Numerical Forecasting of Banded Snow: A Case Study

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ABSTRACT

Banded snow is challenging to forecast using numerical models because the bands have varying temporal and spatial scales. Although numerous ingredients-based forecasting strategies have been developed, their successful application relies on accurate forecasting of the location and intensity of the ingredients themselves. One possible way to improve numerical forecasts of banded snow or banding indicators is through the use of convection-permitting and/or ensemble modeling techniques. The study examines three forecasts of a banded snow event in association with a shallow, short-lived low-pressure system over southern Indiana on 3 February 2009. The forecasts include two single deterministic experiments with 12- and 3- km grid spacing (S12km and S3km, respectively) and a 30-member 12 km ensemble forecast with a 12-h data assimilation training period (EnKF12km). Of the three experiments, the ensemble mean of EnKF12km provides the best forecast of the position and strength of the surface low pressure. Banding ingredients, including frontogenesis and low-level moisture, are also considered; and again, the EnKF12km experiment provides the best forecast of the position of these fields. The convection-permitting simulation, on the other hand, positions the indicators slightly too far to the south, but resolves the northwest to southeast oriented bands over southern Indiana. These findings are consistent with previous studies that suggest for spring time mesoscale convective systems the most effective forecasting strategy is to couple high-resolution and ensemble forecasts to assess the character and location of a given event, respectively.

1. Introduction

Cold-season mesoscale banding is challenging to anticipate using the current suite of operational models provided by the National Weather Service (NWS) due to the varying spatial and temporal scales of this type event. Numerical forecasts of banded snow commonly have erroneous predictions of the location and amount of snow. Although the likelihood of banding can be assessed via inspection of fields such as frontogenesis, weak moist symmetric stability, and moisture content (e.g. Thorpe and Emanuel 1975; Nicosia and Grumm 1999; Novak et al 2006 and citations therein), NWP models can sometimes fail to accurately resolve and position these features. Thus, there is a vital need for forecasting techniques that, unlike the current operational approaches, are able to accurately resolve winter weather mesoscale banding or provide improved forecasts of those fields that can be used to infer banding.

Banded precipitation is defined herein as a narrow, elongated band of locally heavy precipitation embedded within a large precipitation shield. Novak et al (2004) assigns certain criteria to banded snow fall; namely they have “a linear reflectivity structure of approximately 250 km in length, 20 to 100 km in width, with an intensity > 30 dBZ lasting at least 2 h”. Bands are commonly observed in the comma-head section of mid-latitude cyclones—northwest of the surface low (e.g. Nicosia and Grumm 1999; Novak et al 2004), but have also been noted along cold fronts and embedded in the warm-frontal precipitation shield (Houze et al 1976; Nicosia and Grumm 1999; Novak et al 2004). Although several banding mechanisms have been proposed (e.g. Bennetts and Hoskins 1979; Schultz and Schumacher 1999), numerous theoretical and observational studies suggest that the primary forcing for band formation is frontogenesis in the presence of small or weak moist symmetric stability (e.g. Thorpe and Emanuel 1975; Sanders and Bosart 1985; Nicosia and Grumm 1999). Within recent years, some ingredients-based conceptual models and forecasting strategies have been developed using indicators like frontogenesis, weak or small moist symmetric stability and moisture (e.g. Wetzel and Martin 2001; Novak et al. 2006). However, Evans and Jurewicz (2009) note that although the aforementioned fields are good indicators of banding, they do not necessarily provide a reliable measurement of the intensity or location of a given event. Hence, ingredients-based forecasting strategies, by themselves, are not a reliable method for the accurate forecast of banded snow.

Some numerical forecasting techniques, such as increased horizontal resolution, ensemble modeling and ensemble data assimilation may prove helpful for forecasting banded snow. For example, convection-permitting simulations, which are those that have a high enough horizontal resolution to allow grid-scale convection and, hence, do not require a cumulus parameterization scheme (Weisman et al 1997), have been used in order to resolve springtime mesoscale convective systems, like bow echoes, squall lines, and rotating storms (e.g. Roebber et al 2002; Roebber et al 2004; Weisman et al 2007). Novak et al (2008) show that increasing horizontal resolution improves quantitative precipitation forecasts (QPF) as well as the detection of indicators like frontogenesis, stability and moisture for a case study of banded snow.

Ensemble modeling could also help improve forecasts of mesoscale banded snow. Numerous comparison studies of ensembles versus single deterministic forecasts for springtime convective events show ensembles generally have greater skill at the placement and timing of convection (e.g. Wandishin et al. 2001; Roebber et al 2004). Ensembles also provide a direct probability forecast, which allows the forecaster to better assess the uncertainties of the forecast (Roebber 2004). Likewise, the ensemble Kalman filter (EnKF; Evensen et al 1994), a data assimilation technique that relies on the computed statistics of an ensemble short-range forecast (Houtekamer and Mitchell 1998), has been shown to improve winter weather forecasts (e.g. Zang et al 2006). In a study on the performance of an EnKF forecast of a coastal snowstorm, Zang et al (2006) finds EnKF assimilations reduce temperature and pressure errors by up to 80 %. It is possible that ensemble forecasting and data assimilation could similarly improve forecasts of the timing and location of banded snow and/or banding indicators; but this has not been previously tested.

In this paper, the aforementioned modeling approaches are tested using a case study of banded snow over Indiana in February 2009. Special consideration is given to the location, timing and intensity of the banding. The models' ability at predicting indicators such as frontogenesis, stability and moisture are also considered. This paper is organized as follows. Section 2a summarizes the event and the forecasting challenges associated with it, while section 2b contains a description of the numerical techniques applied in the experiments. Sections 3 a,b,c present the results of the experiments. Concluding thoughts are presented in section 4.

2. Data and Methodology

a. Case Study: 3 February 2009

The need for accurate forecasting of cold season mesoscale banding is highlighted by the snow storm of 3 February 2009 over Indianapolis, Indiana. The radar reflectivity at the peak of the storm exhibits well-defined northwest-to-southeast oriented bands of enhanced reflectivity over south-central Indiana (Fig. 1). The most intense band has composite reflectivities exceeding 35 dBZ. This band is positioned over the Indianapolis metropolitan area from approximately 1200 to 1400 UTC. The storm total snow accumulation was 10.16 cm at Indianapolis International Airport. This amount is sufficient for this event to be considered high-impact given the climatology of

TABLE 1. The Area Forecast Discussion from the Indianapolis NWS Forecast Office from 3:44 EST on 3 February 2009

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FXUS63 KIND 030844
AFDIND

AREA FORECAST DISCUSSION
NATINAL WEATHER SERVICE INDIANAPOLIS IN
344 AM EST TUE FEB 3 2009

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MODELS IN PRETTY GOOD AGREEMENT WITH MOST FIELDS. WILL USE A BLEND EXCEPT FOR MOS
AS NOTED BELOW.

SFC LOW WILL MOVE ACROSS SWRN FA THIS MORNING AS UPPER LOW SLIDES ESE ACROSS MI.
FORCING FROM THE SFC AND UPPER LOWS WILL SPEAD ACROSS THE FA THRU MID MORNING
BEFORE MOVING OFF TO THE E. BRAD FORCING NOTED IN Q VECTOR CONVERGENCE FIELD…BUT
RELATIVELY STRONG FRONTOGENETICAL FORCING NOTED AS WELL. THIS SHOULD ALLOW THE FA
TO SEE THE SNOW.  HOWEVER BY 12Z THE BACK EDGE OF THE WIDESPREAD SNOW WILL BE
ACROSS THE WRN PORTION OF THE FA. WILL GO CHANCE POPS THERE AFT 12Z BUT LIKELY
ELSEWHERE. ATTM SNOW AMOUTN LOOK TO BE AOUND AN INCH WITH PERHAPS 1-2 ACROSS SRN
FA.

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the area (J. Kwiatkowski, personal communication). The greatest hourly accumulation of over 5 cm occurred between 1200 and 1300 UTC (J. Kwiatkowski, personal communication). During this time, the visibility was reduced to below 0.25 miles, resulting in numerous multicar pile-ups in the metropolitan area.

According to analyses by the Rapid-Update Cycle (RUC; Benjamin et al 2004) model, the banded snowfall is associated with a short lived surface low-pressure area that develops in central Illinois around 0600 UTC 3 February (Fig. 2a). The surface low moves eastward, so that it is located over southern Indiana at 1200 UTC 3 February (Fig. 2b) and dissipates after 1800 UTC over western Ohio (Fig. 2c). This low-pressure system is rather shallow. The RUC-analyzed geopotential heights and winds show there is a closed circulation over southern Indiana at 925 hPa at 1200 UTC 3 February, but there is no evidence of a cyclonic circulation at 850 and 700 hPa over this region (not shown).

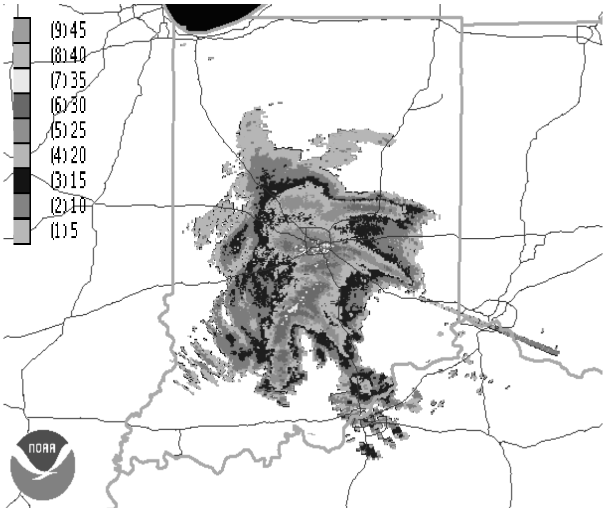

Fig 1. WSR-88D composite radar reflectivity at 1300 UTC 3 February 2009 from Indianapolis, IN.

Forecasters at the Indianapolis NWS office were aware that a surface low-pressure would develop, as mentioned in their forecast discussion (Table. 1). However, the formation of banded snowfall was not anticipated, and only 1 to 2 inches of snow over a 24-h period was predicted (Table. 1).

b. Model Configurations

Four experiments were conducted using the Advance Research Weather Research and Forecasting Model (WRF-ARW; Skamarock et al 2005) version 2. The suite of experiments includes a 12-km grid length, single deterministic forecast with 35 vertical levels. This forecast is initialized 12 h prior to the event, at 0000 UTC 3 February, and integrated for 24 h.

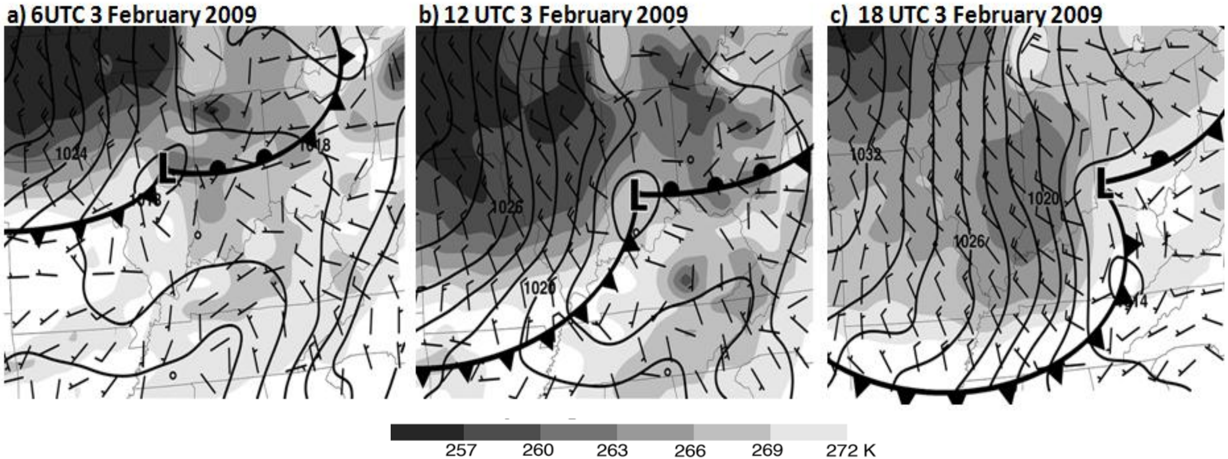

Fig.2 RUC-analyzed 2-m temperature (K; shaded as in legend), sea-level pressure (hPa; contoured) and 10-m winds (barbs; one full barbs is 5 m s^{-1}). The L indicates the position of the surface low-pressure area. Also included is a subjective analysis of the location of cold and warm fronts.

The parametization schemes are identical to those used for the WRF Rapid Refresh forecast (Benjamin et al. 2006). The initial and boundary conditions are obtained from the North American Mesoscale Model (NAM; Roger et al. 2001) forecast initialized at 0000 UTC 3 February 2009. This forecast is referred to as S12km. The effectiveness of a convection-permitting forecast is tested by performing an additional single deterministic forecast that is identical to S12km, but with 3-km horizontal grid spacing, 51 vertical levels, and no cumulus parametization. This forecast is referred to as S3km.

A 30-member ensemble simulation was conducted with data assimilation, EnKF12km. This experiment is also similar to S12km, with variations in the choice of parametization schemes for some members and perturbations of the initial condition for others. EnKF12km is conducted using the Ensemble Kalman Filter (EnKF). The EnKF technique relies on the successive assimilation of available data into an ensemble of runs, and make use of the ensemble error statistics, like the mean and error covariances for the analysis (Burger et al 1998; Evensen 1994) (for additional information about EnKF, see Evensen 1994). The EnKF12km simulation underwent a 12-h assimilation period between 1200 UTC 2 February and 0000 UTC 3 February. During this time, temperature, u-wind, v-wind, humidity, pressure, station and aircraft data from the Meteorological Assimilation Data Ingest System (MADIS) were assimilated hourly into the runs.

3. Results

All three experiments show reasonable agreement in the low-level temperature field, with a low-level cold front near the northern border of Kentucky (Fig. 3). The center of the cyclonic circulation, however, is not the same. The S12km and S3km forecasts have low-pressure centers near the Indiana/Kentucky border (Figs. 3a,b, respectively) while the EnKF12km experiment has the low-pressure system over central Indiana (Fig. 3c). Both the S3km and EnKF12km forecasts put a closed low over southern Indiana at 925 hPa (Figs. 4b,c, respectively). The S12km simulation has no closed low in this area at this time (Fig. 4a). The EnKF12km forecast also has a strong closed low over Michigan (Fig. 4c), consistent with the observations (not shown). Overall, the surface synoptic flow pattern is best forecast by the EnKF12km experiment. The observed depth of the cyclonic circulation over Indiana is unknown, but it is reasonable to presume that the EnKF12km simulation provides better forecasts of banded snow indicators, given that it has the deepest low-pressure system at the surface. Since 1200 UTC is the time of heaviest precipitation (not shown), all subsequent analyses will focus exclusively on this time.

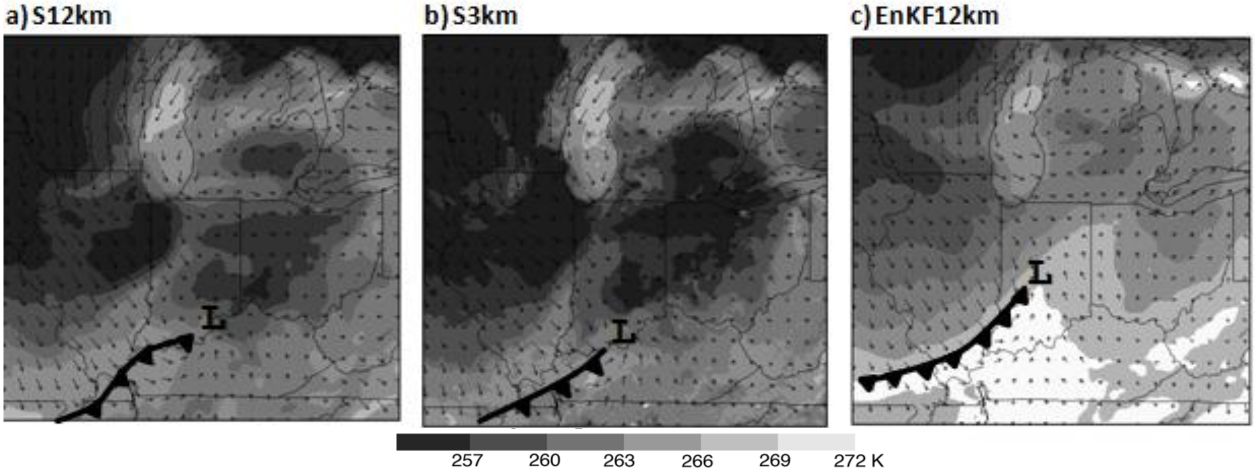

Fig 3. The 2-m temperatures (K; shaded as in legend) and 10-m winds (m s^{-1}) at 1200 UTC 3 February 2009. The position of the surface low-pressure system and cold front are indicated.

a. Frontogenesis

A variable often examined in order to assess the potential for banding is frontogenesis, *F* (e. g. Novak et al 2006; Mahoney and Lackmann 2006; Evans and Jurewicz 2009). Frontogenesis maxima associated with banding are usually located in the lower to mid-troposphere (~900 to 400 hPa; Evans and Jurewicz 2009). For these experiments, *F*, is maximum at the 850 hPa level. Herein, the two-dimensional *F* is computed using,

$$F = \frac{1}{\left|\nabla_p \theta\right|}\left[-\left(\frac{\partial\theta}{\partial x}\right)^2 \frac{\partial u}{\partial x} - \frac{\partial\theta}{\partial y}\frac{\partial\theta}{\partial x}\frac{\partial v}{\partial x} - \frac{\partial\theta}{\partial x}\frac{\partial\theta}{\partial y}\frac{\partial u}{\partial y} - \left(\frac{\partial\theta}{\partial y}\right)^2 \frac{\partial v}{\partial y}\right] \quad (1)$$

where *u* is the zonal wind, *v* is the meridonal wind, and θ is the potential temperature (Nicosia and Grumm 1999). The S12km forecast has an elongated zone of positive *F* along the surface cold front (Fig. 5a). Although there is also a small frontogenesis maximum over central Indiana, this signature is not consistent with the structure usually observed during banded snow events (e.g. Nicosia and Grumm 1999; Novak et al 2004). Despite the noise associated with the increased horizontal resolution, S3km produces a cluster of frontogenesis maxima extending from eastern to southwestern Indiana and another cluster extending from central Indiana to south-central Kentucky, along the surface cold front (Fig. 5b), with maxima exceeding 32 (100 km^{-1} 3 h^{-1}). The position and intensity of the cluster is consistent with that described in some conceptual models (e.g. Wetzel and Martin 2001; Novak et al 2004). The EnKF12km experiment frontogenesis band extends

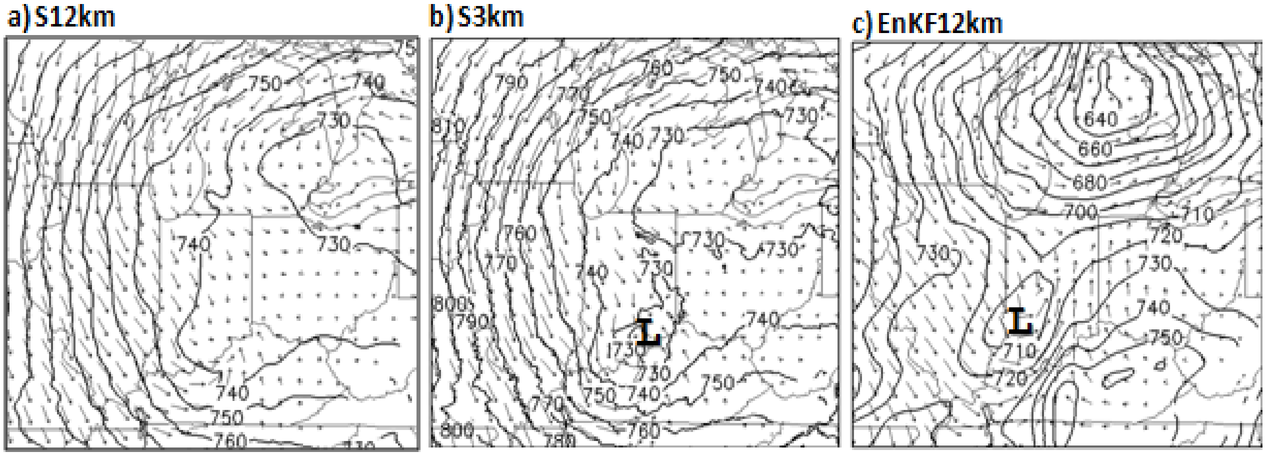

Fig. 4. The 925- hPa geopotential height (m; contoured) and winds (m s^{-1}) at 1200 UTC 3 February 2009.

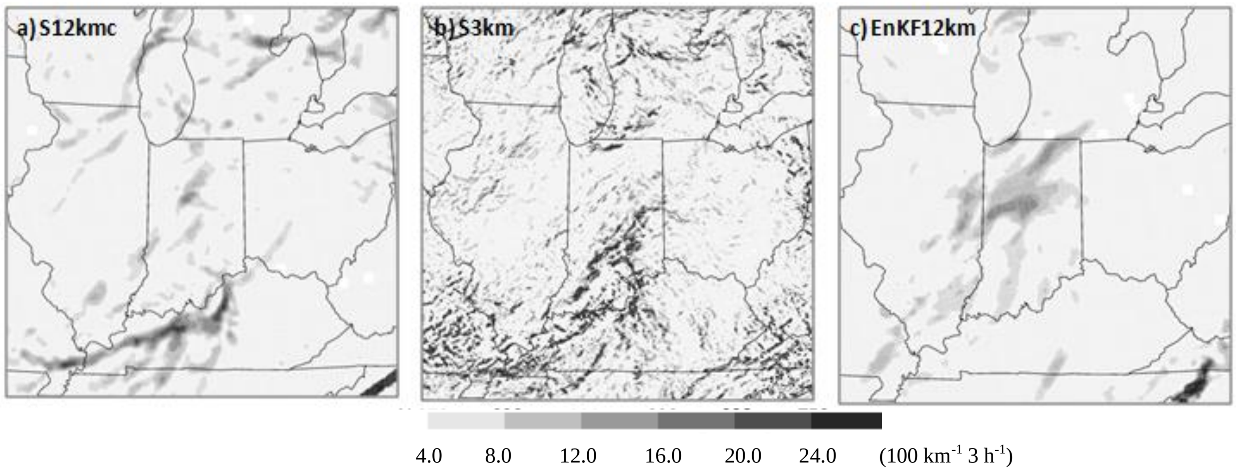

Fig. 8. The 850-hPa frontogenesis (shaded according to scale; 100 km^{-1} 3 h^{-1}) at 1200 UTC 3 February 2009

from north-eastern to southwestern Indiana with a maxima of 8 (100 km^{-1} 3 h^{-1}) located to the northwest of Indianapolis, IN (Fig. 5d). This pattern is most consistent with conceptual models of frontogenesis and banded snowfall.

b. Moisture: Water Vapor Mixing Ratio

To assess banding, forecasters often examine the presence of indicators, like instability and lift, within a saturated layer (e.g. Nicosia and Grumm 1999; Novak et al 2006; Novak et al 2008). The moisture is assessed using the water vapor mixing ratio, q_{vp}, at 925 hPa, which is the level of maximum moisture advection. The S12km forecast has a q_{vp}, maxima over northern and western Kentucky, running approximately parallel to the surface cold front location (Fig. 6a). A similar pattern is observed in the S3km experiment, although the q_{vp}, values are somewhat higher in this experiment (Fig. 6b). The EnKF experiment has an elongated southwest-to-northeast maximum in q_{vp}. The location of this maximum and its shape is consistent with the conceptual models of banded snow (Nicosia and Grumm 1999; Novak et al 2006).

c. Banding: Rain, Snow, and Graupel Mixing Ratio

The ability of the experiments to produce banded precipitation patters is assessed using the hydrometeor mixing ratio, q_{pr} where q_{pr}, is the sum of the mixing ratios for rain, snow, and graupel. The 900-hPa level has the maximum q_{pr} and so is the only level shown herein. All three experiments show a region of precipitation over Indiana (Fig. 7). The S12km and S3km forecasts have this

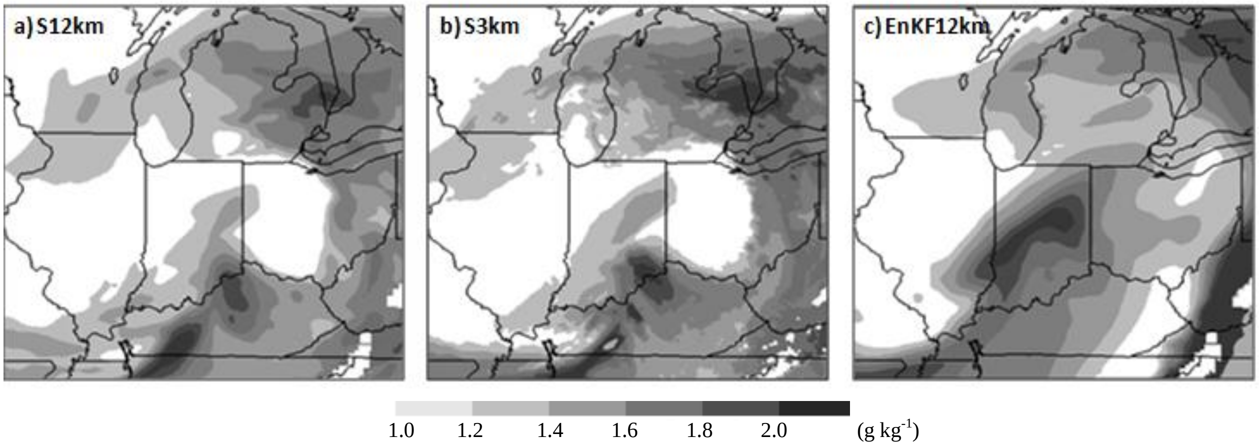

Fig. 6. The 925-hPa water vapor mixing ratio (g kg^{-1}; shaded as in legend) at 1200 UTC 3 February 2009.

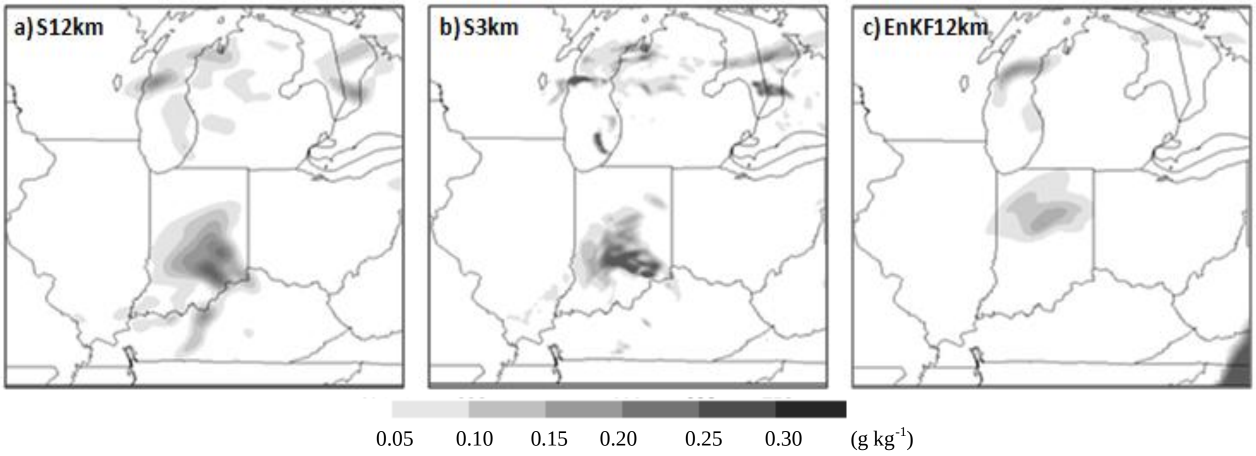

Fig. 8. The 900-hPa hydrometeor mixing ratio (shaded according to scale; g kg^{-1}) at 1200 UTC 3 February 2009

maximum positioned over south-central Indiana Indiana (Fig. 7c). Of these three experiments, only the S3km resolves a banded structure with intensities that are similar to those observed in the (Figs. 7a,b, respectively) while the EnFK12km experiment has the maximum over north-central real atmosphere.

4. Summary and Discussion

Three numerical forecasting techniques—convection-permitting (S3km), ensemble (E12km), and ensemble with data assimilation (EnKF12km)—are analyzed and compared to a forecast similar to that available operationally (S12km) in order to assess their relative value for forecasting banded snow. This comparison was performed using a case study of banded snow that occurred on 3 February 2009 over Indianapolis, IN. The banding for this event is associated with a shallow, short-lived low-pressure center that was positioned over south-central Indiana. The observed precipitation for this event was very heavy and resulted in low visibilities and generally hazardous weather conditions.

When placing key features, like the surface low-pressure system and the cold front, the ensemble mean of EnKF12km provides the most accurate forecast. The EnKF12km also provides a more accurate forecast of the location of indicators, such as frontogenesis and water vapor mixing ratio. The positioning of these features is the most consistent with conceptual models of banded snow (e. g. Wetzel and Martin 2001; Novak et al 2006), which should provide additional confidence in the forecast of banded precipitation. Of the three experiments, only the S3km was able to resolve the banded structure of the precipitation. Although the position of the precipitation was somewhat south of the area where banding was observed, the fact that this forecast was able to produce banding would have provided forecasters with valuable information about the character of the system.

While the Ensemble Kalman filter technique provides an accurate representation of the surface features, like the cold front and the location of the surface low-pressure center and banding indictors such as frontogenesis and moisture, convection-permitting high-resolution forecasts are a better tool to forecast mesoscale banding and the intensity of indicators. These findings are consistent with previous studies (e. g. Roebber et al 2002; Evans and Jurewicz 2009) which suggest a combination of high resolution and ensemble simulations are the most effective approach to accurately forecasting mesoscale banding.

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