for one of the BGME perturbations after 18 h of growth at σ=0.85 is shown in Fig. 10. The zonal wind differences show a large scale structure. It can also be seen from Fig. 10 that the perturbations in the Ed and Flo areas are smaller than those in the others because of the filtering process. Similarly, the perturbations in the BGMV have rather reasonable magnitudes after 24 h of integration (Fig. 11).

In BGME, for E1400, most members give similar tracks as the control, except for one member, the predicted track of which appears to be close to the best track (Fig. 9c). As a result, the ensemble mean track is almost qualitatively the same as that of the control. Similar results are obtained for E1500 (Fig. 9d). In BGMV, almost all members of E1400 deviate to the south of the control, which results in poorer mean simulations (Fig. 9e). For the E1500 case, the ensemble mean track is quite close to the control (Fig. 9f).

In the case of F1400, the EF mean tracks in both BGMV and BGME give the correct direction but larger movement speed (Figs. 9c and e). For the F1500 case, the ensemble means have smaller deviations from the best track in the BGMV and BGME experiments (Figs. 9d and f). The results of the sensitivity experiments show that the failed simulations of Ed are caused by the erroneous simulations of the environment fields. In the EF experiments, although some members have more westward movement when the vortex or the environment is perturbed, the evolution of the environment in the EF simulations is apparently not improved. The ensemble-mean track remains similar to that of the control.

5. Summary and discussion

5.1 *Summary*

The purpose of this study is to examine the effectiveness of two different ensemble forecasting (EF) techniques—the lagged-averaged forecast (LAF) and the breeding of growing modes (BGM)—in predicting tropical cyclone (TC) motion in two difficult forecast situations: a large vortex interacting with its environment, and an apparent binary interaction. The former is Typhoon Yancy and the latter two are Typhoon Ed and super Typhoon Flo, all occurring during the Tropical Cyclone Experiment TCM-90. The model used is the baroclinic model of the University of New South Wales. In the BGM experiments, the vortex and the environment are perturbed separately (named BGMV and BGME respectively).

In the case of Yancy, the ensemble mean forecast of each of the three methodologies is better than that of the control, with LAF being the best. The mean track of the LAF is close to the best track, and predicts landfall over Taiwan. This result suggests the importance of including the perturbations of the environment and the vortex together when the interactions between the two are significant. This point is partly proved from the improvement of the full BGM experiment.

In the binary interaction case of Ed and Flo, the simulations of Ed do not appear to be sensitive to perturbations of the environment or the vortex. An investigation into the possible causes suggests that the model appears to produce an erroneous simulation of the environment, thus reducing the effectiveness of the EF technique. This conclusion is reached through sensitivity experiments on the domain of the model and adding or eliminating certain features in the model atmosphere. The inability of the model to predict interaction between the subtropical ridge and Ed, and the interaction between the two typhoons apparently led to the poor simulations. Although the distance between Ed and Flo is relatively large at the initial time ($\sim$ 1600 km), the outer flows of the two vortices are predicted to merge when Flo moves closer to Ed during the integration. The trend of the simulation does not change even when the environment or the vortex structure is perturbed. Nevertheless, the simulated tracks in some of the cases are improved over that of the control.

5.2 *Discussion*

The results from the study suggest that the EF technique can be useful in predicting tropical cyclone motion in some cases. It appears that for large vortices, it might be better not to perturb the environment and the vortex separately. For binary vortices, the success depends not only on how the two vortices interact but also on whether the model is capable of predicting the evolution of the environment and its interactions with the vortices. Of course, the appropriateness of the bogus vortex needs to be ascertained. More detailed studies with more cases are obviously needed.

The improvement of the forecast track appears to be more closely related to the track type rather than the ensemble methodologies applied. For example, in the F1500 case, improvements are obtained in all three EF methodologies, but for F1400, negative relative skill scores (RSSs) occur in all EF experiments due to the larger speed of the TC movement (Table 2). It would be interesting to test whether the improvement of EF has a preference for some particular track types.

The RSS of the ensemble mean is only used to evaluate the EF effectiveness here. Another essential objective of an ensemble prediction system is to predict the probability density function of the solution. However the ensemble spread provides a measure of expected forecast error only in a perfect model (Hansen, 2002). If the prediction model were perfect, this probability density function would be uniquely related to the uncertainty in the initial condition. The perfect model hypothesis is not fulfilled in practical forecasting, thus skill versus spread displays a highly scattered relationship (Elsberry and Carr, 2000; Goerss, 2000). This is also true in our results. For example, the ensemble member tracks of F1400 in the LAF experiment apparently have a larger spread than in F1500 of LAF (Figs. 9a, b), but the RSSs of the F1400 ensemble mean are much lower (−21.6%) than in F1500 (5.4%) as shown in Table 2. Since the spread and the ensemble mean skill are not necessarily related, the application of TC ensemble forecasting such as probability forecasting becomes challenging and complicated. So the probability distribution of ensemble members is not considered in our work.

This study also points to the limitation of the application of the ensemble forecasting approach using a single model. Even if the initial state is close to reality,

Table 2. The mean Relative Skill Scores (RSSs) for all time periods for all five cases and each of the three EF techniques: LAF, BGME and BGMV.

	LAF	BGME	BGMV
Y1700	24.4	4.4	8.1
E1400	−0.2	−0.4	−22.0
F1400	−21.6	−16.1	−15.5
E1500	1.9	19.4	12.2
F1500	5.4	8.9	6.4
Mean	2.0	3.3	−2.1

the evolution of the real atmosphere may not be estimated correctly by an imperfect model. It is useful to use more than one model in such an approach to be more confident that the true solution would fall within the range of the ensemble. The significance of multi-model ensemble forecasting has been realized due to inevitable model forecasting error (Goerss, 2000). The multi-ensemble forecasting method has been used by some institutes such as NCEP. (Du et al., 2003).

Admittedly our study is actually a simulation, which is different than operational forecasting, and so the conclusions from a simulation cannot completely apply to operational weather forecasting. In addition, the study is based on a small sample so that the conclusions are only tentative. However the results provide a basis for further development of the EF technique as an alternative to traditional deterministic forecasts of tropical cyclone motion.

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