

# ***EXAMINING A SOUTHWARD BIAS IN LAKE-EFFECT SNOW BAND FORECASTS IN THE NORTHEAST REGIONAL ENSEMBLE***

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## ***Abstract***

In this study, simulations from the northeast regional Weather Research and Forecasting (WRF) model ensemble of two lake-effect snow events from the 2007-2008 cool season are examined. In these simulations of lake-parallel, lake-effect snow bands downwind of Lake Ontario, a systematic southward bias in forecast snow band location is found with the Advanced Research WRF (WRF-ARW) members of the ensemble, consistent with previous research on mesoscale modeling of lake-effect snow and with qualitative forecaster assessments of other events during the 2007-2008 cool season. The bias is found to degrade the usefulness of the northeast regional ensemble.

A series of sensitivity simulations is performed to help diagnose the cause of the southward bias. These simulations revealed that the WRF-ARW ensemble members underestimated the frictional slowing of wind, downwind of the central and eastern Great Lakes, when compared to a Rapid Update Cycle (RUC) analysis and WRF-Nonhydrostatic Mesoscale Model (WRF-NMM) simulations. The underestimation served to reposition the mesoscale convergence boundaries associated with the lake-effect snow bands farther south. These simulations also clearly indicate that model core rather than model physics and physical parameterizations is the primary source of the erroneous boundary layer flow. A final set of sensitivity simulations suggest that version 3 of the WRF-ARW improves upon this bias with forecast accuracy more comparable to the WRF-NMM shown in one case study.

Given the results from this study, the feasibility of an operational mesoscale ensemble is discussed. It is shown that while this type of forecast tool shows promise, performing verification studies of each ensemble member is essential to its success.

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## 1. Introduction

The use of ensemble prediction systems (EPSs) has expanded rapidly in the past several years. The success of EPSs in improving and adding valuable information to medium- and even short-range predictions of high-impact, synoptic-scale weather events is well-established (e.g., Junker et al. 2009; Stuart and Grumm 2006). As computational power has increased, EPSs have been more recently developed to study problems on the mesoscale (e.g., Eckel and Mass 2005; Jones et al. 2007) where it is unknown whether equivalent forecast improvement can be achieved (e.g., Gallus et al. 2005). Arnett et al. (2007) described the creation of a sub-regional scale EPS over the northeastern United States (hereafter, Northeast Regional Ensemble, NRE) with the purpose of improving lake-effect snow (LES) forecasts. There are many examples of successful mesoscale model simulations of phenomena tied to fixed forcing mechanisms including LES (e.g. Colby 2004; Tucker and Cook 1999; Ballentine et al. 1998), suggesting that ensemble forecasts of such features may be useful to the operational forecaster.

LES develops over and downwind of the Great Lakes due to the combined effects of frictionally and thermally induced convergence as arctic air travels over the relatively warm lake waters (Holroyd 1971; Niziol 1987). Niziol et al. (1995) described five types of LES bands that can develop from this lake-air interaction. These bands range in character from intense single bands which result from winds that blow parallel to the long axis of the lake, to weaker multiple bands which develop when winds blow parallel to the short axis of the lake. Niziol et al. (1995) also addressed the operational need for improved mesoscale simulations of LES. Ballentine and Zaff (2007) examined Weather Research and Forecast (WRF) model simulations of LES downwind of Lakes Erie and Ontario for the 2006-2007 cool season. The goal of their study was to determine the optimal configuration for the WRF (in terms of model core [Advanced Research WRF (ARW); Skamarock et al. 2005 vs. Nonhydrostatic Mesoscale Model (NMM); Janjic 2004] and horizontal and vertical grid spacing) for forecasting lake-parallel LES (LP-LES) bands. Using numerous case study examples, they found a persistent southward bias in forecast snow band location, which was most pronounced using the WRF-ARW. This led them to conclude that an optimal configuration of WRF for LP-LES simulations would employ the WRF-NMM.

There are two primary objectives of this study: The first is to assess the operational usefulness of a mesoscale ensemble of LES. If the results from Ballentine and Zaff (2007) have continued through the 2007-2008 cool season, one would expect results from the NRE to be degraded, as WRF-ARW members would be expected to have a

southward bias in forecast LP-LES band position, adding artificial spread to the EPS. This would add uncertainty to any operational forecasts using such an ensemble system. This objective will be accomplished through two case studies from the 2007-2008 cool season, described in section 3.

The second goal of this study is to extend the Ballentine and Zaff (2007) research by examining the root cause for the WRF-ARW biases in LP-LES band position. This is carried out through a series of sensitivity simulations in section 4, with a possible improvement also discussed.

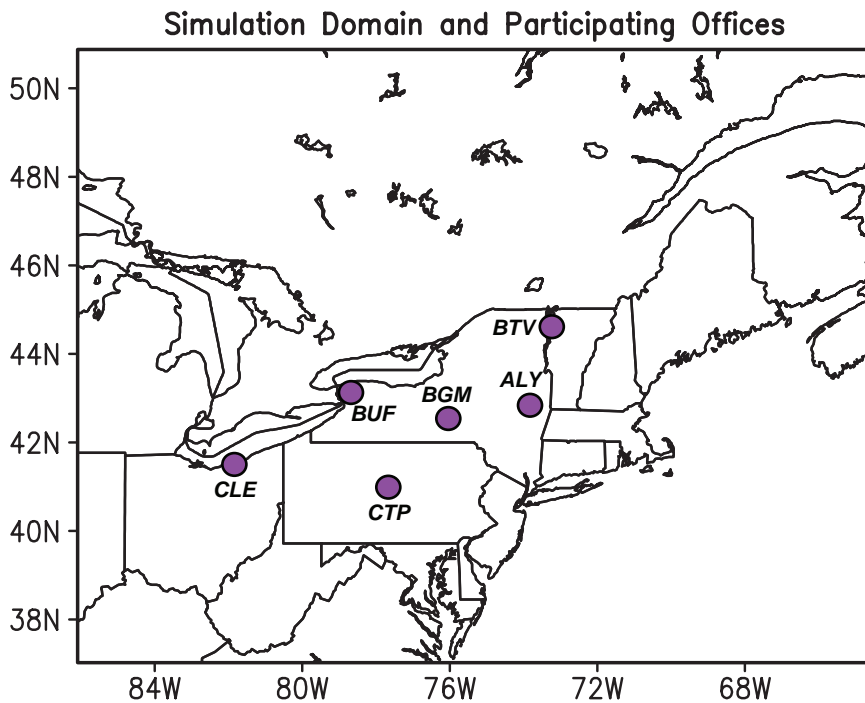
In section 5, conclusions from this study will be made. While it will be shown that a mesoscale ensemble can provide useful information to operational forecasts of LES, biased members severely limit the probabilistic guidance that the EPS provides. This highlights the importance of performing verification studies for each ensemble member to ensure all are of comparable skill.

## 2. Data and Methods

The NRE consists of six simulations produced by six separate National Weather Service (NWS) Weather Forecast Offices (WFOs) using the Workstation WRF Environmental Modeling System (WRF-EMS), distributed by the Cooperative Program for Operational Meteorology, Education and Training (COMET) at the University Corporation for Atmospheric Research (UCAR) (<http://strc.comet.ucar.edu/wrf>). These simulations are carried out on a common domain (see Fig. 1) encompassing the central and eastern Great Lakes and the northeastern United States. A horizontal grid spacing of 12-km is used in the simulations.

To achieve dispersion in the results produced by the six ensemble members, numerous parameters are varied, including model core (ARW vs. NMM), initial/boundary conditions (Global Forecast System [GFS; Kanamitsu 1989] vs. North American Mesoscale [NAM; Janjic 2004]), and various model physics parameters. Table 1 highlights the unique characteristics of each ensemble member. The NRE is basically a "poor man's ensemble" (e.g. Ebert 2001; Arribas et al. 2005), sampling initial condition uncertainty through differences in model observational data, assimilation and initialization schemes, rather than through the use of singular vector or breeding techniques. A local archive of NRE simulations was developed to aid in the study.

NRE simulations of 25 January 2008 and 11 February 2008 were examined in this study. This consisted of six, 24-hour simulations for each case. The outputted gridded binary (GRIB) data were examined using the Grid Analysis and Display System (GrADS; Doty 2002) software package.



**Fig. 1.** Map of NRE simulation domain with locations of participating NWS WFOs indicated as in Table 1.

Verification of the NRE was performed primarily on the quantitative precipitation forecasts (QPF) of the various ensemble members because the first goal of the NRE is to improve forecasts of LP-LES band location, timing and movement (Arnott et al. 2007). The QPF verification dataset used in this analysis was the National Centers for Environmental Prediction (NCEP) stage IV analysis (Lin and Mitchell 2005). For all other kinematic/thermodynamic fields, comparisons were made between the ensemble member forecasts and the closest available 13-km Rapid Update Cycle (RUC; Benjamin et al. 2004) model analysis.

### 3. Case Studies

#### a. Event 1: 25 January 2008

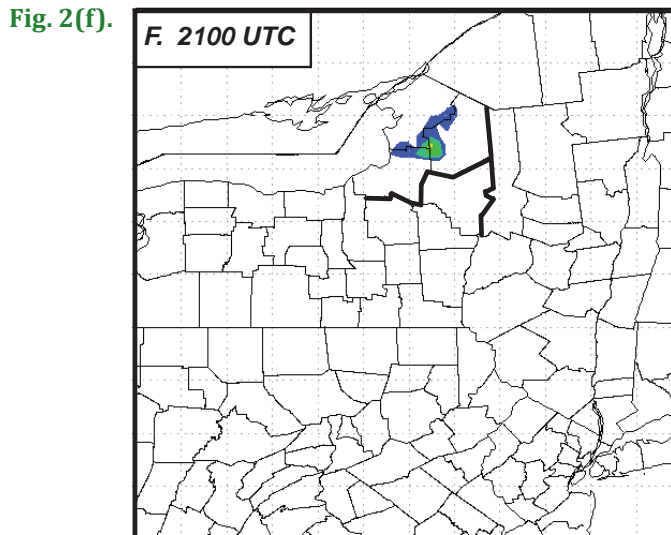
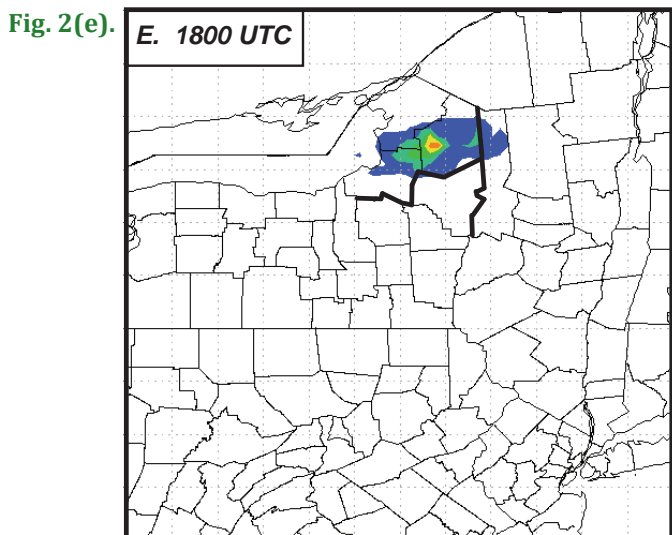
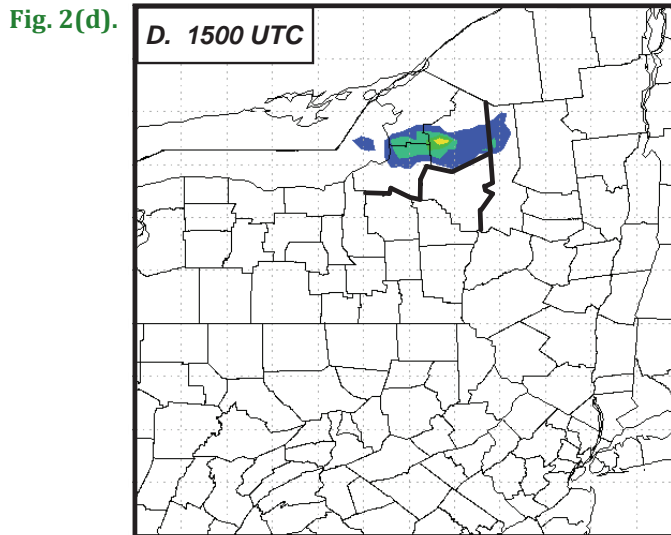
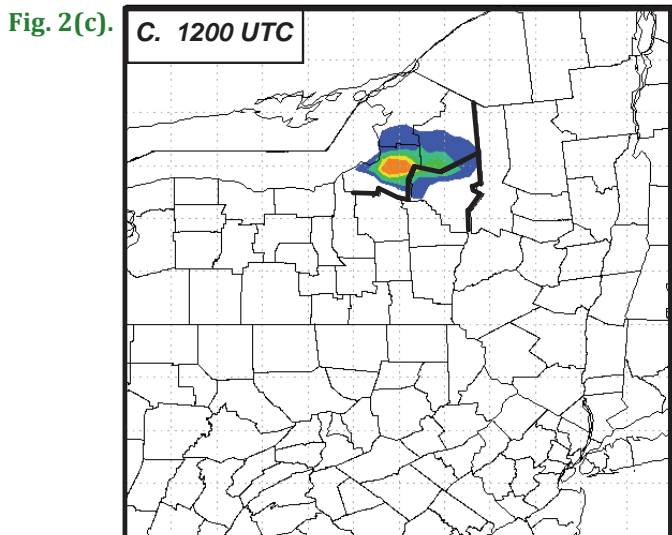
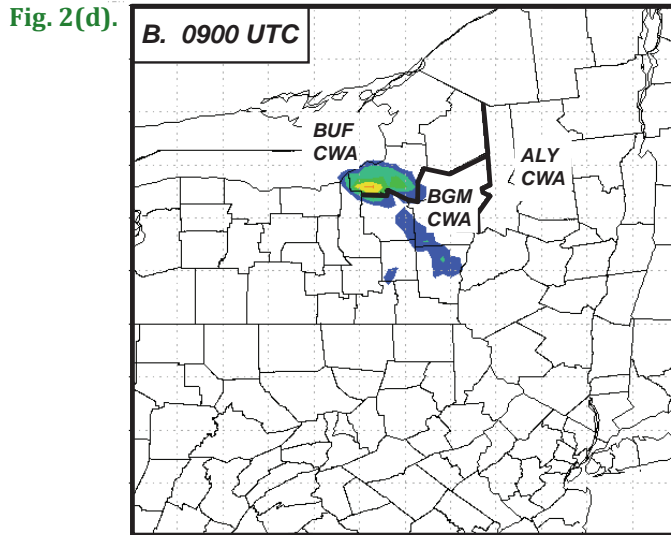
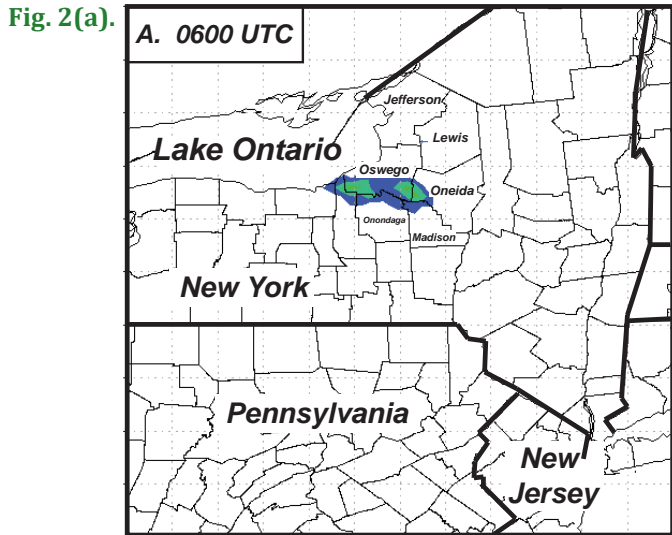
In the predawn hours of 25 January 2008, a relatively weak band of LES developed south and east of Lake Ontario, initially impacting portions of Oswego, Onondaga, Madison, and Oneida Counties in upstate New York (Fig. 2). As shown by the NCEP Stage IV observed precipitation, this LES band lifted north during

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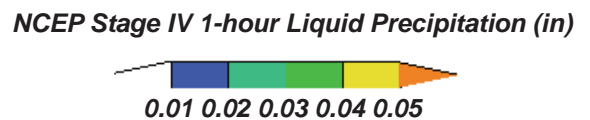
Office	Buffalo, NY (BUF)	State College, PA (CTP)	Burlington, VT (BTV)	Cleveland, OH (CLE)	Albany, NY (ALY)	Binghamton, NY (BGM)
WRF Core	NMM	NMM	NMM	ARW	ARW	ARW
Initial/ Boundary Conditions	GFS	NAM	GFS	GFS	NAM	NAM
Cumulus Scheme	Kain-Fritsch	Betts-Miller-Janjic	Betts-Miller-Janjic	Kain-Fritsch	Kain-Fritsch	Kain-Fritsch
Microphysics	Ferrier	Ferrier	Ferrier	Lin	Lin	Ferrier
Planetary Boundary Layer	MYJ	MYJ	MYJ	Yonsei	Yonsei	Yonsei
Land Surface	NMM LSM*	NMM LSM*	NMM LSM*	NOAH	NOAH	NOAH
Surface Layer	Janjic	Janjic	Janjic	MM5	MM5	MM5
Longwave/ Shortwave Radiation	GFDL	GFDL	GFDL	RRTM/ Dudhia	RRTM/ Dudhia	RRTM/ Dudhia

\*The NMM Land Surface Model (LSM) is another version of the NOAH model, but is fundamentally very similar (S. Jascourt, personal communication, 2008)

**Table 1.** Configuration of each NRE member.



**Fig. 2.** NCEP Stage IV liquid precipitation analyses (inches) for (a) 0600 UTC, (b) 0900 UTC, (c) 1200 UTC, (d) 1500 UTC, (e) 1800 UTC, and (f) 2100 UTC on 25 January 2008. Analyses indicate amount of liquid precipitation observed during the previous one hour. Relevant political boundaries are indicated in a.) and relevant WFO CWA boundaries are indicated in b-f.).



the morning hours of 25 January 2008, eventually taking up residence over Oswego, Jefferson, and Lewis Counties, just north of Oneida County, the northernmost county in the NWS Binghamton, NY (BGM) County Warning Area (CWA) (e.g., Fig. 2d).

Figure 3 shows the evolution of the simulated LES band in the NRE, both in a probabilistic form, as well as in terms of a mean QPF and spaghetti plot. This figure, in comparison to the NCEP Stage IV analysis in Fig. 2 indicates that the NRE had some success in anticipating band development, and the eventual shift northward in band location. However, two potential shortcomings exist in these simulations. First, low relative frequency values shown in Fig. 3 suggest a low confidence in band location, particularly before 1200 UTC. This is because not all of the ensemble members actually forecast a LES band during portions of the simulation (e.g., the CLE WRF-ARW simulation). Secondly, the NCEP Stage IV analysis indicated the LES band had moved north of the BGM CWA by 1500 UTC on 25 January 2008, remaining north of the BGM CWA thereafter. Figure 3c indicates, however, that 30-50 percent of the NRE members kept a band over northern Oneida County during this period, which would have had significant operational ramifications if this solution were used to produce a public forecast.

To help isolate which members had the most difficulty simulating band location, the WRF-ARW and WRF-NMM members are separated into two groups in Fig 4. This figure shows that through much of the run, including the post-1500 UTC window mentioned above, the WRF-ARW NRE members (those that indicated band development) were consistently farther south with band location than the NMM members, and were almost completely on their own in maintaining the band over Oneida County after 1500 UTC.

In summary, while results from the NRE were initially encouraging, in the fact that the guidance indicated the potential for band development in the proper location and the subsequent northward shift in band location, the problems mentioned above are troubling. We next examine a second case from 11 February 2008 to see if the results shown in this case study repeat themselves.

#### *b. Event 2: 10-11 February 2008*

On 10-11 February 2008, a “classic” LP-LES event occurred as a westerly flow of arctic air developed over Lake Ontario behind a departing cold front. The 24-hour simulation examined in this section was initialized at 1200 UTC 10 February 2008. During the second half of the simulation period, an examination of the NCEP Stage IV analysis indicated an intense, LP-LES band persisting along and east of Lake Ontario (Fig. 5).

Output from the NRE encompassing the second half of the simulation is shown in Fig. 6. This figure shows that each of the member forecasts successfully anticipated the development of a LP-LES band. Also, the position of this band was forecast quite well with the greatest overlap between simulations occurring near the location of the band in the NCEP Stage IV data (cf. Figs. 5 and 6). A closer inspection reveals some question as to whether the band would impact the Syracuse metro area and areas of northern Madison County. While the NCEP Stage IV analysis indicated that these areas were not impacted by the actual LES band (Fig. 5), the spaghetti plot in Fig. 6 shows that some of the ensemble members brought the band into the Syracuse area as early as 0000 UTC 11 February 2008, with a majority of the ensemble members bringing precipitation to Syracuse in the final hours of the simulation (0800-1200 UTC; Fig. 6c). As this was not observed, an analysis of member performance is warranted.

In Fig. 7 the color-coding has been changed to group simulations using the WRF-ARW and WRF-NMM. This figure clearly shows that the ARW members forecasted the LES band location to the south of the NMM members, with the ARW members bringing snow to Syracuse earliest and for the longest duration. Forecasts using these members alone might indicate advisory (4-6 inches, 10-15 cm) or even warning-criteria (7+ inches, 18+ cm) amounts of snowfall given the residence time of the forecast LP-LES band over Syracuse in these simulations (not shown). While the NMM band location was also too far to the south towards the end of the simulation, the overall error is less.

The particularly poor skill of the WRF-ARW members in this forecast from 0000-1200 UTC 11 February 2008 is troubling given the consistent southward shift in band location between the WRF-ARW members compared to those using the WRF-NMM.

The persistent southward bias in the forecast LP-LES band location shown in these two case studies is consistent with the results of Ballentine and Zaff (2007), who found that while both WRF cores showed a southward bias with forecast LP-LES band location, the bias for the WRF-ARW was significantly greater. The reasoning for this bias is explored in the next section.

## **4. Sensitivity Simulations**

### *a. Isolating bias source*

To diagnose the cause for this bias, numerous sensitivity simulations were performed, changing model parameters in hopes of identifying a root cause. The

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Fig. 3(a)

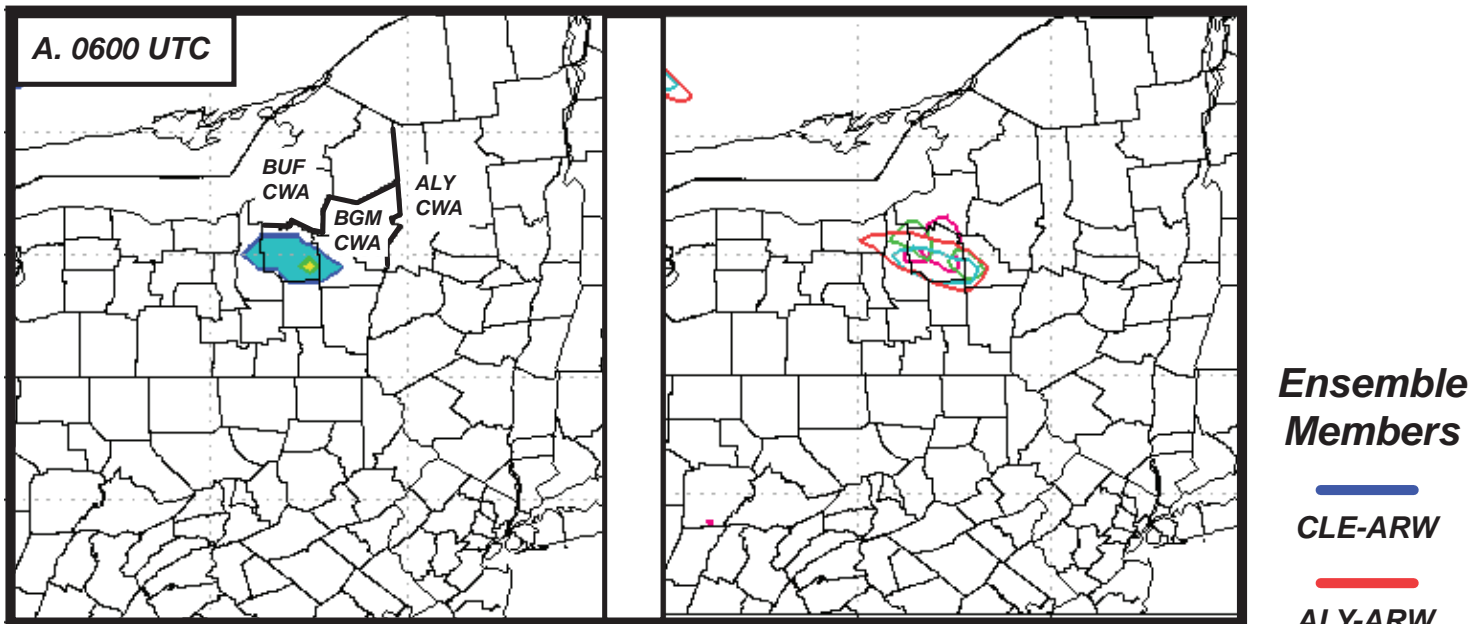
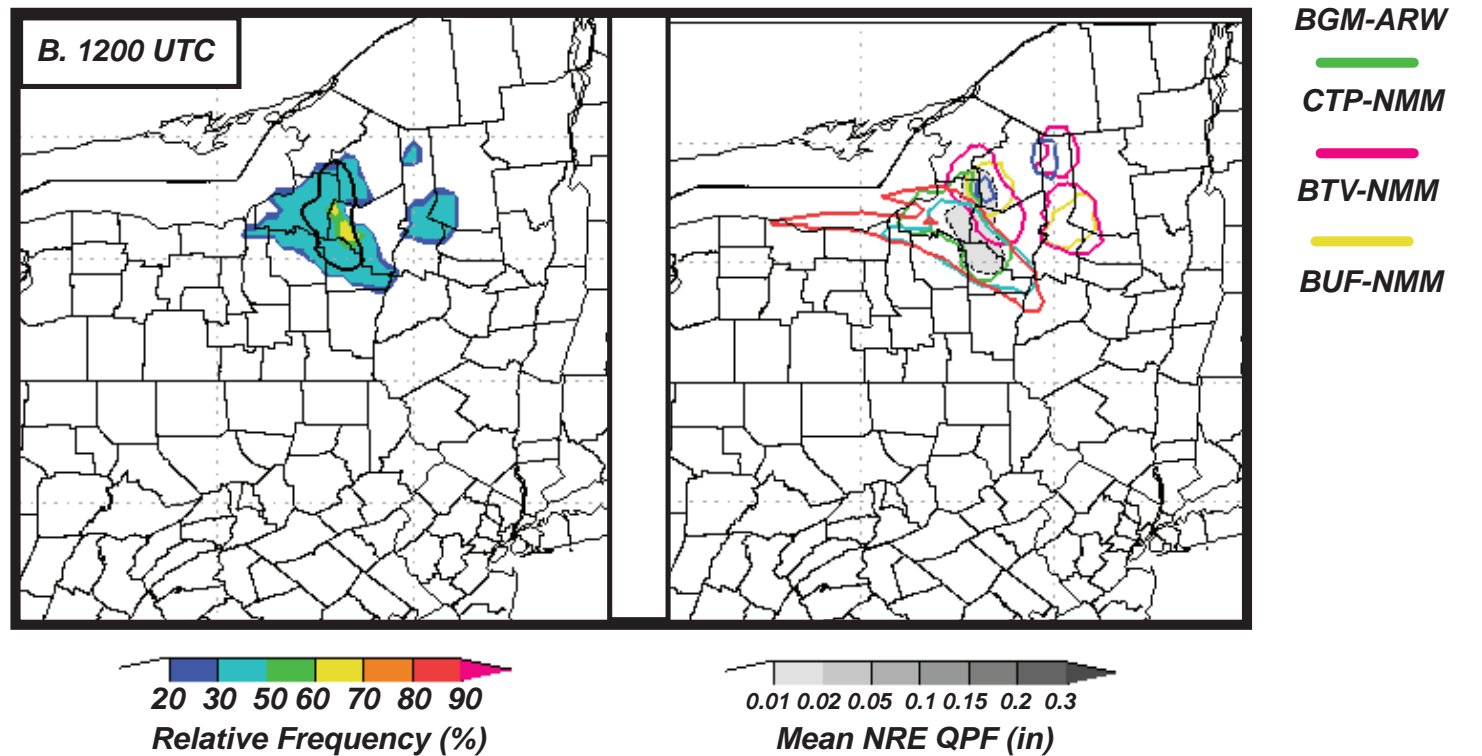
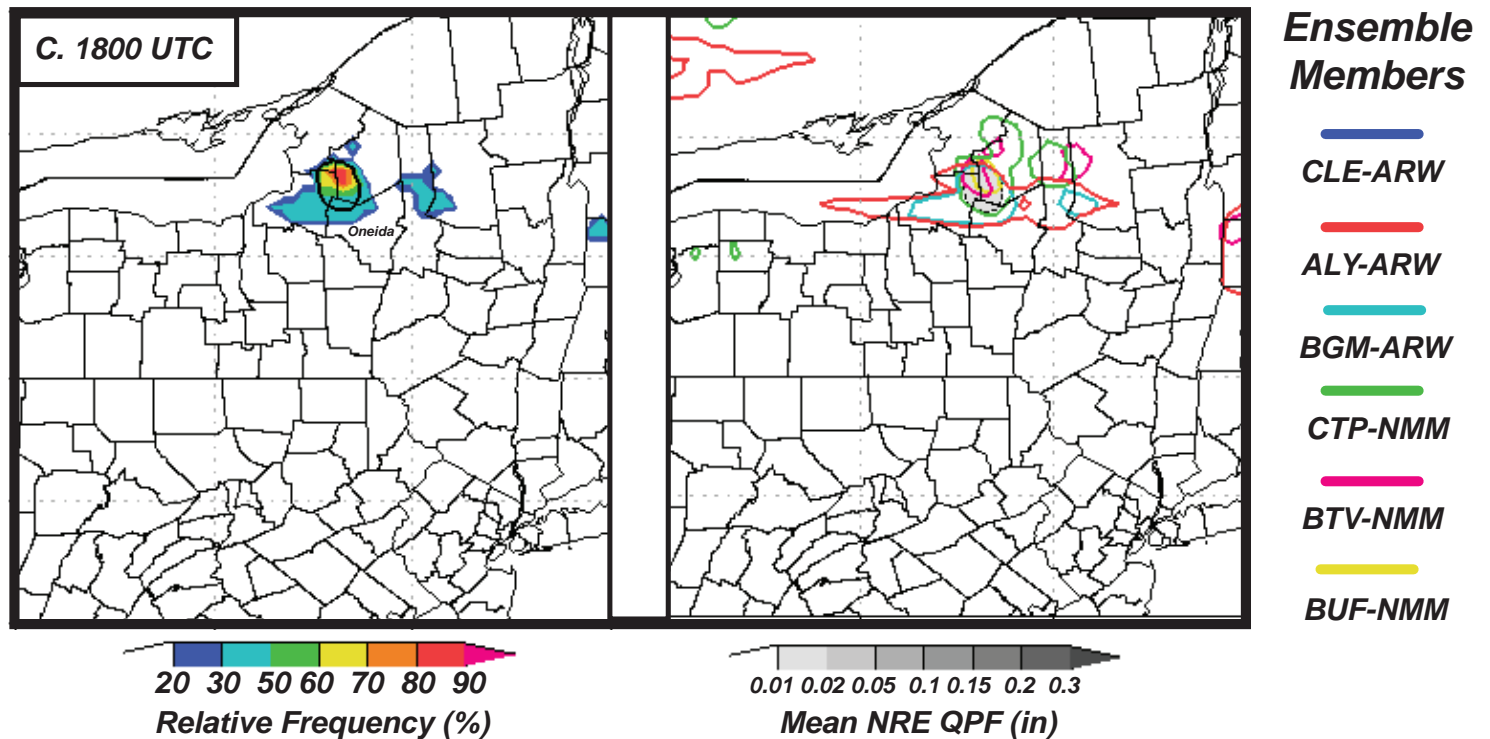


Fig. 3(b)



**Fig. 3.** NRE liquid precipitation forecasts (inches) for (a) 0600 UTC, (b) 1200 UTC, and (c) 1800 UTC on 25 January 2008. Left panels show relative frequency (percent and shaded) of ensemble members forecasting 0.01-in of liquid precipitation in the previous hour along with the ensemble mean 0.01-in contour (solid black line). Right panels show spaghetti plots of 0.01-in QPF contours (solid) from individual ensemble members (members shown at right) as well as the mean QPF forecast (dashed contours and shading). Relevant WFO CWA boundaries are indicated in a.).

Fig. 3(c)



model physics schemes used in the CTP-NMM and BGM-ARW simulations, as well as for three additional sensitivity simulations, are shown in Table 2. Each sensitivity simulation was made to change the BGM-ARW simulation in such a way that it shared more in common with the CTP-NMM simulation, which showed superior LES forecasts for the events mentioned in sections 3a and 3b. In the third experiment the simulations were virtually identical, except for model core (which remained WRF-ARW for all three experiments).

Output from the three sensitivity simulations, plotted against that of the original BGM-ARW simulation, is shown in Fig 8. The sensitivity simulations are virtually identical to the original BGM run with each displaying a similar southward position bias. This result suggests that the southward bias may be caused by the core itself rather than any model physics settings.

#### *b. Physical explanation of bias*

Given that LES bands are strongly driven by boundary layer processes, a closer examination of these processes in the WRF-ARW members of the NRE was performed in an attempt to isolate a cause for the bias. In this section, output from two simulations of the 11 February 2008 event is compared: the CTP-NMM simulation and experiment 3 from section 4a (hereafter referred to as EXP3-ARW). As shown in Table 2, the EXP3-ARW is virtually identical

in configuration to the CTP simulation, aside from the WRF core. The principal goal for these simulations is to isolate core-specific model differences in handling the evolution of this event, and how those differences may be responsible for the southward position bias seen in all ARW simulations shown in this study.

In comparing the CTP-NMM and EXP3-ARW, it quickly became apparent that the low-level wind fields in each of these simulations were dramatically different. To help illustrate this difference, the 10 m wind speed (averaged over the entire 24-hour simulation) is shown in Fig. 9 for each of the simulations. While the minimum and maximum values across the domain in each simulation are similar, wind strength over land areas downwind of the Great Lakes (circled areas in Fig. 9) is significantly greater in the EXP3-ARW simulation than the CTP-NMM simulation. Figure 9 shows wind speed values downwind of Lake Huron over southwest Ontario nearly  $10 \text{ m s}^{-1}$  stronger in the EXP3-ARW simulation. Given that the observational network is not nearly dense enough to provide a gridded verification dataset with which to verify against, we used a RUC analysis as our closest approximation to actual values. This analysis clearly shows the CTP-NMM to be the more accurate simulation. To ensure that this difference is representative of more than just this vertical level (e.g., a potential artifact of the 10 m wind derivation from other model levels), this analysis was repeated at a

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Fig. 4(a).

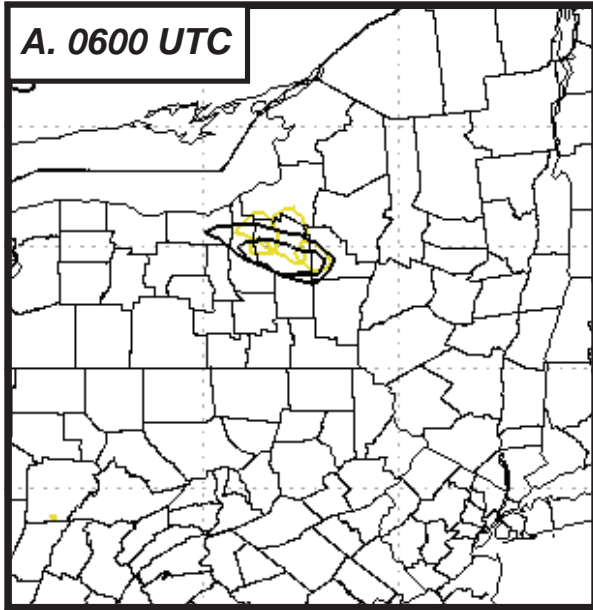


Fig. 4(b).

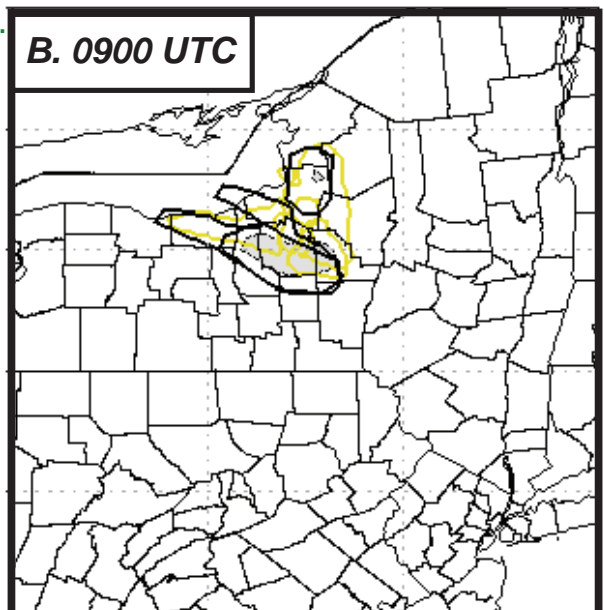


Fig. 4(c).

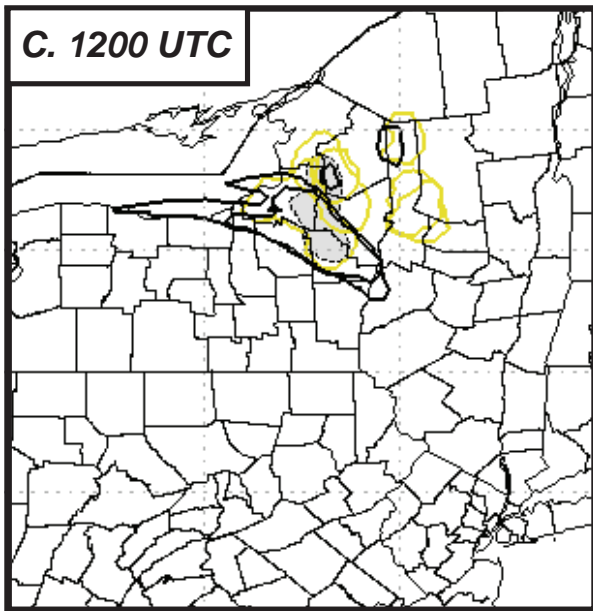


Fig. 4(d).

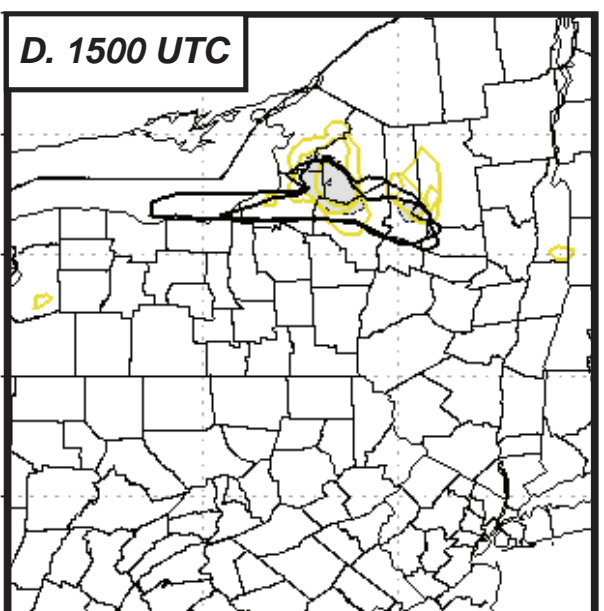
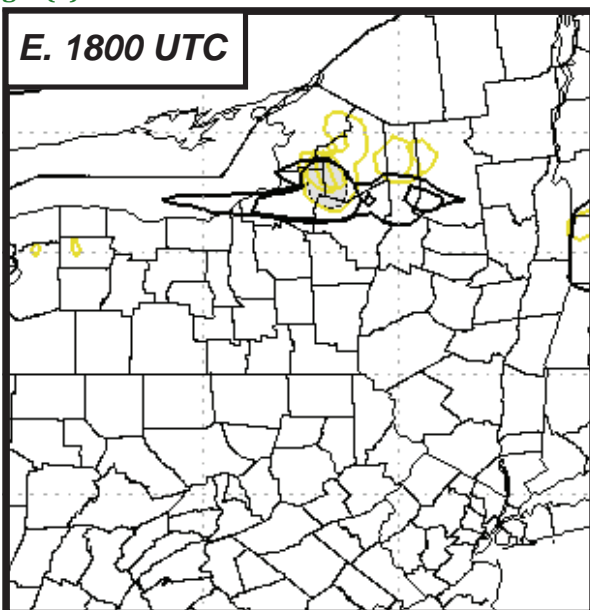


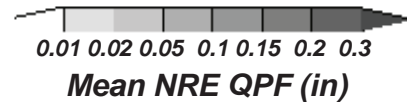
Fig. 4(e).



**Ensemble Members**

— WRF-ARW

— WRF-NMM



**Fig. 4.** Spaghetti plot of one hour 0.01-in QPF contours from individual NRE members with WRF-ARW and WRF-NMM members differentiated by color. Mean NRE QPF is shaded. Times shown are (a) 0600 UTC, (b) 0900 UTC, (c) 1200 UTC, (d) 1500 UTC, and (e) 1800 UTC on 25 January 2008.



Fig. 5(a).

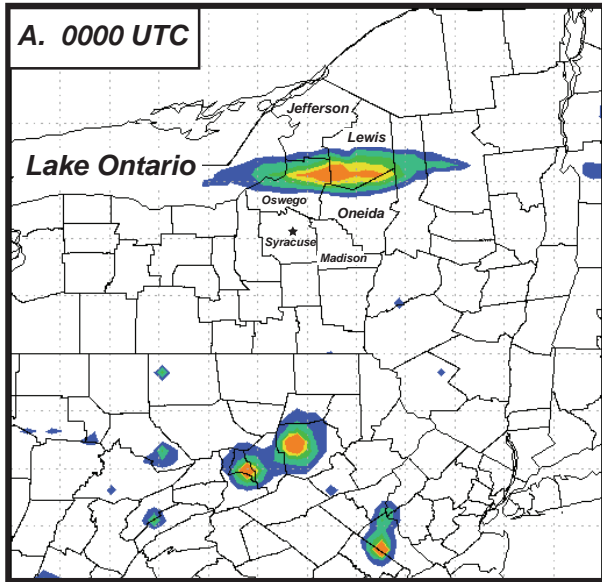


Fig. 5(b).

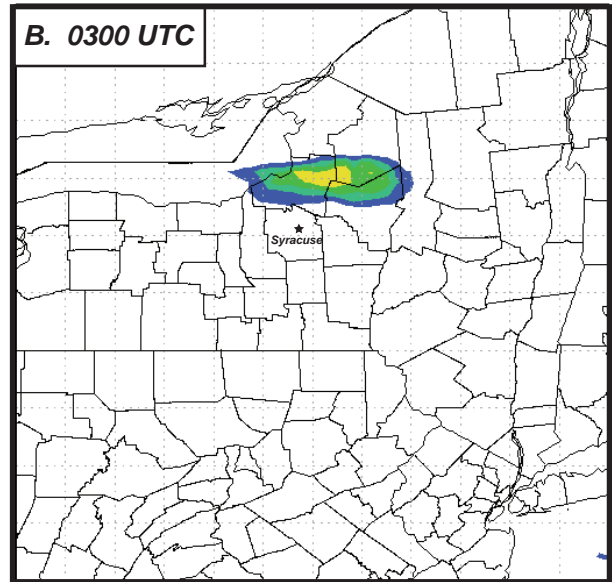


Fig. 5(c).

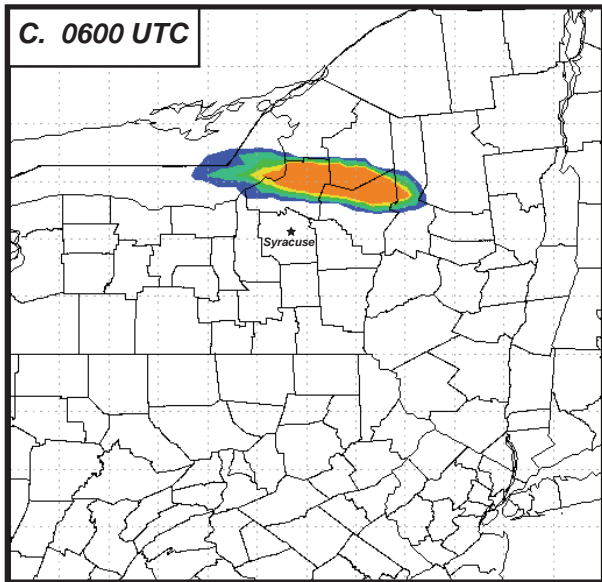


Fig. 5(d).

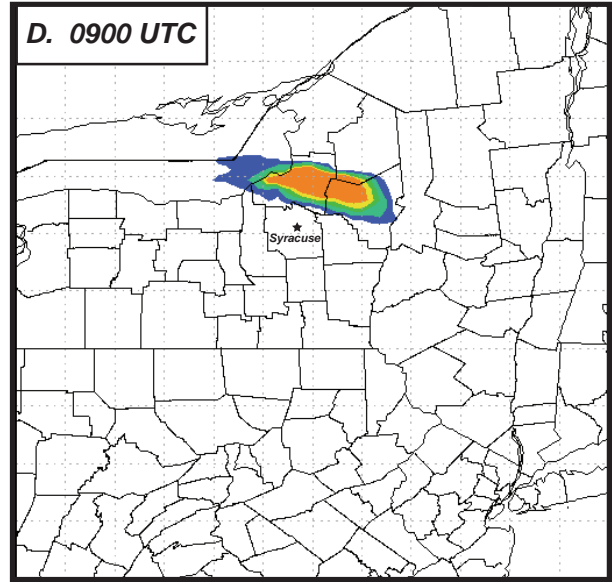
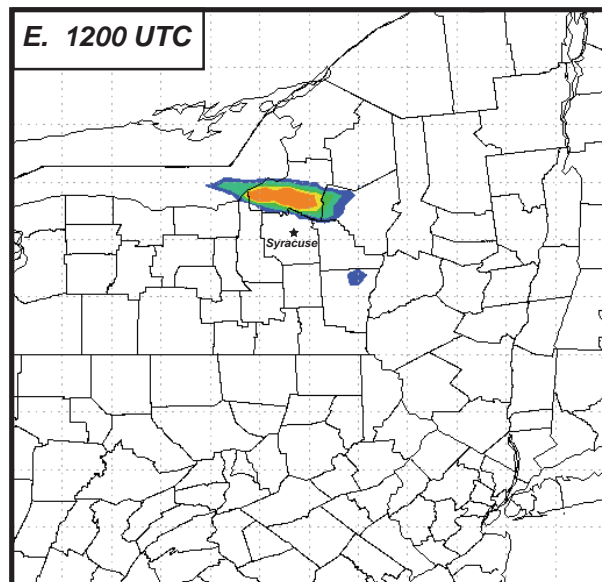


Fig. 5(e).



NCEP Stage IV 1-hour Liquid Precipitation (in)

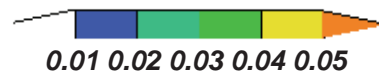


Fig. 5. NCEP Stage IV liquid precipitation analyses for (a) 0000 UTC, (b) 0300 UTC, (c) 0600 UTC, (d) 0900 UTC, and (e) 1200 UTC on 11 February 2008. Analyses indicate amount of liquid precipitation (inches) observed during the previous one hour.

Fig. 6(a)

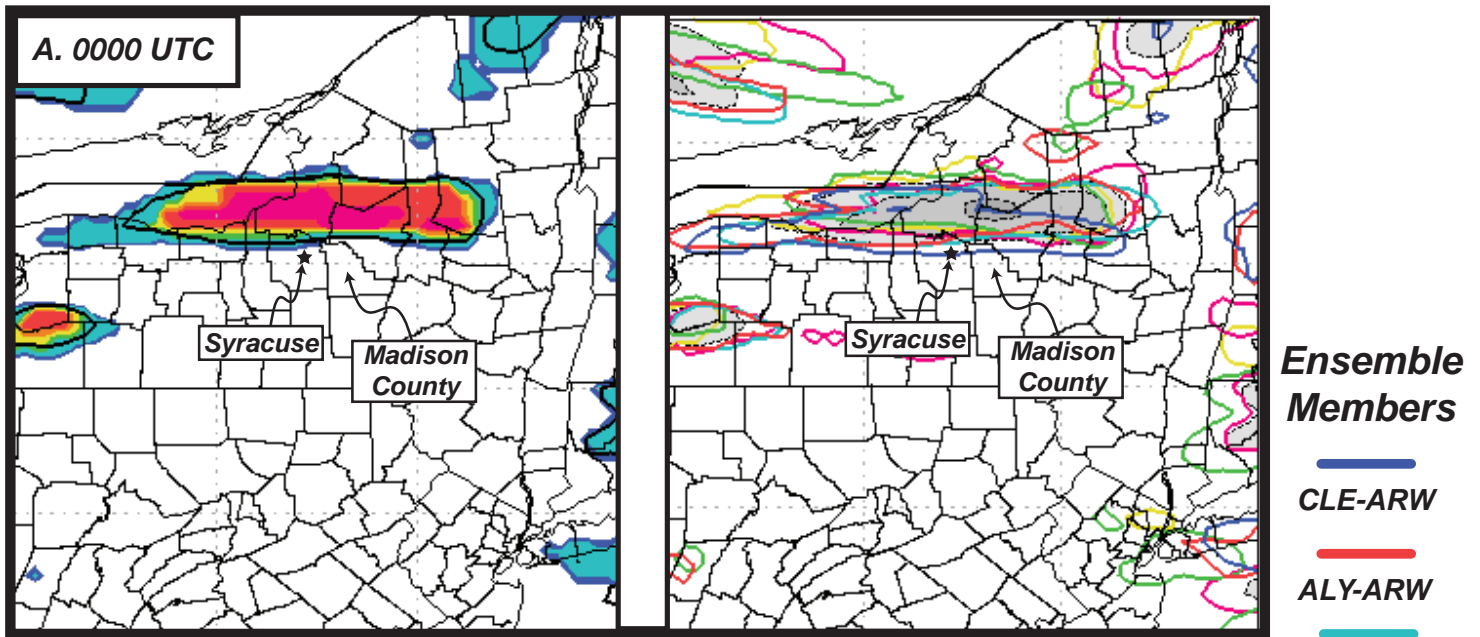
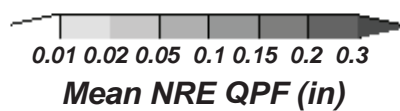
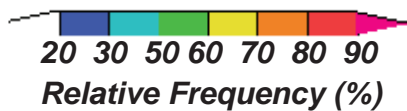
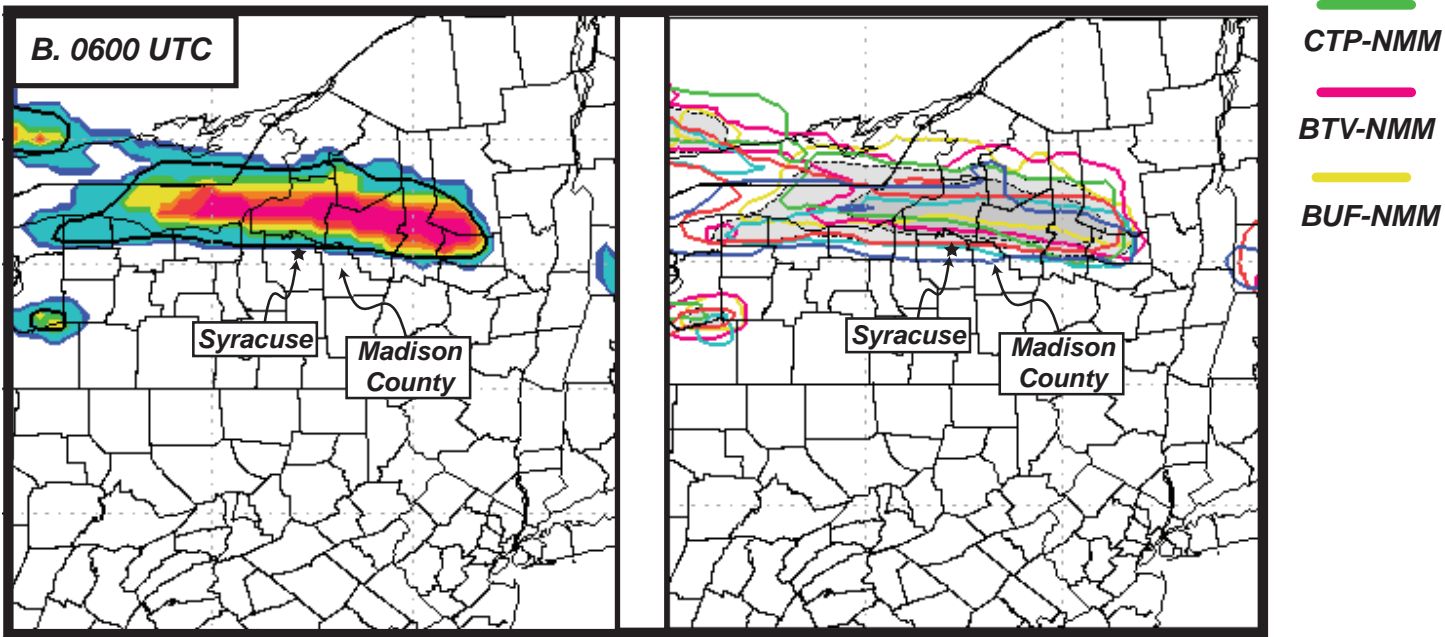
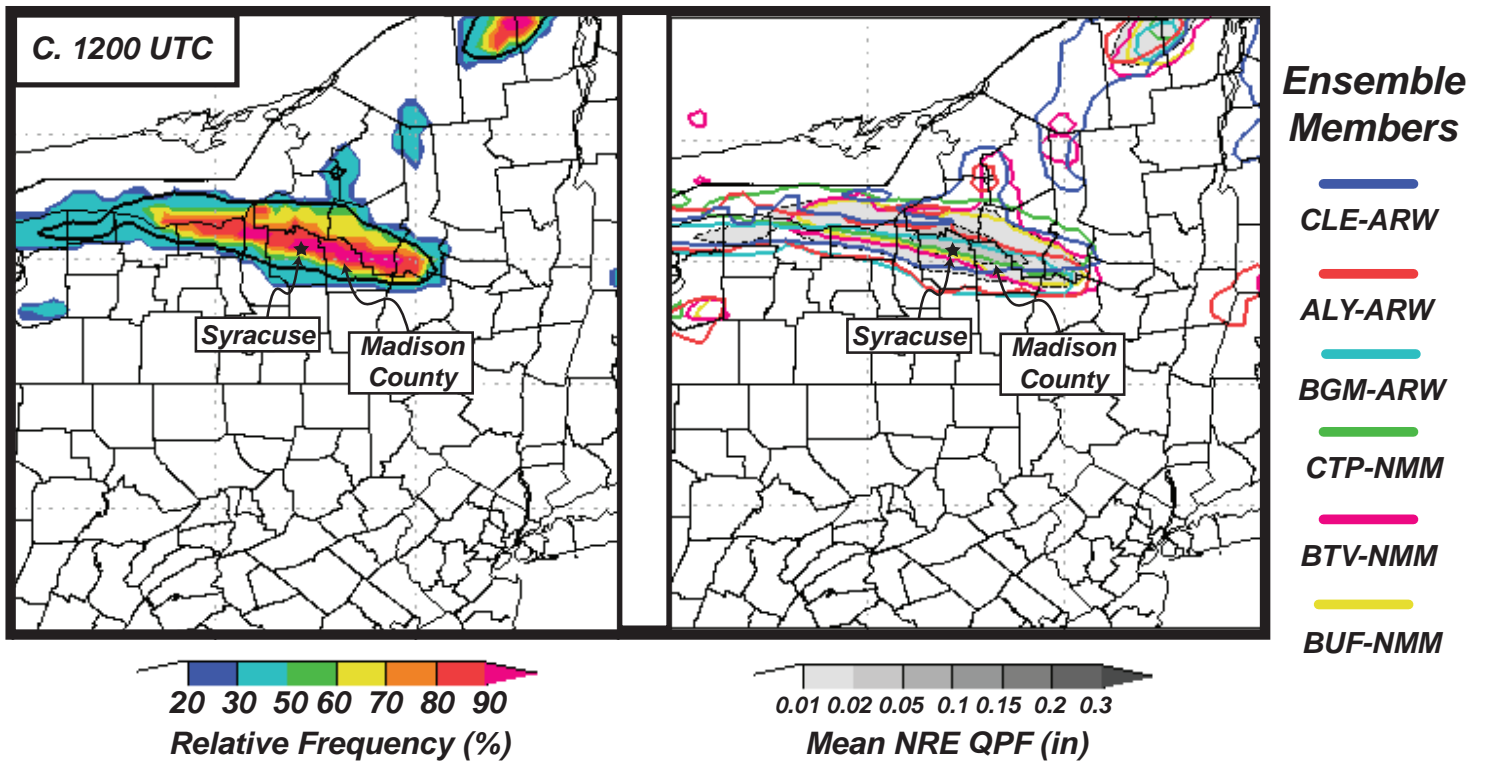


Fig. 6(b)



**Fig. 6.** NRE liquid precipitation forecasts (inches) for (a) 0000 UTC, (b) 0600 UTC, and (c) 1200 UTC on 11 February 2008. Left panels show relative frequency (percent and shaded) of ensemble members forecasting 0.01-in of QPF in the previous hour along with ensemble mean 0.01-in contour (solid black line). Right panels show spaghetti plots of 0.01-in QPF contours from individual ensemble members (members shown at right) as well as mean QPF forecast (shading).

Fig. 6(c)



number of levels in the boundary layer, with all showing the same behavior (not shown). Finally, this behavior was present in all of the WRF-ARW simulations, while none of the WRF-NMM simulations showed such a behavior.

From this cursory examination, it appears that the WRF-ARW simulations underrepresented the frictional effect of the land masses downwind of the Great Lakes. We now examine how this erroneous boundary layer flow led to a southward bias in forecast snow band location. From Holroyd (1971), if the prevailing wind direction is parallel to the shoreline of a lake (in our case, westerly), more cross-isobar flow over the land mass south of the lake versus that over the lake (due to greater friction over the land mass) will result in a convergence band near the shoreline. In the more accurate CTP-NMM simulation, winds east of Lakes Huron and Erie back southwesterly as expected, forcing a convergence zone over the center of Lake Ontario (Fig. 10a). In the biased EXP3-ARW simulation, however, *the lack of frictional slowing downwind of Lake Huron, as well as Lake Erie, led to the flow in these areas being more westerly with only a very weak southerly component* (Fig. 10b). This weaker southerly component allowed the frictionally-induced convergence line associated with the LP-LES band to develop farther south in EXP3-ARW, apparently causing the observed bias.

The next step in our investigation was to determine

when and how these overly-strong winds in the ARW simulations developed. Hourly model output indicated that this bias was already in place one hour into the simulation (not shown). Therefore, minute-by-minute output from EXP3-ARW and CTP-NMM simulations were examined during the first 30 minutes of the simulation. This high-temporal resolution demonstrated the initial development of the overly-strong flow downwind of the lakes. A series of minute-by-minute plots of the zonal ( $u$  component) of the 1000 hPa flow showed how during the first minutes of the simulation, momentum transfer brought the initially stronger winds upstream over Lake Huron onto land over southwest Ontario. Conversely, in the CTP-NMM simulation, these strongest winds remained over water, the differences between these two simulations growing over time (not shown).

Plots of  $\Delta u/\Delta t$  in one-minute intervals from simulation EXP3-ARW show that this behavior was mainly confined to the lowest  $\sim 75$  hPa of the domain, with winds over the land strengthening with time, while winds over the water remained much more constant (not shown). When  $\Delta u/\Delta t$  is plotted for the CTP-NMM simulation, a more interesting behavior is found. Every five minutes in the simulation, there is a strong negative  $u$  tendency that is maximized over southwestern Ontario (Fig. 11). This negative tendency essentially kept the boundary layer winds from becoming

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Fig. 7(a).

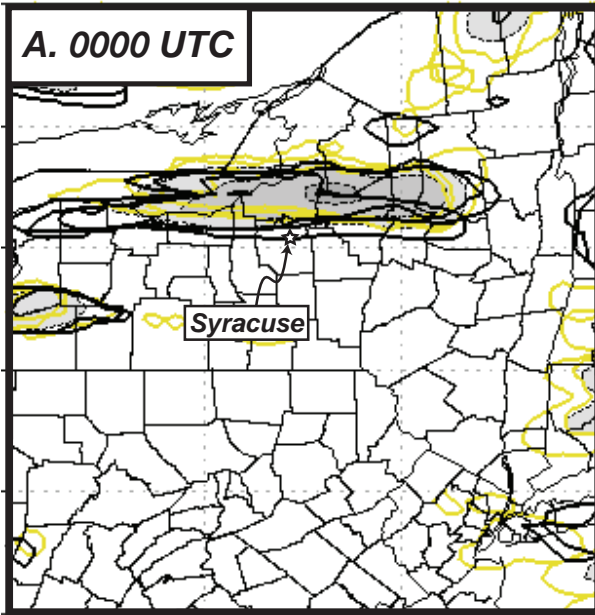


Fig. 7(b).

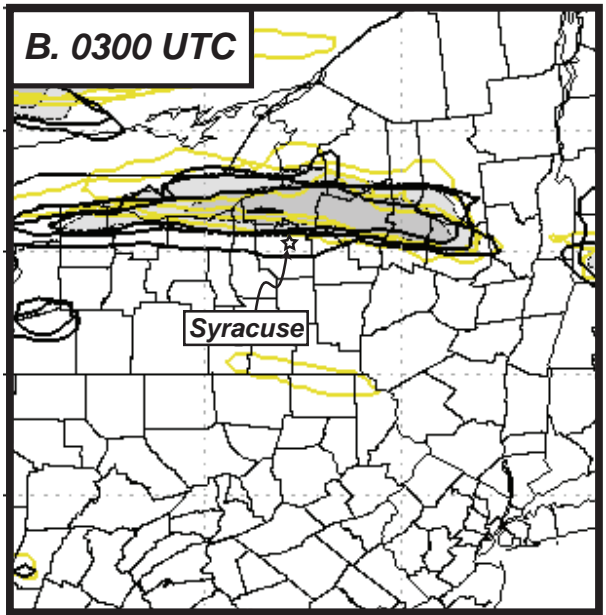


Fig. 7(c).

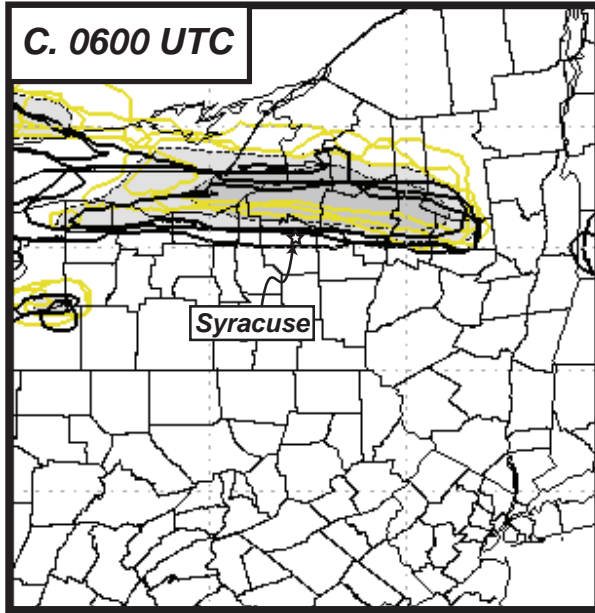


Fig. 7(d).

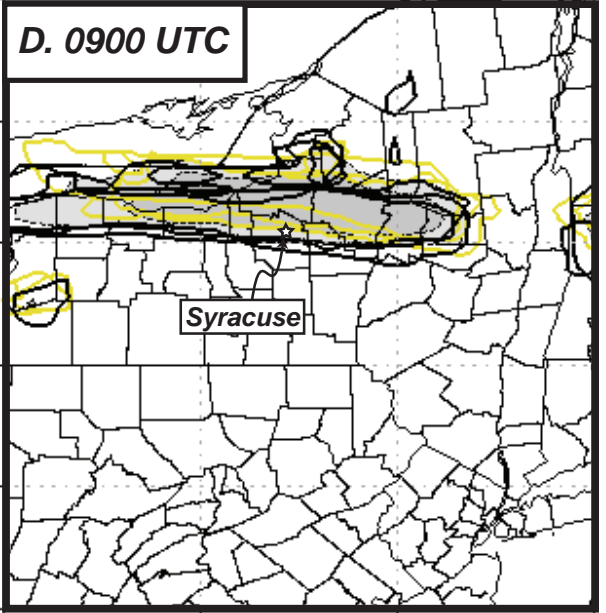
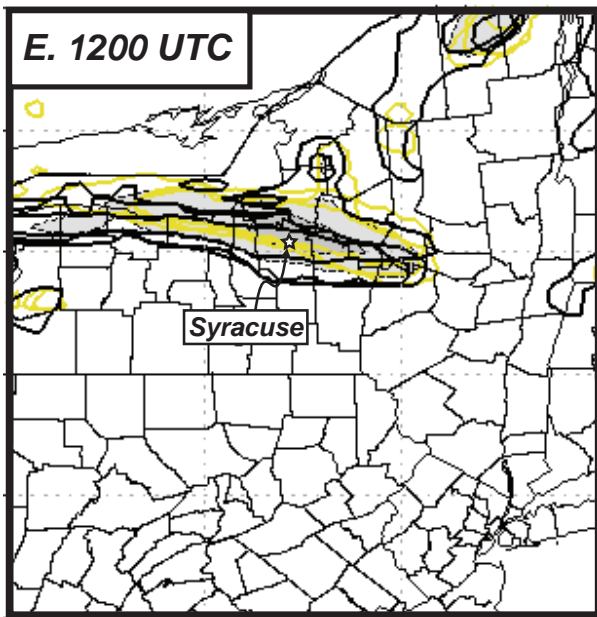


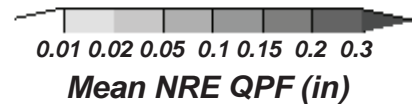
Fig. 7(e).



**Ensemble Members**

— WRF-ARW

— WRF-NMM



**Fig. 7.** Spaghetti plot of one-hour 0.01-in QPF contours from individual NRE members with WRF-ARW and WRF-NMM members differentiated by color. Mean NRE QPF shown in shading. Times shown are a.) 0000 UTC, b.) 0300 UTC, c.) 0600 UTC, d.) 0900 UTC, and e.) 1200 UTC on 11 February 2008.

Simulation Name	CTP	BGM	EXP1	EXP2	EXP3
WRF Core	NMM	ARW	ARW	ARW	ARW
Initial/Boundary Conditions	NAM	NAM	NAM	NAM	NAM
Cumulus Scheme	Betts-Miller-Janjic	Kain-Fritsch	Betts-Miller-Janjic	Betts-Miller-Janjic	Betts-Miller-Janjic
Microphysics	Ferrier	Ferrier	Ferrier	Ferrier	Ferrier
Land Surface	NMM LSM*	NOAH**	NOAH	NOAH	NOAH
Planetary Boundary Layer	MYJ	Yonsei	Yonsei	MYJ	MYJ
Surface Layer	Janjic	MM5	MM5	Janjic	Janjic
Longwave Radiation	GFDL	RRTM	RRTM	RRTM	GFDL
Shortwave Radiation	GFDL	Dudhia	Dudhia	Dudhia	GFDL

\*The NMM LSM is another version of the NOAH model, but is fundamentally very similar (S. Jascourt, personal communication, 2008).

\*\*The NOAH LSM was a collaborative project involving the (N)ational Centers for Environmental Prediction, (O)regon State University, (A)ir Force and the NWS (H)ydrologic Research Lab.

**Table 2.** Configuration of CTP, BGM NRE members and members of sensitivity simulations discussed in section 4.

anomalously strong, unlike what was found in the EXP3-ARW simulation. This behavior is consistent with the fact that the Planetary Boundary Layer (PBL) scheme was set to activate every 5 minutes. The fact that this behavior is not seen in the EXP3-ARW simulation is troubling, especially since the PBL scheme was set to activate at the same time interval in this simulation. This is clearly why the difference in low-level wind speed develops within the first hour of the simulation, and is very likely the reason for the eventual difference in forecast LES band position between these simulations.

*c. Examining a possible fix*

In the spring of 2008, the National Center for Atmospheric Research (NCAR) released version 3.0 of the WRF-ARW. From sections 3 and 4a-b, it appears likely that the LES band forecast position bias was a function of the WRF dynamic core, rather than individual physics settings. Therefore, it is reasonable to question whether an upgraded version of WRF-ARW would help improve the observed bias.

The full code version 3.0 of WRF-ARW was downloaded from NCAR and compiled locally as the WRF-EMS version of this new release was in development but not yet available at the time of this research. A sensitivity simulation was then carried out to compare WRF-ARW version 2 to

WRF-ARW version 3 (as well as the far less-biased CTP-NMM simulation described in section 3). The version 3 simulation was configured with identical physics settings to the version 2 case. This was done to isolate changes solely caused by the core upgrade.

A comparison of 10 m wind speed and QPF from WRF-ARW version 3, CTP-NMM, and EXP3-ARW is shown in Fig. 12. The QPF fields clearly show an improvement in the forecast snow band position from the WRF-ARW version 3 simulation. The results are in much better agreement with the NCEP stage IV analysis, with the band location farther north relative to the EXP3-ARW, and in closer agreement to what was observed. A comparison of the 10 m wind speed from each simulation confirms that the WRF-ARW version 3 simulation outperformed the EXP3-ARW simulation with speed reduction on the order of 20 percent. Even with this improvement, however, the 10 m wind speed remained higher than that in CTP-NMM and the RUC analysis, suggesting that while the upgrade in core provides an improvement, it is not a complete solution to the problem.

While these results are not proof that the upgrade to version 3 of WRF-ARW would improve the position bias in every case, the fact that this sensitivity simulation as described with identical settings apart from the version of

*Continued page 82*

Fig. 8(a).

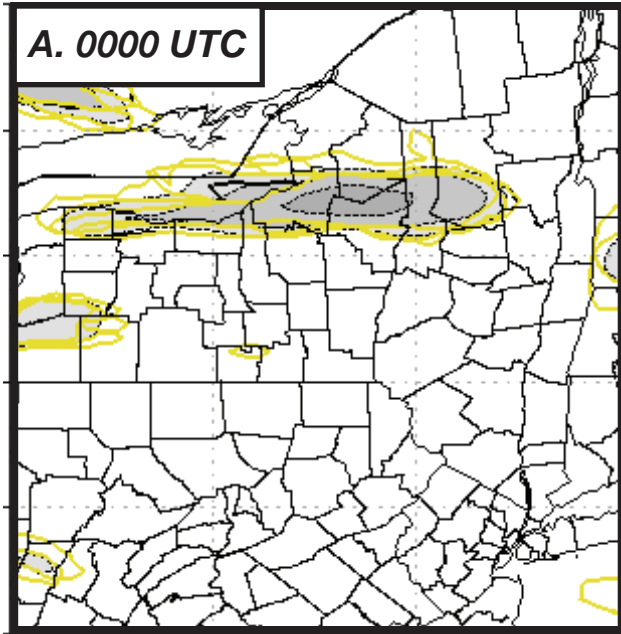


Fig. 8(b).

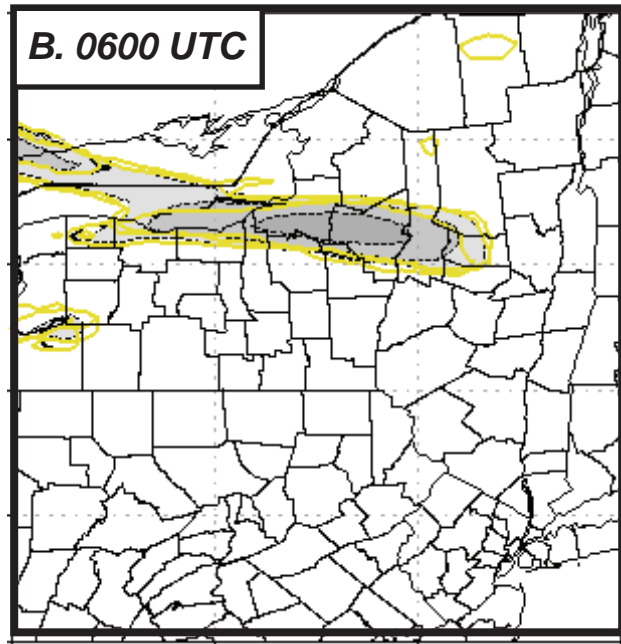
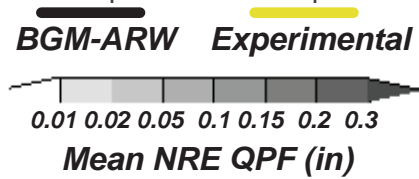
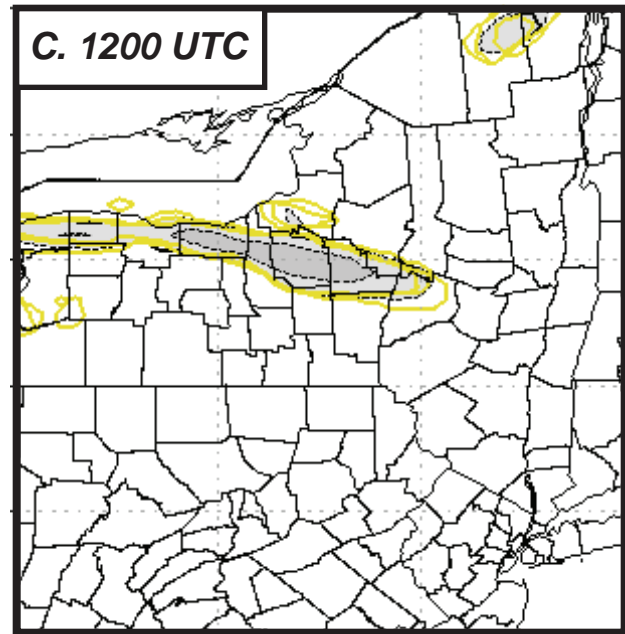


Fig. 8(c).



**Fig. 8.** Plot of 0.01-in one hour QPF contours from BGM-ARW and three experimental simulations. Mean NRE QPF shown in shading. Times shown are (a) 0000 UTC, (b) 0600 UTC, and (c) 1200 UTC on 11 February 2008.

Fig. 9(a).

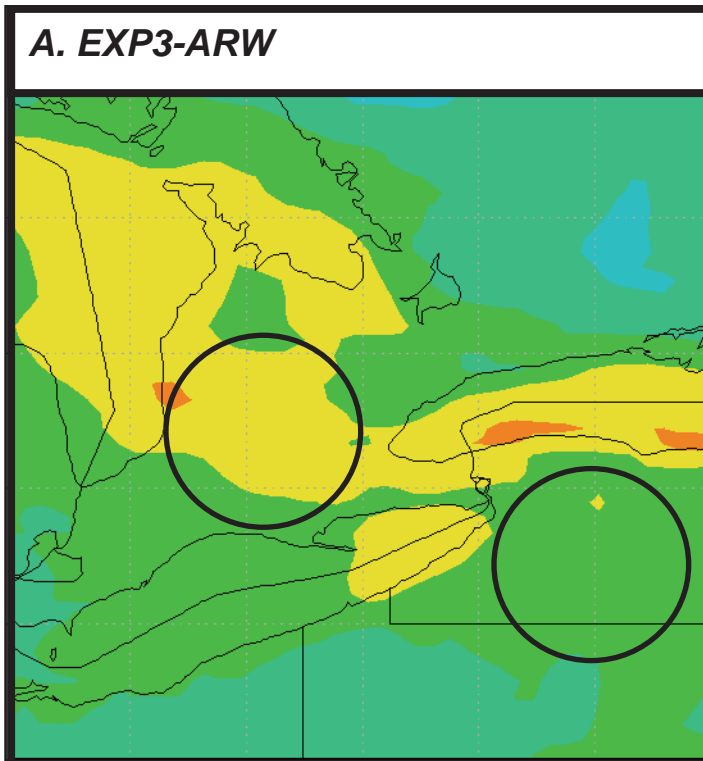


Fig. 9(b).

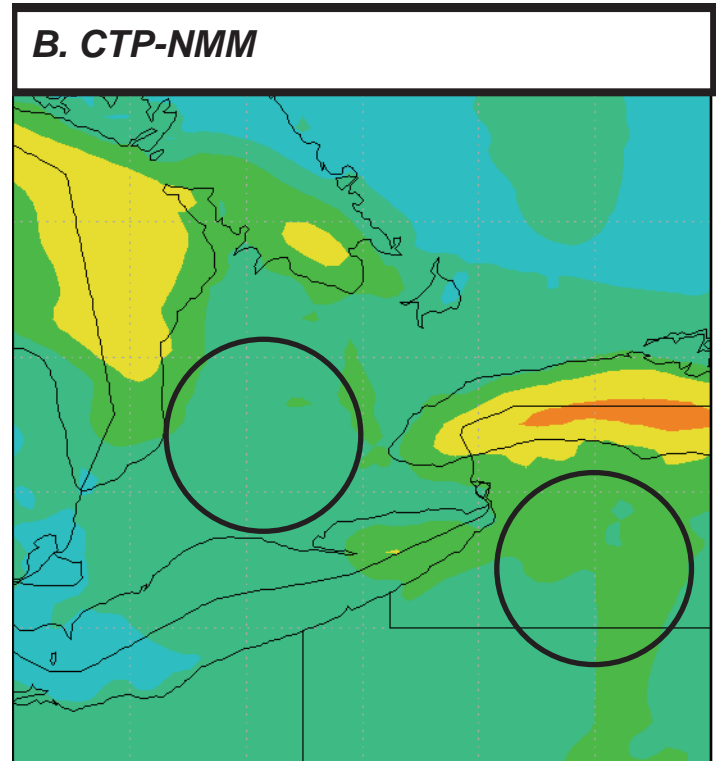
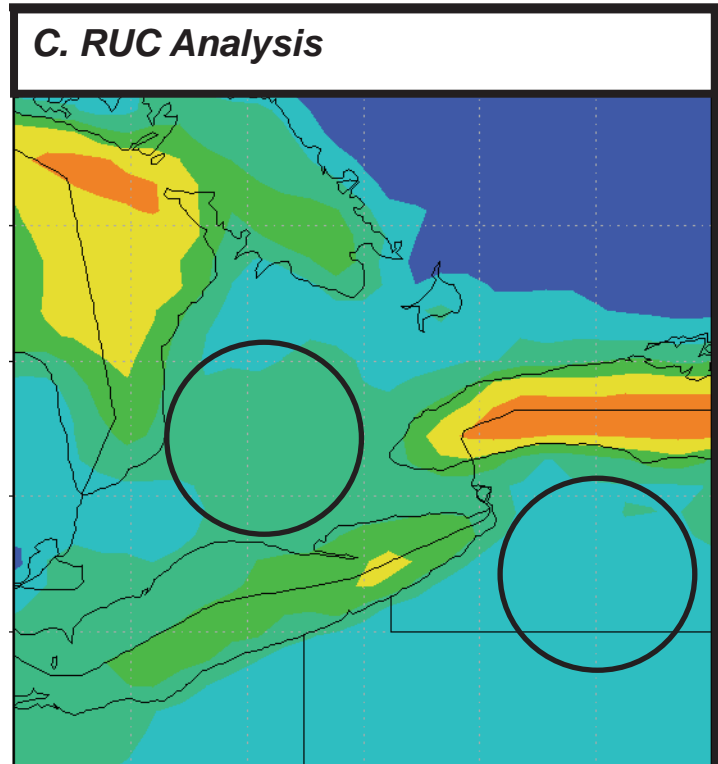


Fig. 9(c).



**Fig. 9.** Plot of 10-m wind speed averaged from 0000 UTC 11 February 2008 through 0000 UTC 12 February 2008 for (a) EXP3-ARW, (b) CTP-NMM, and (c) the RUC analysis. Circled areas described in the text.

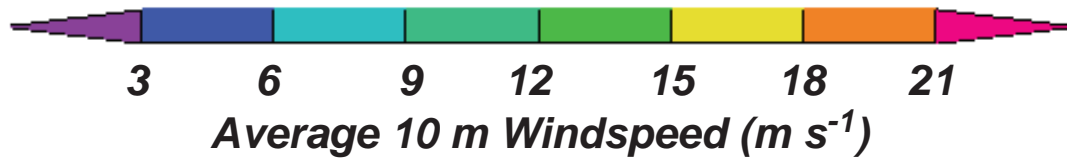


Fig. 10(a).

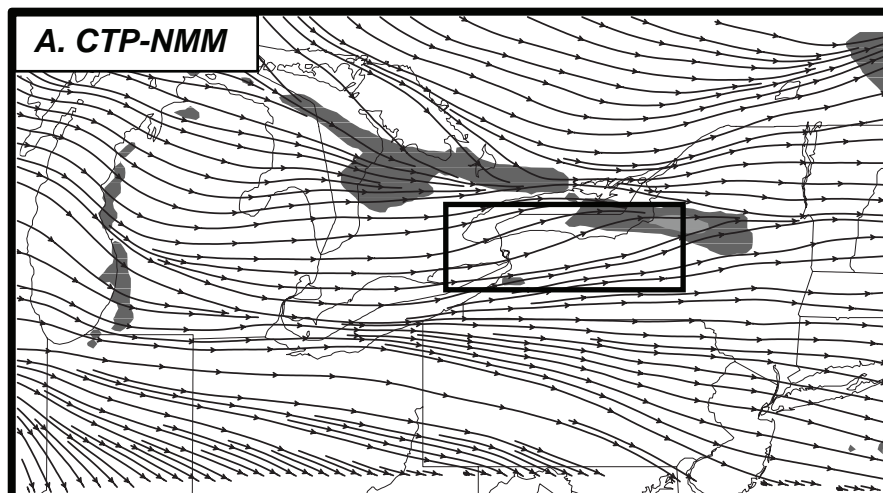
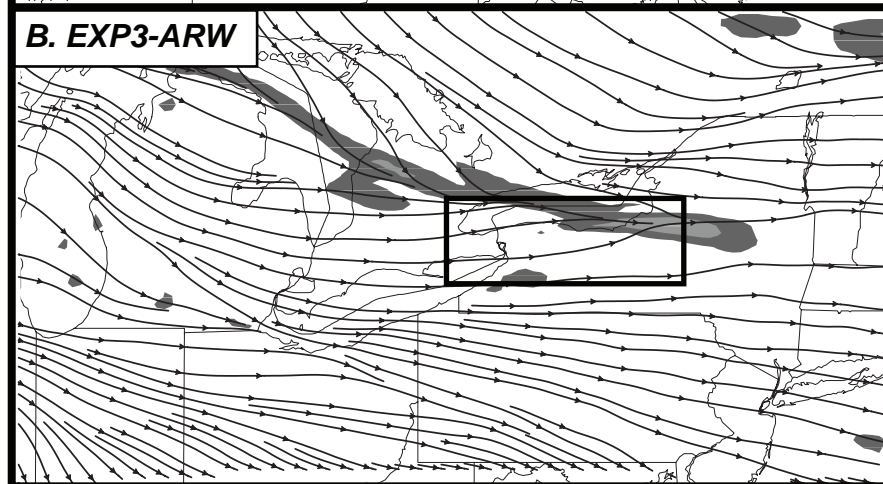
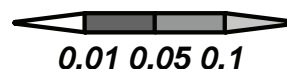


Fig. 10(b).



1 Hour QPF Ending 0600 UTC  
11FEB2008 (in)



**Fig. 10.** 10 m wind streamlines and 1-hour QPF (inches and shaded) for 0600 UTC 11 February 2008 as simulated by a.) CTP-NMM and b.) EXP3-ARW. Box shows area discussed in the text.

the core, had such different results, strongly suggests that the new version of WRF-ARW represents an improvement to the problem.

## 5. Discussion and Conclusions

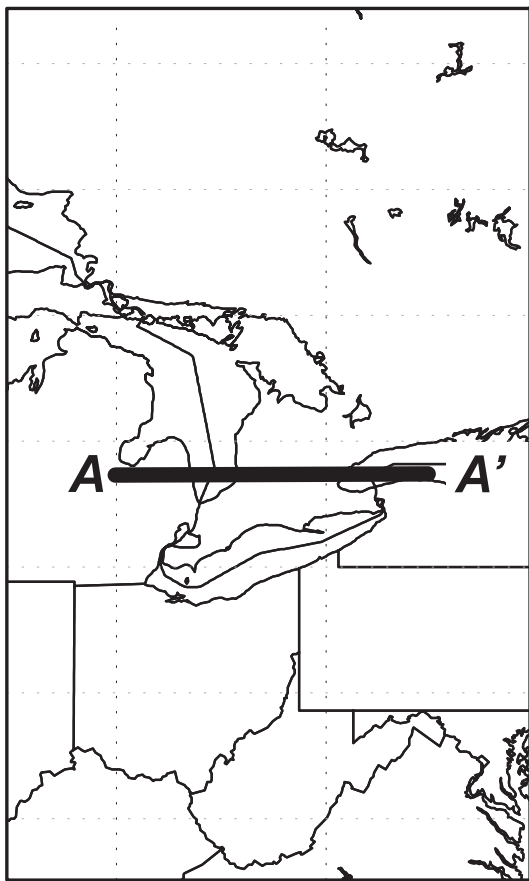
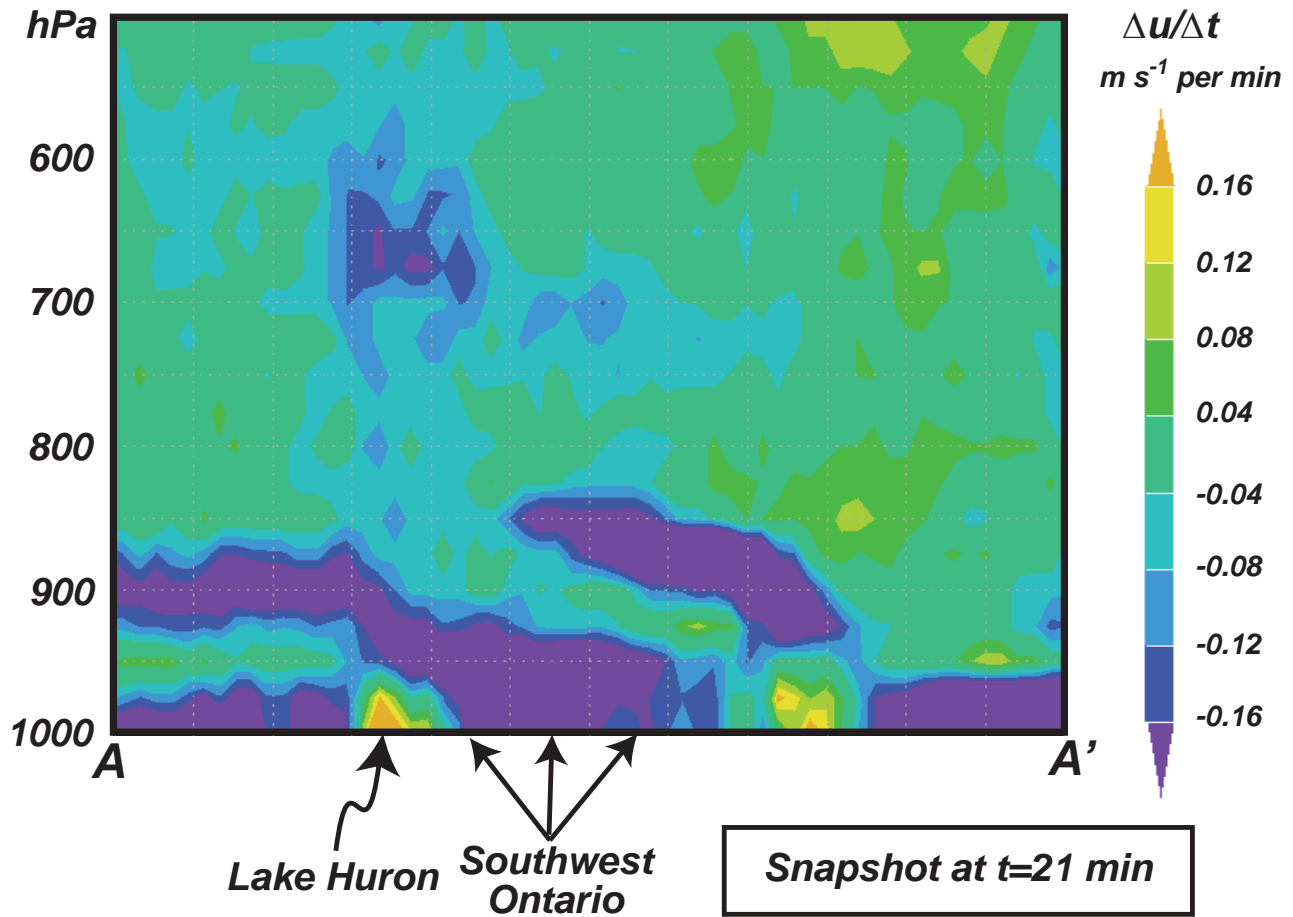
This study has shown that the results from Ballentine and Zaff (2007) are reproducible for the 2007-2008 cold season with WRF-ARW simulations consistently showing a southward bias in LP-LES band location. We have extended these initial results to show that overly strong low-level winds, downwind of the eastern Great Lakes, were the root cause for the bias which was shown to be solely related to model core rather than an individual physical parameterization. These results have implications to any study of phenomena in the vicinity of lakes, where low-level wind accuracy is vital to forecast success. A

sensitivity simulation using version 3 of WRF-ARW shows that this upgrade in model core may improve the model bias. Although the single case shown in this study cannot prove that this improved performance will always occur, the fact that the biased and improved simulations only differed in terms of the *version* of WRF-ARW is compelling evidence that this behavior would likely be repeatable in other events. Therefore, users of version 2 of WRF-ARW should consider an upgrade to version 3.

Ensemble spread is often described as a desirable quantity (Toth and Kalnay 1993). Numerous research examples have documented that EPSs are “under-dispersive” (i.e., the actual atmospheric pattern realized falls outside the “envelope of solutions”) (Buizza 1997; Stensrud et al. 1999). In a well-posed ensemble system,

*Continued page 85*

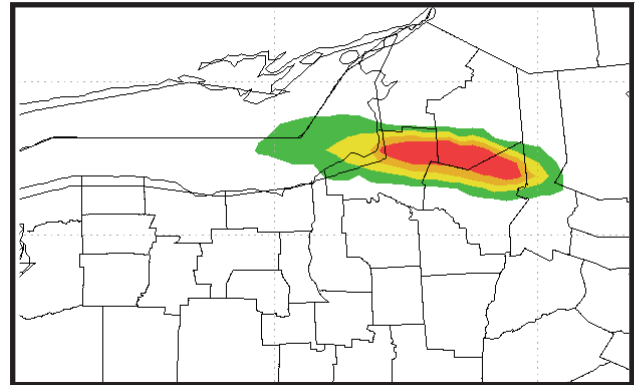
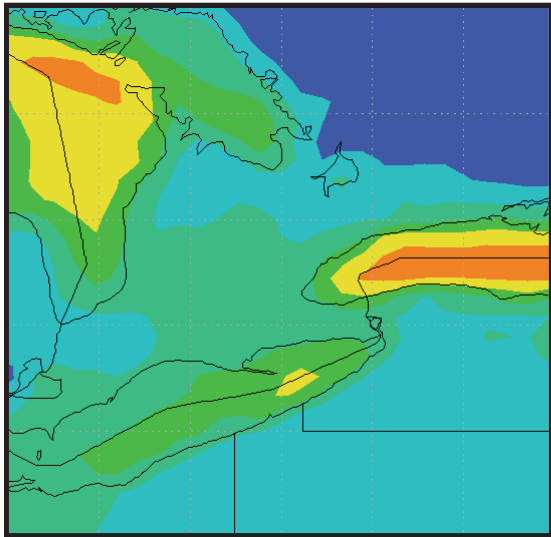




**Fig. 11.** Cross section (location shown at left) of one minute zonal wind component ( $\Delta u/\Delta t$ ) taken at 0021 UTC 11 February 2008 for simulation CTP-NMM. Locations of Lake Huron and southwest Ontario are denoted.

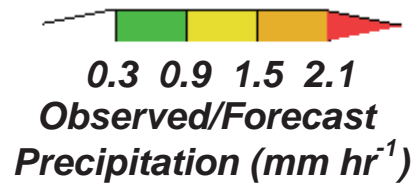
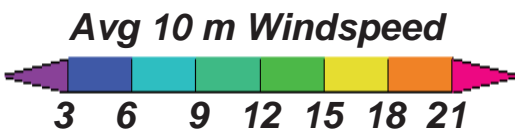
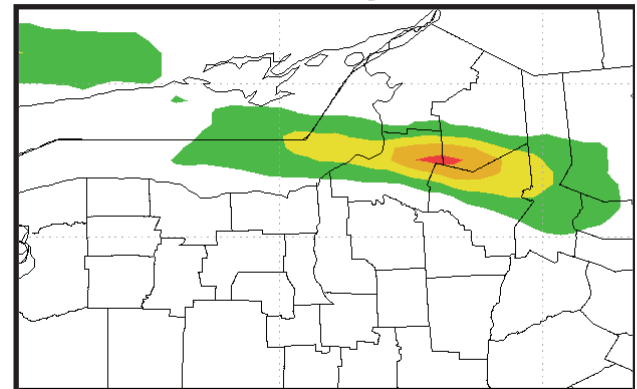
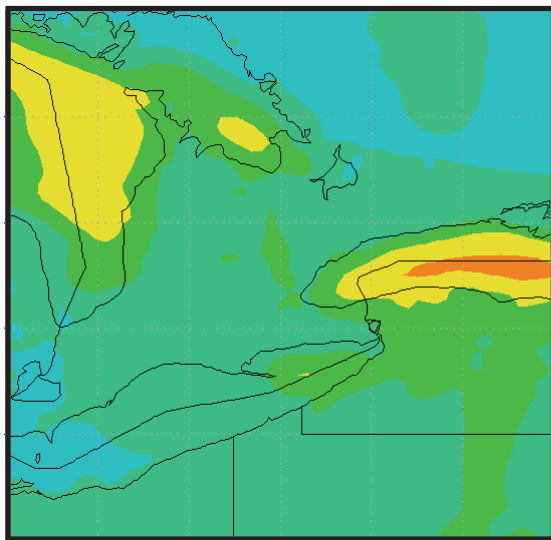
**A. RUC/NCEP Stage IV Analyses**

Fig. 12(a).



**B. CTP-NMM**

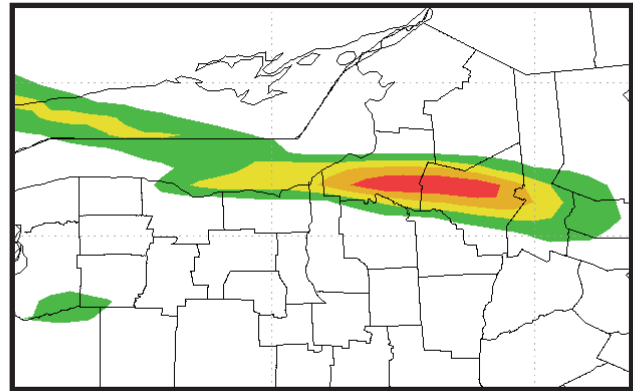
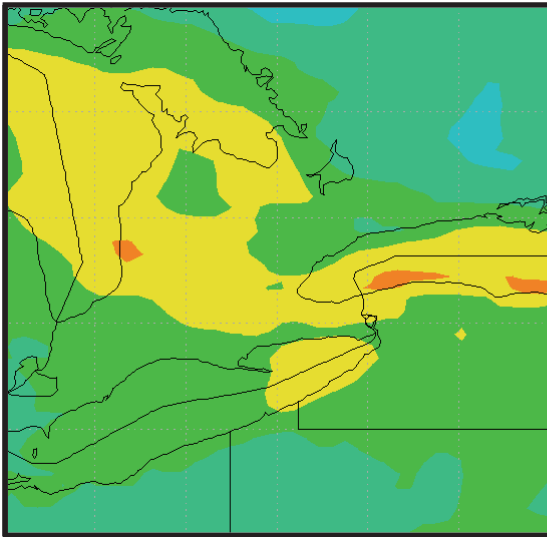
Fig. 12(b).



**Fig. 12.** Plot of 10-m wind speed averaged from 0000 UTC 11 February 2008 through 0000 UTC 12 February 2008 (left side) and 1-hour QPF for the hour ending 0600 UTC 11 February 2008 (right side) for (a) RUC (wind) and NCEP Stage IV (liquid precipitation) analyses, (b) CTP-NMM, (c) EXP-ARW3 and (d) ARW Version 3.

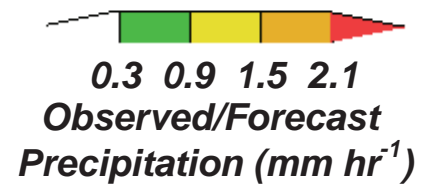
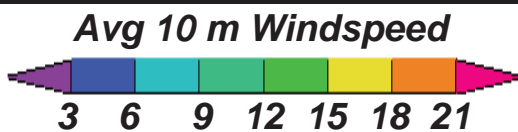
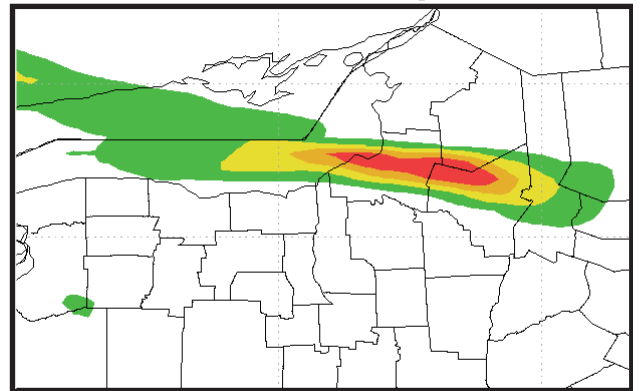
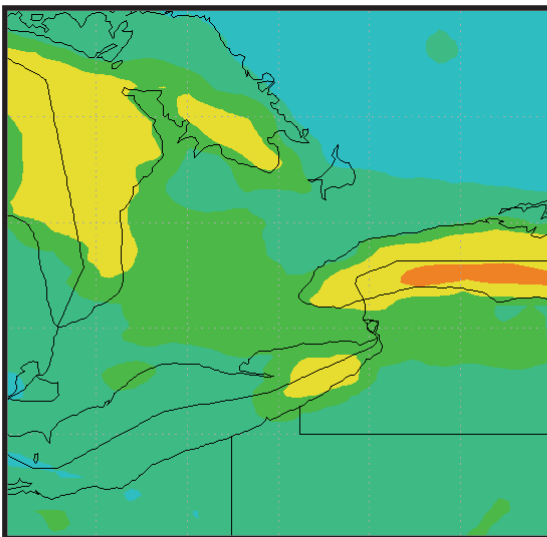
**C. EXP3-ARW**

Fig. 12(c).



**D. ARW Version 3**

Fig. 12(d).



spread correlates with the predictability of the atmospheric state, providing forecasters a sense of confidence in addition to probabilistic forecast information (Sivillo et al. 1997). Unfortunately, while the biases described in sections 3 and 4 do introduce spread in the NRE; spread caused by a *persistent* bias is not desirable because it will always exist, regardless of the true predictability of the atmospheric state. As shown in section 3, this will serve to weaken forecaster confidence, exactly the opposite of what the EPS is designed to do! Ensemble developers should therefore perform thorough verification of all members, ensuring each member is of comparable skill. If deficient members are discovered, they must be replaced

or improved before the EPS will reach its full potential as a forecast tool. If these steps are not taken, the additional probabilistic information provided by the EPS will likely be of little benefit to the operational forecaster.

Finally, this study shows that a mesoscale EPS can be successful in the operational setting. While the WRF-ARW members of the ensemble were clearly biased, the overall accuracy of the EPS was encouraging, with WRF-NMM members showing a great deal of skill in anticipating the timing and location of LP-LES bands. With a potential improvement documented for the WRF-ARW members, it appears that a well-posed EPS of WRF simulations is possible.

## Author

**Justin Arnott** is the Science and Operations Officer at the National Weather Service Forecast Office in Gaylord, MI. Prior to coming to Michigan, Justin worked as a Senior Forecaster at the Northern Indiana Forecast Office. Before this he worked as a General Forecaster in Binghamton, New York and as a Meteorologist Intern and General Forecaster in Fairbanks, Alaska. Justin received Bachelor's degrees in Meteorology and Mathematics from Lyndon State College in 2002 and his Masters degree in Meteorology from The Pennsylvania State University in 2004. Justin's primary research interests are broad, encompassing all areas where research advances will promote improved operational weather forecasting.

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