2.7 Mesoscale Ensemble Prediction of Mid-Latitude Cyclones

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1. INTRODUCTION

Motivated by the rapid development and success of the medium range ensemble forecasts, the operational and research communities start to consider the research and implementation of mesoscale ensemble predictions. Compared to the medium range ensemble there are more potentially difficult when creating a useful mesoscale ensemble. Because our understanding of the fine-scale structure of analysis error is poor, it is especially difficult when we try to define the uncertainty of the true atmospheric state for the mesoscale ensemble. The limited computer resources will also restrict the number of forecasts that can comprise an ensemble. For these reasons, the generation of initial perturbations is one of the crucial aspects of an ensemble strategy. Currently, there are several methods in common use for the creation of ensemble members. This includes the breeding method (Toth and Kalnay 1993) used in NCEP, the singular vector decomposition approach (Molteni et al. 1996) used in ECMWF, multiple analysis cycle techniques (Houtekamer et al. 1996, 1997) used in CMC and a fourth approach, the Monte Carlo procedure, which has also been used successfully (Mullen et al. 1989, 1994). However, it continues to be a topic of active research to choose the best method to generate initial condition (IC) perturbations for mesoscale ensemble prediction.

Except for problems involving ICs, careful consideration should be given to the model errors and lateral boundary condition (LBC) problems. Identical LBCs used in the IC perturbation ensemble forecasts will constrain error growth, and lead to reduced dispersion as forecast time increases (Vukicevic et al. 1990). The lateral boundary perturbation ensemble can be set up through perturbing the lateral boundary of the outer grid to minimize this shortcoming. However, the importance of LBCs on ensemble and the application methods are unknown.

While the use of different constraints can create different sets of perturbations, the model and its associated physical parameterizations are tied directly to the creation of the perturbations (Stensrud et al. 2000). Global models are thought to be reliable enough that the synoptic-scale forecast errors are due primarily to initial value uncertainty and not to model deficiencies (Reynolds et al. 1994). For short-range predictions, the effect of model errors cannot be avoided.

The intent of the present and any future study is to design and examine a mesoscale ensemble prediction system (MEPS), which incorporates most possible error sources causing inaccurate mesoscale prediction. The ensembles with respect to different error uncertainties are not combined together, allowing us to investigate their roles separately.

Mid-latitude cyclones are chosen for implementation of the MEPS. Rapid cyclogenesis is an appropriate phenomenon for this study. It is an important forecasting challenge to predict the cyclone's track, intensity and precipitation amount and distribution. Moreover, it has been suggested that rapidly intensifying storms are more sensitive to the uncertainty of ICs and physics parameterizations than ordinary cyclones (Mullen 1989, 1994). Using an intense cyclone is desirable for us to evaluate the practicality of the different mesoscale ensemble strategies. Through the examination of the ensemble prediction results such as verifying cyclone central pressure, cyclone track, and etc., combining with statistical analysis, we hope to gain a good understanding of the ability of the MEPS for mid-latitude cyclone prediction. Questions to be addressed will concern the relative merits and role of the each ensemble subset in the MEPS. The ensemble that can provide sufficient information to contain realistic atmospheric states will lead us to examine whether an ensemble forecast could provide insight into the potential forecast skill and improve the accuracy of subsequent probabilistic forecasts for mid-latitude cyclones.

2. METHODOLOGY

Schematic illustrations of the MEPS are presented in Figure 1. It incorporates most possible error sources causing inaccurate mesoscale prediction including the uncertainties of (a) the initial data, (b) model physics, (c) lateral boundary conditions and (d) boundary forcing. Our current research focuses on the first three error sources, and three separate ensemble subsets are created with respect to the three uncertainties, respectively. They are initial condition perturbation ensemble forecasts (IPEF), model physics perturbation ensemble forecasts (MPEF) and lateral boundary perturbation ensemble forecasts (LBEF), respectively.

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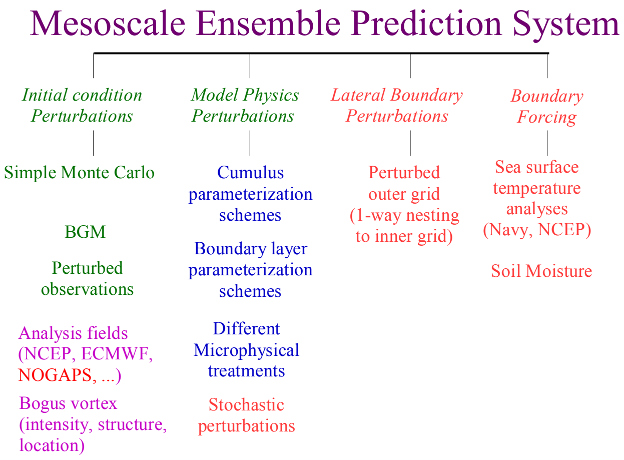

Fig. 1. *Schematic configuration of the mesoscale ensemble prediction system*

The fifth-generation NCAR/Penn State Mesoscale Model (MM5, Grell et al. 1994) is employed in our mesoscale ensemble experiments. Details of the model options for IPEF, MPEF and LBEF are summarized in Table 1. Note the model formulation is fixed for all IPEF members, no matter which one of the initial perturbation methods is used. The model formulation for LBEF is identical to IPEF. The only difference between them is the choice of lateral boundary tendencies and initial conditions. In MPEF, the model formulation is designed to change in terms of physical options.

	IPEF and LBEF	MPEF
Number of grids	2	2
Outer-grid resolution	75 km	75 km
Inner-grid resolution	25 km	25 km
Number of layers	27	27
Lateral boundary condition	Time-dependent inflow/outflow	Time-dependent inflow/outflow
Upper boundary condition	Radiative	Radiative
Cumulus parameterization	Kain-Fritsch	Kain–Fritsch, Betts–Miller, Anthes-Kuo and Grell
PBL parameterization	Blackadar	Blackadar , Hong-Pan and Burk-Thompson
Microphysics	Simple ice	Simple ice, Mixed phase, Schultz, and Goddard
Radiation scheme	Cloud radiation	Cloud radiation

Table 1. *MM5 configuration for the mesoscale ensemble prediction system*

The perturbations used to represent the IC errors in this study are generated by three breeding methods, which are the Bred Monte-Carlo Perturbations method (MC), the Breeding of Growing Modes (BGM) method and the Perturbed Observations (PO) method. Schematic illustrations of the three IPEF designs are presented in Table 2. Every IPEF ensemble includes two continuous 48-h periods, a 48-h breeding stage and a 48-h forecasting stage, respectively. Ramamurthy et al. (2002) have given detailed descriptions to the three methods.

In the MPEF design, the uncertainties existing in model physics is explored by changing model physical parameterizations. The permutation of four cumulus parameterizations, three planetary boundary layer schemes and four explicit moisture schemes shown in Table 1 generate a 48-member ensemble. These schemes were selected on the basis of their widespread use in numerical models and the representativeness of different assumptions and scale considerations (Wang et al. 1997; Braun et al. 2000). Another factor is the desire to include schemes representing a range of complexity and physical detail. We assume that all members of the ensemble model are equally skillful, although this assumption has not been verified. Stochastic perturbations of key physics parameters will also contribute to the spread of the ensemble solutions, and will be explored in the future.

Work to explore the influence of LBC perturbations on mid-latitude cyclones is underway. The BGM breeding method is used again during LBEF creation process. Compared to IPEF, the key difference between the IPEF and LBEF is that the breeding approach imposes a dynamic constraint on the ICs in IPEF, but on the LBCs in LBEF. The idea is as follows (Table 3): a) Expand the model domain to be big enough with resolution of 75km such that the new domain boundary is far away from the border of the original domain. The new domain has grid points of 120 × 244. b) Apply the BGM breeding method on the expended model grid with a breeding period 48-h long. c) Like in the IPEF, add or subtracted perturbations obtained from previous 48-h breeding to the IC at time t_0, the model integrates for 48-h with perturbed ICs from t_0 to t_0+48h. d) Then, the 48-h model forecasting results are used to generate the LBCs for the original outer domain for the same time period with three-hour interval. In this manner, a set of perturbed LBCs can be obtained. e) Using the identical IC for the original domain at time t_0, while changing the LBC from one member to another, the LBEF ensemble is established.

3. PRELIMINARY RESULTS

The ensemble approaches outlined in section 2, i.e. the MC, BGM, PO, MPEF and LBEF methods, have been applied to three mid-latitude cyclones, respectively: (1) The Midwest Cold Season Synoptic Storm on October 17 – 18, 1996, which has classical development and pressure pattern for the cold season. (2) The New Year's Day Storm on January 1 – 3, 1999, which produced over 20" of snow in the Midwestern United States, and (3) The Edmund-Fitzgerald II Storm on November 9 –12, 1998, which was an intense extratropical cyclone and characterized by rapid development of the surface low with deepening rates on the order of 11mb/6hr. In all cases, each ensemble subset consists of 20 48-h forecasting members except for MPEF, which has 48 members.

The ensemble performances during the breeding and forecasting stages were examined and preliminary results are summarized as follows. The MM5 model was shown to be a very useful tool to apply to mesoscale ensemble prediction. Ensemble subset-to-subset and member-to-member variation exist in the ensemble system, and do not follow any strict pattern, which imply that our IPEF, MPEF and LBEF designs are effective. Each ensemble subset has its own characteristic distinguishing it from the others, and each member forecasts in an ensemble differs from one another.

Results from the preliminary analysis of these cases suggest that the mesoscale ensemble prediction system does produce divergence and suggest a range of plausible solution possibilities, including quantitative and areal extent of precipitation, time of frontal passage, as well as location, central pressure, and maximum winds in cyclone. As an example, results from the New Year's Day Storm are shown here (Fig. 2). The verification of the cyclone intensity in five ensemble subsets implies considerable variability among them. The BGM, PO and LBEF ensembles can produce more dispersion than does the MC ensemble.

The domain averaged spread for the geopotential heights at 500 hPa for the five sub-ensembles in the model outer domain were also noted in Figure 3. Though the spread analysis indicates that all five methods lead to forecast that are underdispersive, the comparison can show the optimal perturbations that perform the best. The BGM and PO and LBEF methods (curve B, C and D) can capture the fast growing perturbations and generate larger errors than the MC and MPEF. The large values of LBEF spread clearly show the importance of the LBCs in the mesoscale ensemble system. Moreover, the comparison of the three initial perturbation ensembles (curve A, B and C) shows that the large spreads represent strong sensitivity to the initial states. Our results also suggest that the cyclogenesis regions are much more sensitive to initial error than ordinary flow regions.

Additional experiments on more cases and verifications against observations will be carried out before our results can be considered definitive. In addition to the subjective analysis for the cyclone intensity and track, and quantitative look of the spread, other ensemble products to verify and examine the performance of the ensemble forecasts is currently being investigated. Updated results will be presented at the Conference.

4. ACKNOWLEDGEMENT

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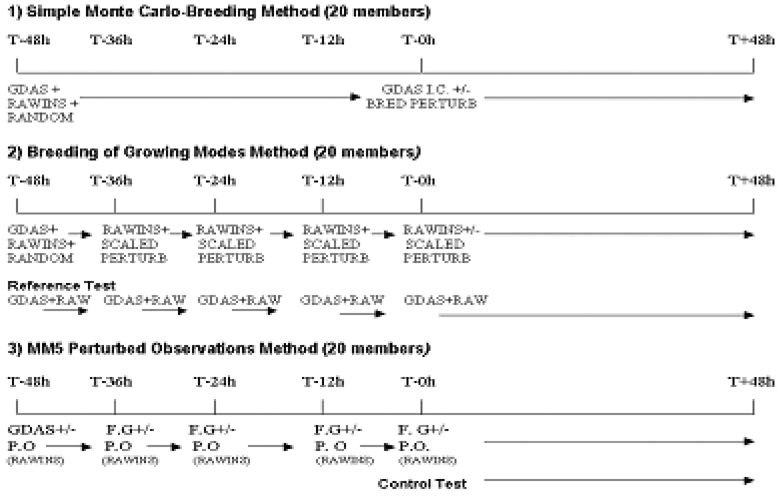

Table 2. *Schematic configuration of the three initial perturbation ensemble experimental designs*

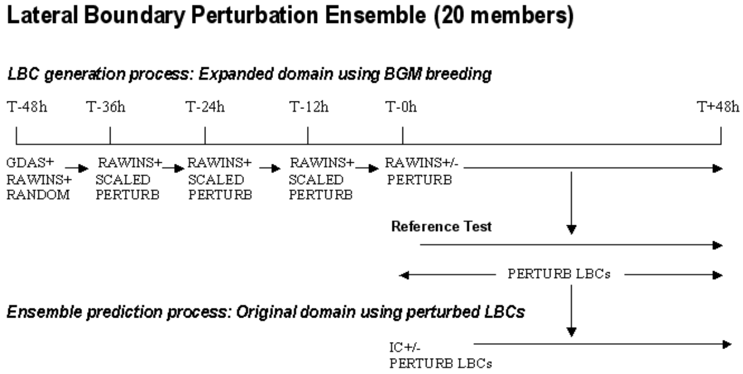

Table 3. *Schematic configuration of the lateral boundary perturbation ensemble design*

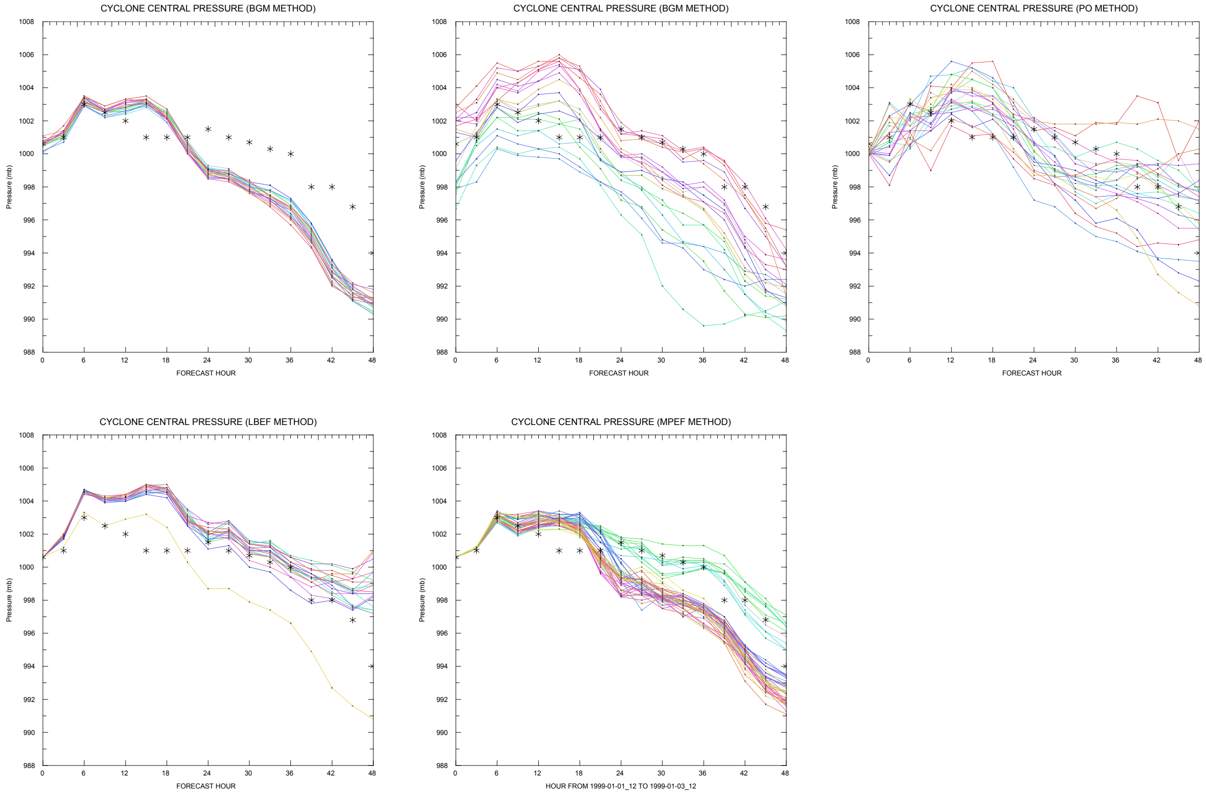

Fig. 2. *January 1-3, 1999 cyclone. The cyclone central pressure time series from 1200 UTC January 1 to 1200 UTC January 3, 1999. The black stars represent the observations. (a) MC (b) BGM (c) PO (d) LBEF (e) MPEF forecasting ensemble*

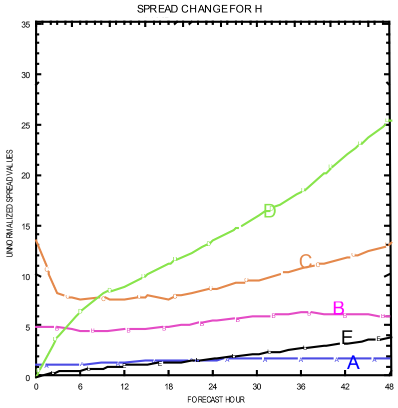

Fig. 3. *January 1-3, 1999 cyclone. Time series of the ensemble spread for 500 hPa heights averaged over the model outer domain. Curve A: MC ensemble. Curve B: BGM ensemble. Curve C: PO ensemble. Curve D: LBEF ensemble. Curve E: MPEF ensemble.*