Ensemble Forecasting of Tropical Cyclone Motion Using a Baroclinic Model

Xiaojong ZHOU* (周海琼) and Johnny C. L. CHEN (陈仲良)

Laboratory for Atmospheric Research, Department of Physics and Material Science,
City University of Hong Kong, Hong Kong

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ABSTRACT

The purpose of this study is to investigate the effectiveness of two different ensemble forecasting (EF) techniques—the large-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-96. 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 techniques, 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


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-
turbulent 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 (1994a, 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 the 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 tight 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 Warming 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 (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, 0.9, 0.93, 0.95, 0.975, 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°E to 170°E.

The modified Kuo (Kuo, 1995) 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