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ASSESSING THE PREDICTABILITY OF BAND FORMATION AND EVOLUTION DURING THREE RECENT NORTHEAST U.S. SNOWSTORMS

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1. INTRODUCTION

Accurate predictions of mesoscale precipitation features often challenge operational models (Ralph et al. 2005). Zhang et al. (2003) have suggested that deterministic precipitation forecasts from mesoscale models are impractical beyond 2–3 days due to the upscale error growth associated with moist convective processes. Recently, this result has been demonstrated for mesoscale convective vortices in the southern Great Plains (Hawblitzel et al. 2007) and heavy precipitation along the Mei-Yu front in eastern China (Bei and Zhang 2007). However, there may be predictive skill for shorter forecast periods, especially with the use of Short-Range Ensemble Systems (SREFs). These systems help provide objective information regarding the predictability of mesoscale features by accounting for initial condition and model uncertainty, given that the ensemble has sufficient resolution to resolve the feature of interest.

Mesoscale precipitation bands are frequently observed in the comma-head portion of extratropical cyclones in the northeast United States (Nicosia and Grumm 1999; Novak et al. 2004). Accurate operational predictions of mesoscale bands have been demonstrated using an ingredients-based, time- and scale-dependent forecast strategy utilizing modern observational and modeling datasets (Novak et al. 2006). Given mesoscale models such as the MM5 and WRF are able to predict the primary aspects of mesoscale precipitation bands, even at 12-km grid spacing (Novak and Colle 2005), Novak et al. (2006) recommended the exploration of using high-resolution ensembles to assess the predictability of band formation and evolution. Following this recommendation, this study utilizes a 12-km-resolution multi-model, -initial condition, and -physics ensemble to assess the predictability of observed band formation and evolution during the 25 December 2002, 12 February 2006, and 14 February 2007 snowstorms over the northeast U.S.

2. DATASETS

A 16 member multi-model, -initial condition, and -physics ensemble system was developed (Table 1). The ensemble system is composed of two models (MM5v3.7 and WRFv2.2). Initial and boundary conditions were used from the operational National Centers for Environmental Prediction (NCEP) North American Mesoscale (NAM) model, Global Forecast Systems (GFS) model, and select NCEP SREF system perturbation members (N1, N2, P1, and P2; Du et al. 2003). Microphysics and convective parameterizations were varied for the GFS and SREF_P2 members. The ensemble was integrated over an outer 36-km domain covering the eastern two-thirds of the U.S. and adjacent coastal waters, and 12-km (one way) nested grid over the Northeast U.S. The 12-km ensemble output is the focus of the subsequent analysis in section 3. Detailed observations and deterministic 4-km model results from these cases are presented in Novak et al. (2007). The ensemble was initialized 19-, 18-, and 15-h prior to observed band formation during the 25 December 2002, 12 February 2006, and 14 February 2007 cases, respectively.

In order to determine the statistical properties of band predictability from the ensemble, a subjective assessment of each ensemble member's hourly output was undertaken. A simulated band in the 12-km domain was defined as a simulated reflectivity feature which has an aspect ratio (length/width) of 4:1 or greater, with an intensity of at least 30 dBZ, maintained for at least 2 h. Band formation was noted at the time when these conditions were first met (after determining the feature persisted for at least 2 hour). The intensity threshold was reduced to 26 dBZ for the 12 February 2006 banded event to document the occurrence and evolutions of generally weaker band predictions. The simulated bands were compared to the observed bands, defined as reflectivity features > 250 km in length, 20-100 km in width, with intensities of > 30 dBZ maintained for at least 2 h, following Novak et al. (2004).

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Table 1.Ensemble system configuration.

Member	Model	Initial/Boundary Conditions	Microphysics	Convective	PBL
NAM-MM5	MM5	NAM	Simple	Grell	MRF
GFS-MM5	MM5	GFS	Simple	Grell	MRF
GFE-R2-MM5	MM5	GFS	Reisner2	Grell	MRF
SREF_N1-MM5	MM5	SREF_N1	Simple	Grell	MRF
SREF_N2-MM5	MM5	SREF_N2	Simple	Grell	MRF
SREF_P1-MM5	MM5	SREF_P1	Simple	Grell	MRF
SREF_P1-KF-MM5	MM5	SREF_P1	Simple	Kain Fritch	MRF
SREF_P2-MM5	MM5	SREF_P2	Simple	Grell	MRF
NAM-WRF	WRF	NAM	Simple	Grell	MRF
GFS-WRF	WRF	GFS	Simple	Grell	MRF
GFS-Thom-WRF	WRF	GFS	Reisner2	Grell	MRF
SREF_N1-WRF	WRF	SREF_N1	Simple	Grell	MRF
SREF_N2-WRF	WRF	SREF_N2	Simple	Grell	MRF
SREF_P1-WRF	WRF	SREF_P1	Simple	Grell	MRF
SREF_P1-KF-WRF	WRF	SREF_P1	Simple	Kain Fritch	MRF
SREF_P2-WRF	WRF	SREF_P2	Simple	Grell	MRF

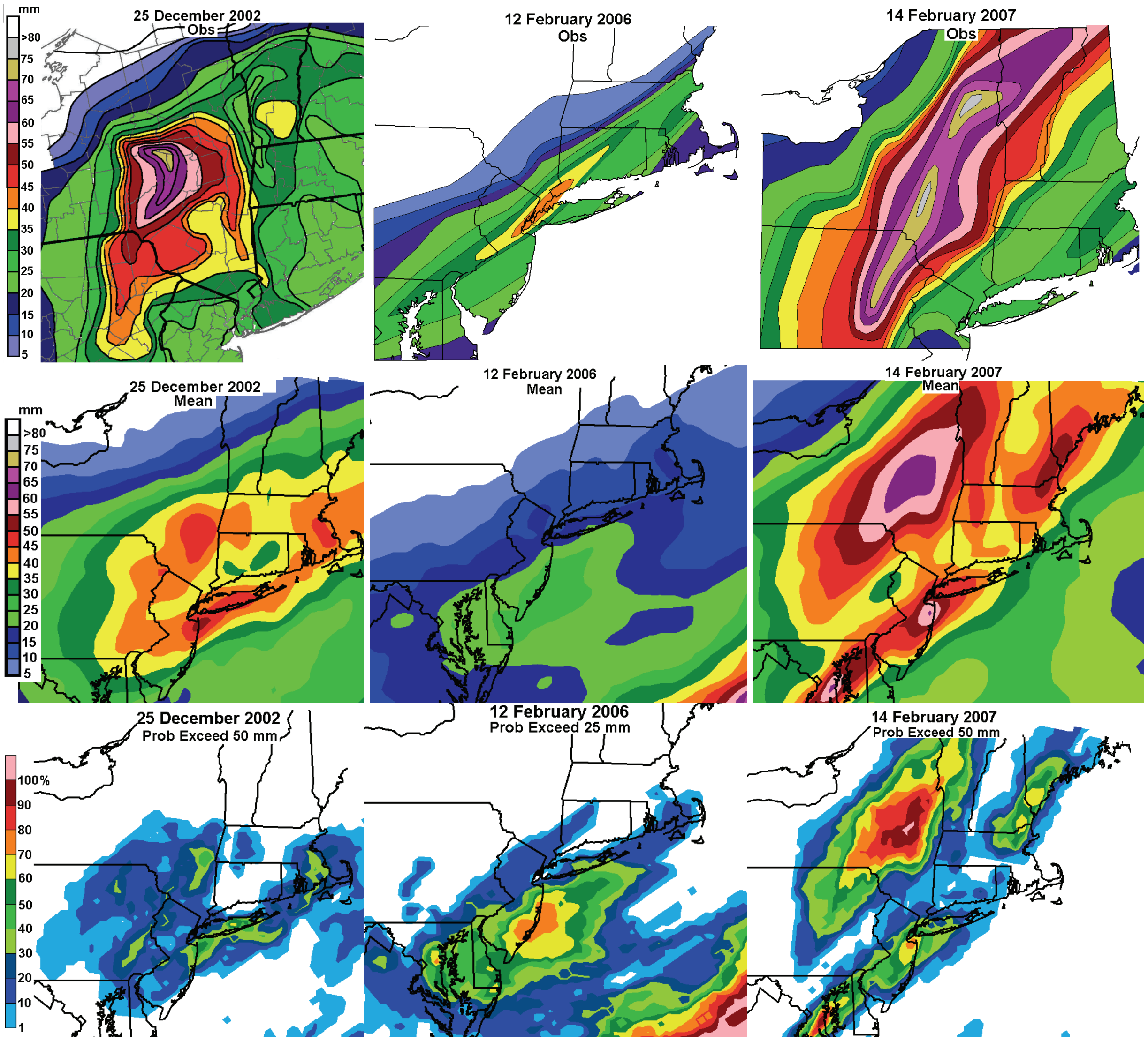

Fig. 1. (top row) Manually analyzed cooperative observer storm total liquid equivalent precipitation (mm, shaded every 5 mm according to scale) for the 25 Dec 2002, 12 Feb 2006, and 14 Feb 2007 cases, as labeled. (middle row) Corresponding 16 member 12-km ensemble mean forecast storm total precipitation. (bottom row) Corresponding ensemble probability (%) of exceeding 50 mm, 25 mm, and 50 mm for the 25 Dec 2002, 12 Feb 2006, and 14 Feb 2007 cases, as labeled.

3. RESULTS

The three cyclones exhibited rapid cyclogenesis, with the 25 December 2002 event exhibiting the greatest deepening (25 hPa in 18 h), while the 12 February 2006 event exhibited the least (17 hPa in 18 h). All three events met the criteria of a "bomb", as defined by Sanders and Gyakum (1980). Common features of banded cyclones (e.g., Novak et al. 2004) were present in each case, including the presence of coupled jets, and the development of a closed midlevel circulation (not shown).

Snowfall was extreme in all three banded events, with maximum totals of ~100 cm (40 in) during the 25 December and 14 February cases in eastern New York, and a record setting 68.3 cm (26.9 in) in New York City during the 12 February 2006 case. Liquid equivalent precipitation exceeded 40, 70, and 75 mm in the 12 February 2006, 25 December 2002, and 14 February 2007 cases, respectively (Fig. 1). The 12-km ensemble mean forecast storm total precipitation exhibits elongated precipitation maxima in the 25 December 2002 and 14 February 2006 cases (Fig. 1), suggesting several members predicted bands in the same general location in these cases. The rather small underprediction in the 14 February 2007 case is impressive, given the expected dilution of precipitation maxima by averaging in the ensemble mean, and suggests a greater predictability of precipitation relative to the other cases.

The probability of exceeding various precipitation amount values was also calculated from the storm total precipitation from the ensemble members for each case. Exceedance thresholds were chosen at roughly 2/3 of the observed precipitation maximum, which equated to 50 mm in the 25 December and 14 February 2007 cases, and 25 mm in the 12 February 2006 case. The results show (Fig. 1, bottom row) that at locations along the observed band, the ensemble predicted a 10–20% probability of exceeding 50 mm in the 25 Dec 2002 case, a 10–20% probability of exceeding 25 mm in the 12 February 2006 case, while over a 90% probability of exceeding 50 mm in the 14 February 2007 case. These results highlight the varied predictability of precipitation substructure within these cases, with the 14 February 2007 case exhibiting the most predictability.

Analysis of the individual ensemble member forecasts showed that band occurrence was favored in the ensemble for each case. All members exhibited band formation during the 14 February 2007 case, and over 80% of the members predicted bands at some time during the 25 December 2002 and 12 February 2006 cases (Table 1). However, the location and timing of band formation and the subsequent band evolution varied considerably. For example, the ensemble band predictions at the time of observed band formation, maturity, and dissipation for each case are shown in Fig. 2. In each case a favored SW–NE oriented envelope of band locations was predicted by the ensemble. The observed band generally fell within this envelope at the time of band maturity in the 25 December 2002 and 14 February 2007 cases, but was ~100 km southeast of the ensemble envelope in the 12 February 2006 case. As will be shown, several members in the 12 February 2007 case also forecasted band formation *after* observed band dissipation. The particularly narrow (~100 km wide) corridor of band predictions in the 14 February 2007 case (Fig. 2), once again illustrates the relatively large predictability of this case.

Table 2. Ensemble member band predictions. Members which forecasted a band are denoted by an "X" for each case.

Member	**25 Dec 2002**	**12 Feb 2006**	**14 Feb 2007**
NAM-MM5	X	X	X
GFS-MM5	X	X	X
GFS-R2-MM5	X	X	X
SREF_N1-MM5	X	X	X
SREF_N2-MM5	X	X	X
SREF_P1-MM5		X	X
SREF_P1-KF-MM5	X	X	X
SREF_P2-MM5	X	X	X
NAM-WRF	X	X	X
GFS-WRF	X	X	X
GFS-Thom-WRF	X	X	X
SREF_N1-WRF		X	X
SREF_N2-WRF		X	X
SREF_P1-WRF	X		X
SREF_P1-KF-WRF	X		X
SREF_P2-WRF	X	X	X

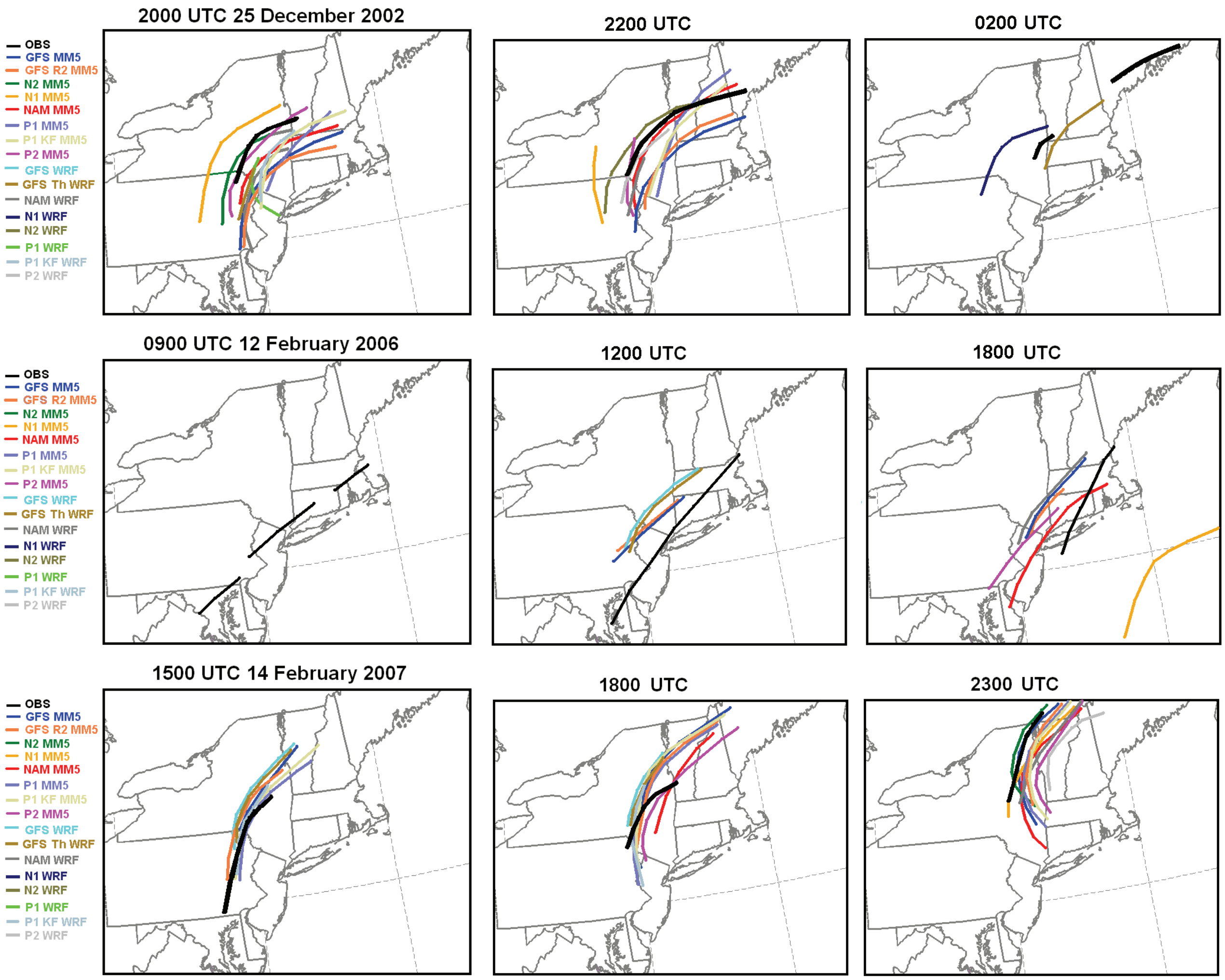

Fig. 2. Summary of ensemble band predictions for the 25 Dec 2002 (top row), 12 Feb 2006 (middle row), and 14 February 2007 (bottom row) cases. Ensemble predictions are shown at the time of observed band formation (left column), band maturity (middle column), and band dissipation (right column).

The ensemble predictions also highlighted varied uncertainty in the timing and duration of the predicted bands. In general, ensemble predictions of the timing of band formation and dissipation during the 25 December 2002 case were relatively successful, with the maximum frequency of members exhibiting bands coinciding at a time when the band was observed (Fig. 3). However, band formation was favored several hours later than occurred during the 12 February 2006 case, with none of the members forecasting a band at the time of observed band formation (Fig. 3). In fact, 6 members forecast band formation after the observed band had dissipated. Despite the high certainty in band occurrence and small spread in the location of banding during the 14 February 2007 case, the timing of band formation and duration was less accurate. Only ~45% of the members forecasted a band at the time of observed band formation, while over 70% of the members forecasted a band after the observed band had dissipated (Fig. 3). These results highlight the challenge of predicting not only band occurrence, but band location and timing.

4. DISCUSSION

The results of this study show that even at forecast projects less than 24 h, there is considerable uncertainty in the occurrence, timing, and location of band formation and subsequent evolution. Despite this uncertainty, these cases illustrate that a simple 16 member 12-km multi-model, -initial condition, and -physic ensemble can provide quantitative information on the magnitude of this uncertainty, and help differentiate between a case with unusually high predictability (14 February 2007) and unusually low predictability (12 February 2006). Although band occurrence was favored in the ensemble for each case, the specific timing and location of the bands had considerable spread, especially in the 25 December 2002 and 12 February 2006 cases. This suggests that answering whether a band will occur during a given case may be easier to answer than when and where it will occur, even for a relatively short (12–24 h) forecast. However, a 12-km-resolution ensemble can help identify favored time periods and corridors of band formation threat.

Although the ensemble provided uncertainty information, the observed location solution and timing of band formation fell outside the ensemble envelope in the 12 February 2006 case. These ensemble errors may be symptomatic of an under-dispersive ensemble system (e.g., Stensrud et al. 2000; Grimit and Mass 2002; Jones et al. 2007). These errors may be improved by including greater diversity in model cores, initial conditions, and physics options. Increasing the ensemble system resolution to convective-resolving scales (i.e., <4 km) may also improve band prediction. The development and testing of such high-resolution ensemble systems and their utility to provide feature-based uncertainty information in a real-time forecast environment is encouraged. The use of object-oriented approaches (e.g., Davis et al. 2006) to identify and track band predictions in an objective manner may accelerate the real-time application of such a high-resolution ensemble system.

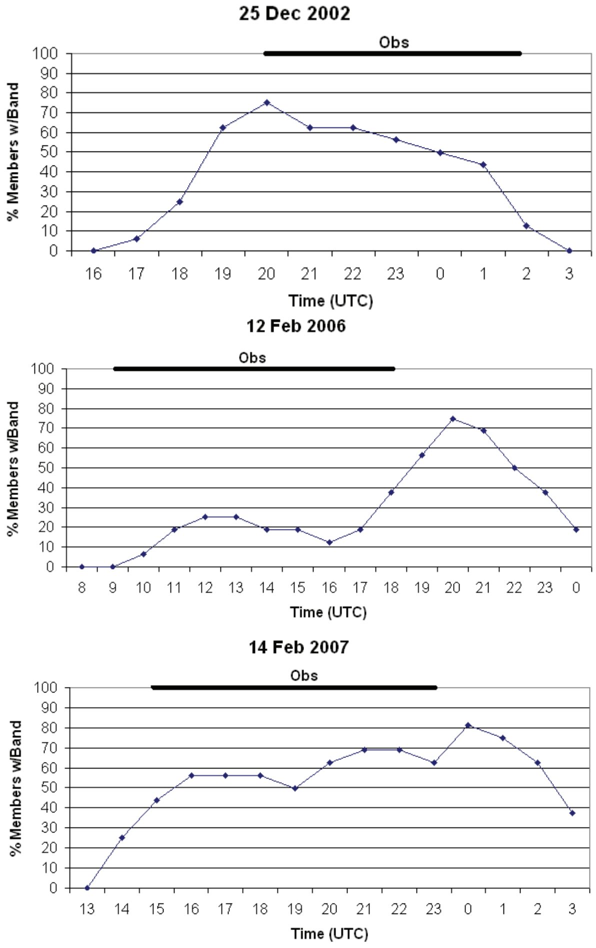

Fig. 3. Time series of the % of members forecasting a band during the 25 Dec 2002 (top), 12 Feb 2006 (middle), and 14 Feb 2007 (bottom) cases. The timing and duration of the observed banded event is shown by a black bar at the top of each graph.

Additional cases are needed to assure the results presented here are representative of a larger sample of banded cyclones. Furthermore, the observed cases examined in this study were known to exhibit band formation. Application of the ensemble system to observed nonbanded cases may reveal false alarms, where the ensemble exhibits a high probability of band formation, yet band formation does not occur. Future work will compare and contrast the individual ensemble member predictions to explore possible reasons for differences in the predictability of band occurrence between cases, and band location and evolution amongst individual ensemble members.

5. ACKNOWLEDGMENTS

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