11.4 Mesoscale Ensemble Prediction of Tropical and Mid-latitude Cyclones

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1. INTRODUCTION

The success of ensemble forecasting in the medium range forecasts in the past decade has spurred considerable interest in the operational and research communities to consider adopting ensemble techniques for mesoscale predictions. While the medium range ensemble experiences are valuable, the degree to which those results are applicable to mesoscale ensemble predictions is unclear. Here, we describe a mesoscale ensemble prediction system (MEPS) that is being developed at the University of Illinois and demonstrate its usefulness in mesoscale predictions. The MEPS system has heretofore been applied to predictions of two types of mesoscale phenomena: hurricanes and mid-latitude cyclones.

Hurricane Prediction

Accurate prediction of hurricane track, intensity, timing and landfall is both a critical research problem and is of great importance from a societal impact standpoint. According to the U. S. Weather Research Program (USWRP), it costs \$1 million to evacuate one mile of populated coastline, whether or not the hurricane hits land. Flooding from Tropical Storm Allison caused \$15 billion in damages and 43 deaths. Damage costs from hurricane Andrew (1992) reached \$27 billion, and Floyd (1999) totaled \$6 billion. However, an additional cost is associated with hurricane forecast track errors as residents and tourists flee coastal cities, businesses suffer losses and communities prepare for a landfall that does not occur. This problem is particularly acute for tropical cyclones paralleling the U.S. east or Gulf coasts before landfall. For example, Hurricane Floyd resulted in the largest peacetime evacuation in U. S. history. The USWRP estimates that a 20% reduction in coastline warning area would save \$80 million in preparation costs. Clearly, improved track forecasting has many potential benefits to coastal communities. Improved predictions will reduce evacuation time and cost, mitigate property damage and save lives.

The coastal hurricane prediction problem includes location and time of landfall and storm intensity when it moves onshore. The propagation speed is also of interest since severe inland flooding is now understood to produce damage comparable to, if not greater than, that inflicted by the storm surge and high winds along the immediate coastline. Improvements in weather prediction models, coupled with rapid strides in our observing capability and advances in assimilation techniques, have led to significantly improved tropical cyclone (TC) track guidance in recent years. Despite these improvements, however, there still exist many uncertainties in the dynamical prediction of TC tracks. The uncertainties stem from not only poor initialization of tropical cyclone structure, intensity and location in dynamic models, but also inaccurate specification of the large-scale environment in the vicinity of tropical cyclones. Errors in observations of initial hurricane position, structure, intensity, and environment are compounded by approximations inherent in numerical model treatment of physical processes, such as precipitation and boundary layer physics. As a result, significant errors currently appear in hurricane track, intensity, timing and landfall location. Presently, operational numerical hurricane forecasting is carried out using a *deterministic* approach – meaning each model prediction employs a *single* prediction for a given storm. There is a considerable body of research that this approach has serious limitations and improvements will require a fundamental shift towards a *probabilistic* approach through the use of ensemble modeling techniques.

Mid-latitude Cyclone Prediction

Rapid cyclogenesis is an important forecast challenge for forecasters. It has been suggested that rapidly intensifying storms are more sensitive to the uncertainties in initial conditions and physical parameterization schemes than ordinary cyclones. Specifically, predicting a cyclone's track and intensity remains a critical forecast challenge. Also, the cool season precipitation prediction problem is tied to the prediction of mid-latitude cyclones. For example, diagnosing the onset and duration of precipitation, as well as precipitation type and amount, is closely related to uncertainty in cyclone track and in the evolving local thermodynamic environment. Small variations in cyclone track, intensity and structure can result in significantly different thermodynamic environments where precipitation occurs. As a result, substantial variations in precipitation type can occur during the passage of winter storms. The result may be incorrect placement and timing of the mesoscale regions of mixed precipitation and of heavy snowfall and blizzard conditions. For these

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**Corresponding author address*: Mohan K. Ramamurthy, Department of Atmospheric Sciences, 105 S. Gregory St., Urbana, IL 61801. Email: mohan@atmos.uiuc.edu reasons, it is important to both reduce the uncertainty in the prediction of mid-latitude cyclones and their impact at a particular location and to quantify the uncertainties in the prediction via a probabilistic, ensemble forecasting approach.

2. METHODOLOGY

While the concept of ensemble forecasting can be applied to any temporal and spatial scale, the design of a mesoscale ensemble prediction system (MEPS) poses particular challenges. Specifically, what types of uncertainties are important and, as such, need to be included in a MEPS is not known. From a mesoscale forecaster's standpoint, an ideal MEPS should include any uncertainty that is likely to result in forecast divergence, providing indication of the different scenarios that are likely to unfold.

The MEPS described here is based on the NCAR/Penn State MM5 Version 3 modeling system, although a more comprehensive multi-model, multi-analysis MEPS system is currently being developed and tested as part of a collaborative COMET Partners Project effort with the National Weather Service Office in Lincoln, IL. The MM5 modeling system not only includes a sophisticated atmospheric prediction model, but also affords the flexibility for preparing different initial conditions and, more importantly, provides options for using myriad physical parameterization schemes for boundary layer, convective and microphysical processes. As described in the following sections, all these attributes are exploited in developing our mesoscale ensemble prediction system.

Table 1: MM5 Configuration for

Mid-latitude and Tropical Cyclone Prediction

	Mid-latitude Cylone	Hurricane
Number of grids	2	2
Outer grid resolution	75 km	60 km
Inner grid resolution	25 km	20 km
Number of layers	27	35
Lateral boundary Condition	Time-dependent inflow/outflow	Time-dependent inflow/outflow
Upper boundary condition	Radiative	Radiative
Cumulus parameterization	Kain-Fritsch, Grell, Betts-Miller, and Anthes-Kuo	Kain-Fritsch, Grell, Betts-Miller, and Anthes-Kuo
PBL paramterization	Blackadar, Hong-Pan, and Burk-Thompson	Blackadar, Hong-Pan, and Burk-Thompson
Microphysics	Simple Ice, Mixed Phase, Schultz and Goddard	Simple Ice, Mixed Phase, Schultz and Goddard
Radiation scheme	Cloud radiation	Cloud radiation

MM5 Configuration

As stated earlier, the MM5 modeling system forms the basis of our ensemble prediction system. The specifics of the mode configuration are given in Table 1.

MEPS Configuration

The current MEPS configuration includes ensemble members or subsets resulting from: a) Initial condition perturbations; b) Different (combinations of) parameterization schemes; and c) Different lateral boundary conditions. Simulations incorporating variations in model input data, physical processes and parameters, lower boundary forcings and lateral boundary conditions make up the ensemble set (Fig. 1).

For the mid-latitude cyclone application, the initial condition uncertainties are explored using three different methods (Fig. 2) for generating the initial perturbations: 1) a simple breeding of Monte Carlo or random perturbations; 2) the breeding of growing modes (BGM) method (Toth and Kalnay, 1993); and 3) a regional implementation of the perturbed observations (PO) method (Houtekamer et al, 1996). The key distinction between Methods 1 and 2 is that in Method 1, there is no reanalysis of new observations throughout the breeding period. In contrast, the Method 2 breeding period involves analysis of new observations at 12-hour intervals with the bred forecasts providing the background fields in each cycle.

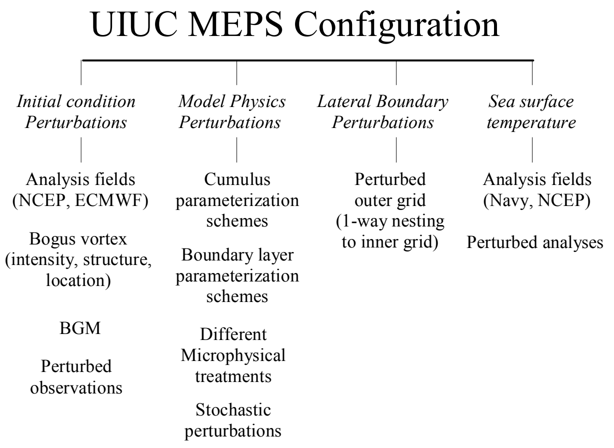

Fig. 1: Ensemble configuration for spanning the key uncertainties in tropical and mid-latitude cyclone prediction

The subset to explore initial condition uncertainties consists of 62 members, resulting from 20 members from each of the above three initial condition perturbation methods. All ensemble members are generated using a doubly-nested (two-way) model grid, with the outer and inner domains having a grid spacing of 75 km and 25 km, respectively. In our implementation the above three methods, perturbations are grown during a 48-h pre-forecast breeding period, similar to the approach proposed in Houtekamer and Derome (1995). Each 20-member subset includes 10 pairs of positive and negative perturbations that are created by adding or subtracting the bred perturbations to the initial condition fields at the beginning of the forecast cycle. Perturbations are added either directly to the grid point field (for Method 1 and 2) or to the observations using vertically correlated errors that are based on Bergman (1979). The 48-hour breeding period in Methods 2 and 3 comprises of 12-hour breeding segments where analyses are performed at 12 h intervals using the bred forecasts as first guess and an analysis step using a simple objective analysis step that is available in the RAWINS component of the MM5 system.

In the current implementation, the perturbed variables include temperature and horizontal winds (i.e., mass and momentum only). In the future, we will explore the importance of and sensitivity to errors in the initial moisture distribution. Following the 48-hour breeding period, the bred perturbations are added to and subtracted from the initial conditions, from which subsequent forecasts are generated.

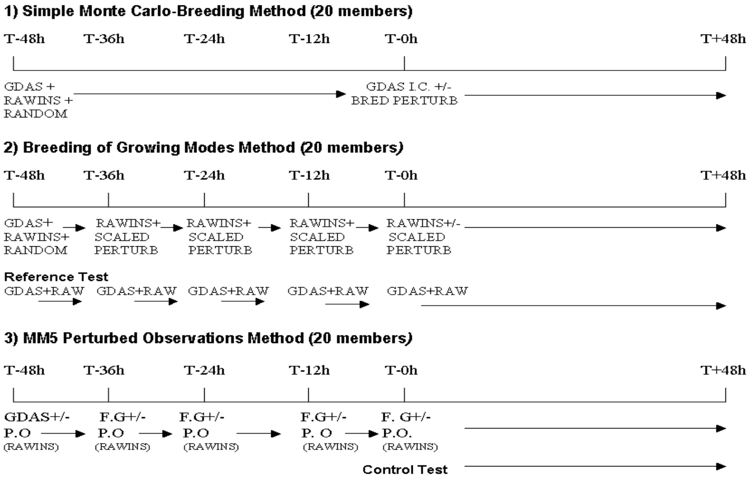

Fig 2. *Schematic diagram of the three initial perturbation methods*

For the hurricane prediction application of MEPS, we introduce perturbations to the initial TC structure and evaluate the impact on hurricane track, landfall and intensity. To that end, we are first utilizing a cyclone structure known to be compatible with MM5 by extracting the mature vortex from the model simulation at a later time. Implementation of a bogus TC requires first diagnosing and removing the existing vortex, thus defining a base state upon which to superimpose the new structure. Removal of axisymmetric profiles retains other "non hurricane" features in the environment. The larger environmental state is blended with the new vortex fields utilizing a hyperbolic tangent relationship. The resulting synthetic vortex has the structure of a mature hurricane. The intensity predictions resulting from the insertion of the bogus vortex indicated that the spin up period was reduced dramatically.

It is now widely recognized that uncertainties in the physical parameterization schemes in a model cannot be ignored in ensemble forecasting. Forecast errors can grow both due to initial condition errors as well as model deficiencies. Results from parameterization schemes can provide feedback and influence baroclinic and convective development in a prediction. Since all parameterization schemes have inherent uncertainties and there is little consensus on which parameterization scheme works best in all instances, we are exploring the importance of physics-based ensembles. One common approach to generate physics-based ensembles is to use different model physical parameterization schemes to construct different versions of a model and produce an ensemble of simulations that start from the same initial condition. This procedure has been successfully applied by Houtekamer et al. (1997), Mullen et al. (1988) and Stensrud et al. (2000). In our current MEPS configuration, the model physics uncertainties are explored through the use of three well known planetary boundary layer parameterization schemes (Blackadar, 1979; Hong et al., 1996; Burk-Thompson, 1989), four different convective parameterization schemes (Kain and Fritsch, 1990; Betts and Miller, 1986; Anthes-Kuo, 1974; Grell, 1993), and four different microphysical schemes (simple ice, mixed phase, Schultz, and Goddard microphysics). The permutation of these parameterization schemes yields 48 members for each initial condition. Stochastic perturbations of key physics parameters will also contribute to the spread of the ensemble solutions. Therefore in the future, the use of stochastic perturbations within each scheme will be explored.

3. PRELIMINARY RESULTS

The above three initial perturbation strategies have so far been applied to three mid-latitude cyclone cases: i) November 9-11, 1998 explosive cyclone case, which set all time record low surface pressure readings in Iowa and Minnesota; ii) January 1-2, 1999 winter storm, which produced over 20 inches of snow in the Midwestern United States, and iii) March 12-14, 1993 Storm of the Century case, one of the most devastating storms to hit the east coast of the United States in the last several decades. In all cases, 48 hour forecasts are made using the above initial condition perturbations.

Results from the preliminary analysis of these cases suggest that the mesoscale ensemble prediction system using just initial condition perturbations does provide value for a range of sensible weather forecasts, including quantitative and areal extent of precipitation, time of frontal passage, as well as location, central pressure, and maximum winds in a cyclone. In most runs, error growth begins to occur after an initial adjustment period of 6-10 hours. The forecasts using Method 1 and Method 2 showed a slightly smaller dispersion compared to those from the perturbed observations method. However, our analysis of the forecasts indicates that all three methods lead to forecasts that are underdispersive, an observation noted in several previous studies. Our ongoing work is focused on increasing the dispersion, including the use of analyses from different data assimilation systems from various operational NWP centers (e.g., NCEP GDAS and ECMWF analyses). Our results also suggest that nonlinear error growth occurs even in short range forecasts, especially during rapid cyclogenesis phase.

As part of the development of ensembles of model physics and initial condition perturbations, simulations have been carried out for hurricanes Opal (1995), Georges (1998), and Floyd (1999). As an example, results from Hurricane Floyd predictions are shown here. We introduced perturbations to the initial TC structure and evaluated the impact on hurricane track, landfall and intensity. We are first utilizing a cyclone structure known to be compatible with MM5 by extracting the mature vortex from the model simulation at a later time. Implementation of a bogus TC requires first diagnosing and removing the existing vortex, thus defining a base state upon which to superimpose the new structure. Removal of axisymmetric profiles retains other "non hurricane" features in the environment.

The larger environmental state was blended with the new vortex fields utilizing a hyperbolic tangent relationship. The resulting bogus vortex had nearly 135 mph winds above the surface, significant warming within the eye and a large region of 90% or greater humidity surrounding the eye. The intensity prediction resulting from the insertion of the bogus vortex (Fig. 2) reduced the spin up period dramatically, although the predicted minimum central pressure was still about 10 mb too high. However, this higher predicted minimum central pressure of the hurricane should not be surprising given the relatively-coarse horizontal grid spacing of 20 km.

The track of Floyd was found to be sensitive to the choice of model physics (Fig. 3). Inspection of results from Floyd also reveals that the ensemble spread in the tracks does not bracket the observed storm track, suggesting a model bias. We believe this bias results largely from the interaction of Floyd with an approaching mid-latitude system over the United States. The use of ice microphysics results in deeper cyclones whereas initial condition changes produced significant spread in the track. Similar sensitivities and spread in track and intensity prediction are observed in the predictions of Opal and Georges. These and other results will be presented at the conference.

4. ACKNOWLEDGEMENT

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5. REFERENCES

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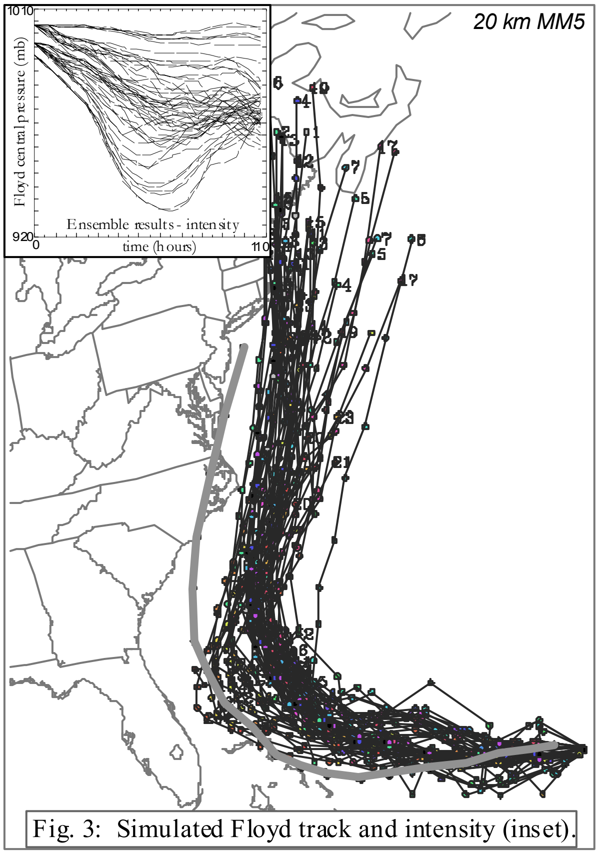

Fig. 3: Simulated Floyd track and intensity (inset).