VERIFYING MODEL FORECASTS OF ARCTIC FRONTS IN ADVANCE OF WINTER STORMS IN THE SOUTHERN PLAINS

William E. Leatham IV[1, 2], Patrick C. Burke[3] and Andrew A. Taylor[3]

[1]National Weather Center Research Experiences for Undergraduates
Program, Norman, OK
and
[2]Plymouth State University, Plymouth, NH

[3]NOAA National Weather Service, Norman Weather Forecast Office,
Norman, OK

ABSTRACT

Arctic fronts and associated freezing line positions are of concern in winter storm forecasting. In the southern Great Plains of the United States the arrival of shallow arctic air plays a major role in the development of severe ice storms. At other times, the cold air becomes deep enough to support snowstorms and even blizzard conditions. Forecasters' providing at least twelve to twenty-four hour advanced warning allows the public and other groups time to prepare for these potentially dangerous events. Therefore, determining how operational forecast models perform in these situations is crucial to improving forecast accuracy and increasing our understanding of shallow cold air. This paper compares the observed surface freezing line and cold front location with model forecasts of both these features during the twenty-four hour period leading up to the onset of four winter storms. The model forecasts tend to move arctic fronts southward much too slowly. This has strong implications for the southward extent of winter storm warnings based on model forecasts, and their associated lead time.

1. INTRODUCTION

Forecasting winter storms with at least twelve to twenty-four hour lead time is helpful for the public to prepare for these potentially dangerous events. Winter storms cause power outages and deterioration of road conditions, along with other wind and precipitation related hazards. A winter storm event that occurred on January 28-29, 2010 is one example. This winter storm caused widespread damage throughout southwestern and central Oklahoma. Ice accumulations ranging from 2.5 to 4 cm (1-1.5 inches) occurred in southwestern Oklahoma. Falling tree limbs and power lines caused widespread power outages, leaving many without electricity for days (Oklahoma Department of Emergency Management, 2010). Public awareness in advance of these events is essential.

Operational models are used heavily in forecasting when and where the greatest winter weather impacts will be located. Specifically, advancement of both the arctic front and freezing line (0°C) associated with winter storms are of particular interest. The progression of the front delineates a change in air mass, and the freezing line is important in forecasting precipitation type associated with these storms. Various operational models are available to those forecasting these events. Verifying how models perform in these situations is useful in helping to understand and forecast winter storm impacts with greater geographical accuracy and greater lead time in the future.

2. BACKGROUND

There are several theories on how cold fronts move, including movement as a density current (Miller et al. 1996, Colle and Mass 1995); discrete frontal propagation (Bryan and Fritsch 2000a, 2000b); steering by synoptic scale flow (Smith and Reeder 1988); and movement forced by density gradients (Smith and Reeder 1988).

---

[1] William Leatham IV
Address: 13 Gage Lane
Shrewsbury, MA 01545
Email: Weleatham@plymouth.edu

There has been little previous literature found on the verification of model forecasts of a southward progressing arctic front and freezing line. The study that came nearest to this concept was Colucci et al. (1999). In Colucci et al. (1999), an ensemble mean model was used. The objective from this verification was to see how the ensemble model performed in a cold air outbreak event in January of 1985, looking specifically at 850 hPa temperatures. The ensemble model, including the individual members and the ensemble mean, tended to place the location of the cold air north of its observed location, and the air in the model was not cold enough.

3. DATA AND METHODS

For this study, four winter storm events were examined. The National Weather Service (NWS) definition of a winter storm was used for this study: winter hazards associated with freezing or frozen precipitation, specifically in the form of freezing rain, snow or sleet. The NWS Norman Weather Forecast Office criteria for winter storm warnings are ice accumulations of 6.5 mm (.25 in), snowfall accumulations of 10.25 cm (4 in) in 12 h, snowfall accumulations of 15.25 cm (6 in) in 24 h, or sleet accumulations of 1.25 cm (.5 in). Arctic fronts, arriving just in advance of the onset of precipitation, were observed to be the source of sub-freezing surface air in all four events. Two events (January 28, 2010 and December 9, 2007) were severe ice storms consisting primarily of freezing rain. A third ice storm (January 12, 2007) included freezing rain and heavy sleet, and a fourth event (November 29, 2006) began with a period of light freezing rain before transitioning to a snow storm with blizzard conditions. The focus for this study was on the surface cold front and location of the surface freezing line.

Various types of model and observational data were utilized in this study, including Surface METAR and Oklahoma Mesonet data. The North American Model (NAM12) and the Global Forecast System (GFS40) were used in all cases. Other models used were the National Severe Storms Laboratory Weather Research and Forecasting model (NSSL WRF) for the December 9, 2007 case as well as the European Centre for Medium-range Weather Forecast model (ECMWF) and Short Range Ensemble Forecast mean (SREF mean) for the January 28, 2010 case.

The model initialization time was 24 hours prior to the onset of freezing precipitation for all models except the SREF mean. For the January 28, 2010 case the SREF mean was initialized 21 hours before the event occurred. This is due to the SREF model run time being offset from the 6-hourly synoptic times by 3 hours. Specifically, for the January 28, 2010 case the models were initialized at 12 UTC, with the exception of the SREF, which was initialized at 15 UTC. In all of the other cases all of the models were initialized at 00 UTC. These runs represent those nearest to the onset of the winter storms that would still allow forecasters to provide twelve to twenty-four hour lead time with warnings after reviewing the model output. The forecast times for which the model error was quantified, were 12, 18 and 24 hours.

The objective was to quantify model accuracy in determining the location of both the cold front and freezing line. First, hand analyses of temperature, dew point and pressure were created using surface observations. The cold front was analyzed and plotted if present within the domain (Fig. 1). In this study a cold front is defined as the leading edge of a strong temperature gradient, which tended to but did not always coincide with a strong dew point gradient and a wind shift. This is important because in some cases in the western portion of the domain, a prefrontal trough was present. When this occurred, the cold front placement by wind shift was not as clear, and greater importance was placed on the temperature gradient and dew point gradient to determine the location of the cold front. Also, for both the observed and model output the freezing line was analyzed and plotted, respectively. We note that the SREF mean temperature forecast on the WES displayed the freezing line as .3 °C (32.5 °F).

To quantify error, the distance was measured from the analyzed cold front and freezing line to the model cold front and freezing line, as shown in Fig. 2. As arctic fronts entering the southern Great Plains tend to be oriented west to east, error measurements were made at specified longitudes varying from 102°W to 95°W as seen in Fig. 1. By convention, a negative error distance was determined if the model output was too far north and a positive error if the model was too far south. Also, if either the cold front or freezing line was outside the domain the error distance was undefined. This yielded 165 measurements of forecast error for the location of the cold front; henceforth, frontal error, and 211 measurements of forecast error for the location of the freezing line; henceforth, freezing line error. Forecast error was measured by plotting the observed and modeled cold front or freezing line on the Weather Event Simulator (WES), placing the cursor "home" on the observed data, and measuring the distance to the model output at each of the longitudes of interest. By convention, a model forecast that fell north (south) of the observed feature was said to be of negative (positive) sign.

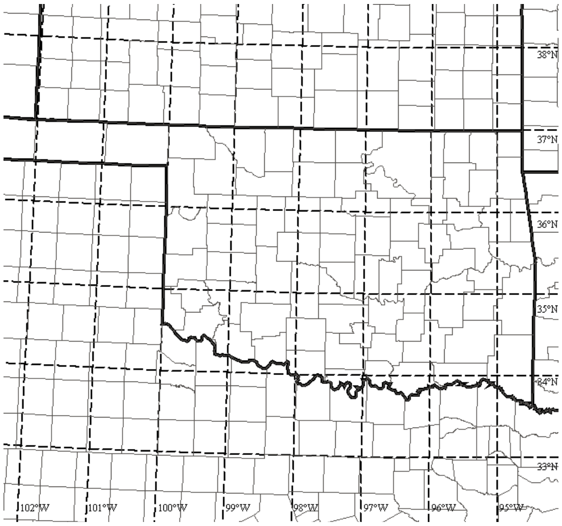

Fig. 1: Map of the domain of the study. The dashed lines oriented north to south are the longitudes of interest.

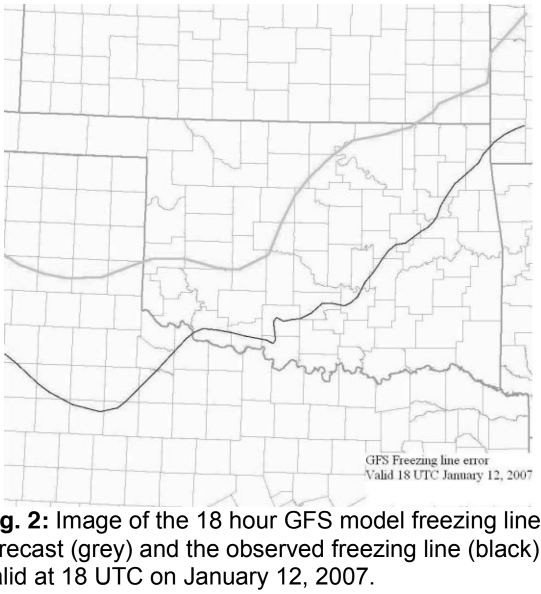

Fig. 2: Image of the 18 hour GFS model freezing line forecast (grey) and the observed freezing line (black), valid at 18 UTC on January 12, 2007.

4. Results

4.1 Mean error for all models

Basic descriptive statistics were calculated using the data collected. In general, a negative (model output placing the feature too far north) error was present for both the freezing line and front location at all longitudes. The average model (GFS, NAM, NSSL WRF and ECMWF) frontal error was -59.41 km and the average freezing line error was -107.74 km. The frontal error was worst at -188 km and best at 0 km. Positive (model output placing the feature too far south) error was, however, sometimes measured, with the greatest positive error being 20 km. There was only one 0 km error present from all the measurements. The freezing line error ranged from -380 km to 5 km. The lowest absolute error was 3 km. The model forecast and observed freezing lines never matched exactly at any one of the measuring points.

As one would expect, the model error, on average, increased over time with the location of both features. This can be seen clearly in Fig. 3. With regard to the cold front, however, the models, on average, became more accurate from 18 h to 24 h into the forecast. The models consistently displayed a negative (northerly) error relating to the progression of cold air, similar to the results of Colucci et al. (1999). There is a model tendency to keep the freezing line and cold front farther north than observed. Possible reasons why the models have this tendency will be discussed within section 5.

4.2 Mean error for individual models

Although the average of all models combined (NAM, GFS, ECMWF NSSL WRF) is revealing, it is also informative to look at average error from each individual model. Both the GFS and NAM have a similar temporal trend in frontal error (Fig. 4). As with the mean frontal error shown in Fig. 3, the GFS and NAM frontal positions are closer to the observed front at the 24 hour forecast compared to the 18 hour forecast. Both of these models tend to forecast the front too far north. The ECMWF forecast frontal error is less at 18 h than at 12 h and is greater at 24 h than at 18 h (Fig. 4).The NSSL WRF forecasts cold fronts too far south on average, with a decreasing frontal error as time increases (Fig. 4). Lastly, the SREF Mean shows a trend of increasing error as the forecast time increases. These last three models were only available for one case, whereas the NAM and GFS were used for all cases, meaning that in Fig. 3 the average is weighted toward the NAM and GFS. Regardless, four out of the five models do not allow the cold front to move far enough south. The greatest frontal error at the 12 h forecast was the NSSL WRF, and the GFS was worst at both 18 h and 24 h. In general the GFS had the largest error, and the ECWMF and the SREF Mean had the lowest frontal error as seen on Fig. 4.

Looking at the mean freezing line error for individual models (Fig. 5), four out of the five models forecast the freezing line too far north. The only model to have a decreasing trend of the mean freezing line error over time is the SREF Mean, which is unexpected. With all of the other models, as the forecast time increases the freezing line error increases as well. The NSSL WRF has a positive (southerly) mean freezing line error as it does with the frontal error. Interestingly, the NSSL WRF freezing line error has the opposite trend over time compared to the frontal error. The model shows increasing error over time with the freezing line and decreasing error with the front from 12 h to 18 h. The model with the highest freezing line error is the GFS, and the ECWMF has the smallest freezing line error. Looking at Fig. 6 and Fig. 7, during the January 28, 2010 case, the model with the greatest forecast error in both frontal and freezing line error is the GFS. The SREF Mean has the lowest frontal position error, and the least forecast error for freezing line is the ECMWF.

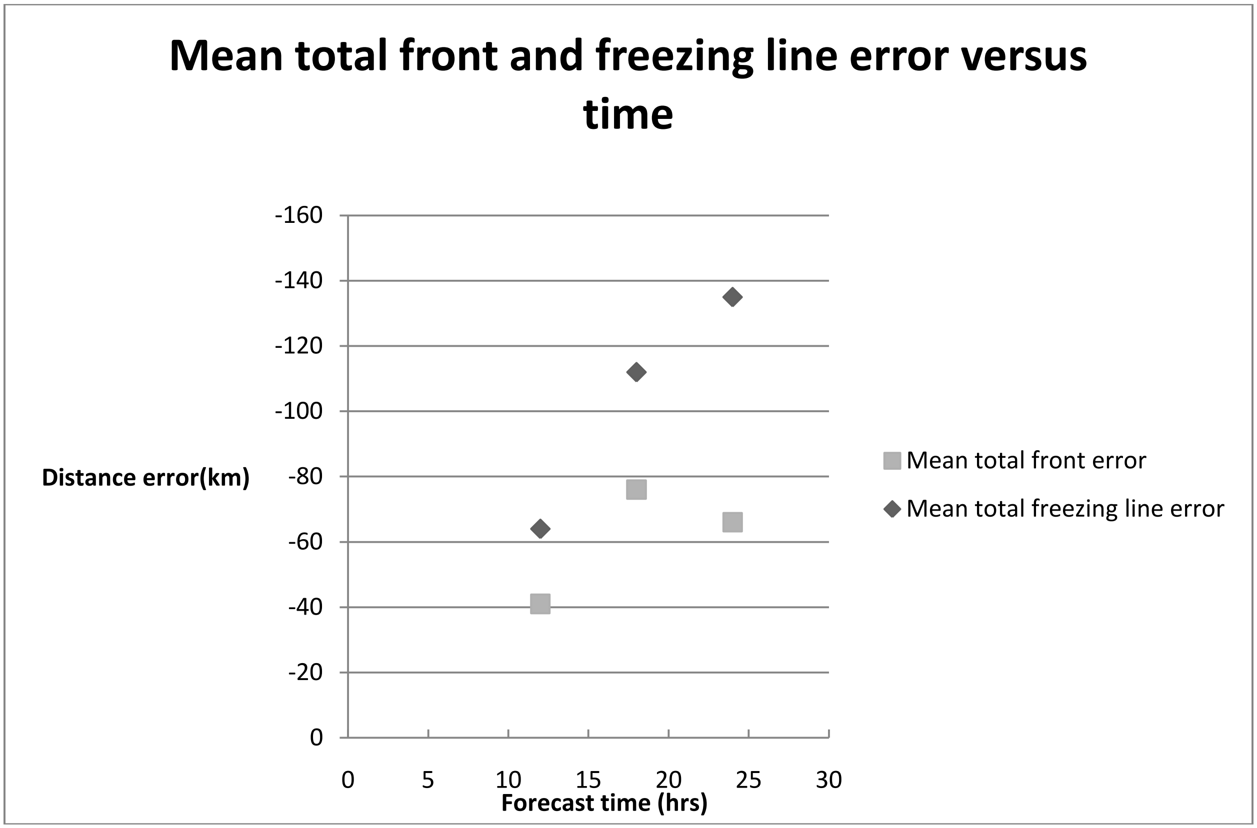

Fig. 3: Average cold front (square) and freezing line forecast error (diamond) in kilometers combining the NAM, GFS, ECMWF and NSSL WRF for the specified forecast hour.

4.3 Error along the length of the front

To view the model performance along the length of the fronts, we examined error at each of the predetermined longitudes. In Fig. 8, the maximum and minimum values are shown along with the mean. Fig. 8 clearly shows that, on average, there is a negative frontal error (northerly inclination) along the length of the front. The greatest mean error is -78 km at 102°W. Both the mean and maximum frontal error vary along the front. The freezing line errors (Fig. 9) show there is an increasing error trend from east to west. This is the general trend for all the data including the minimum values. Fig. 9 demonstrates that model freezing lines are, on average, north of the observed ones throughout all of the longitudes. However, the mean clearly shows there is a northerly model trend with the freezing line location.

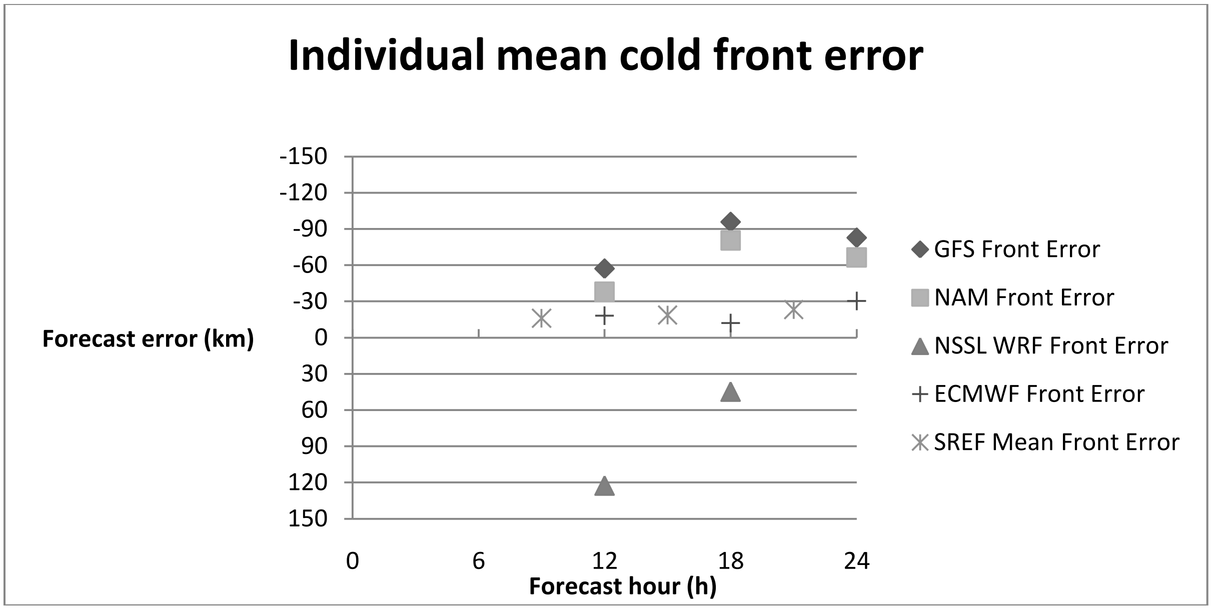

Fig. 4: Individual model average frontal error in all applicable cases for the specified forecast hour.

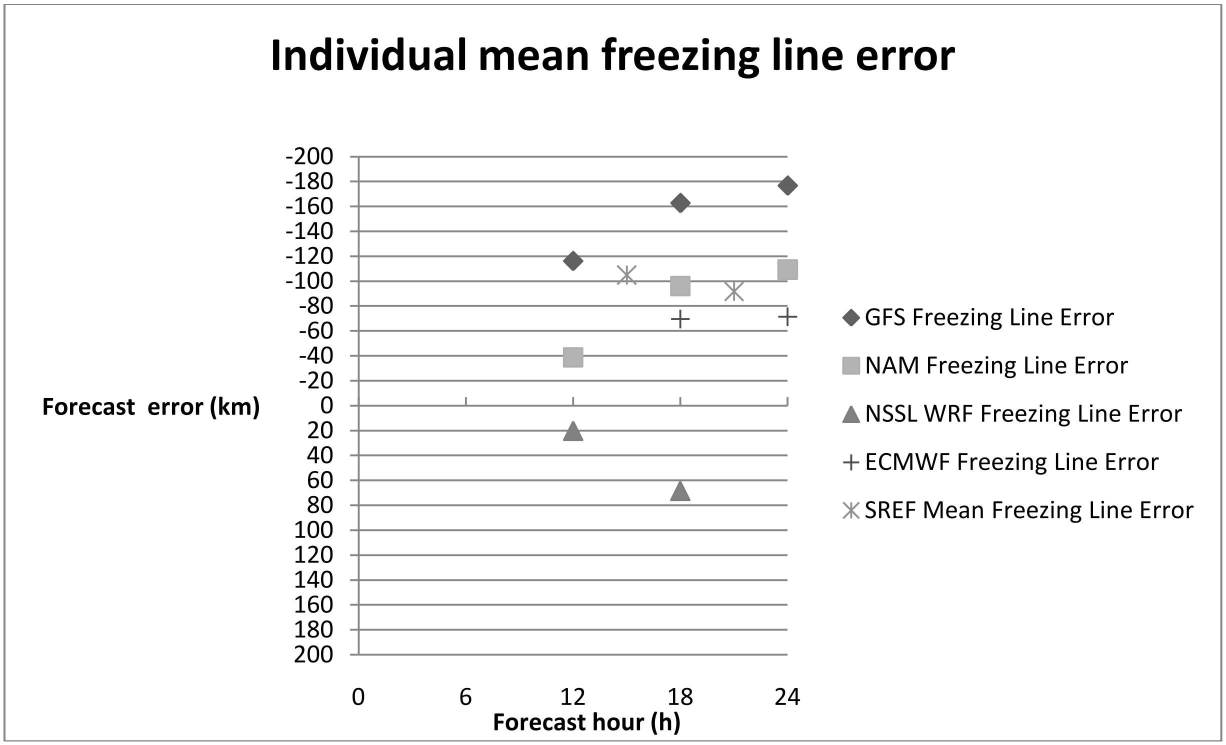

Fig. 5: Individual model average freezing line error in all applicable cases for the specified forecast hour.

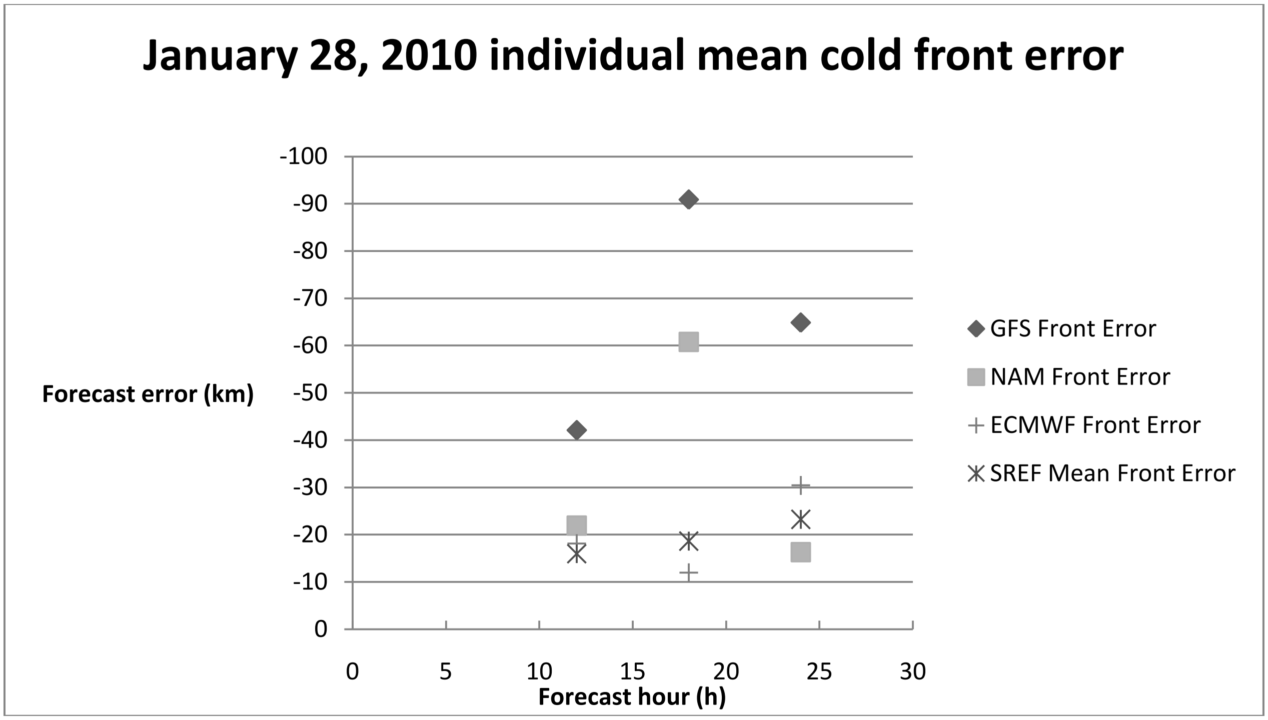

Fig. 6: Individual model average frontal error on January 28, 2010 for the specified forecast hour.

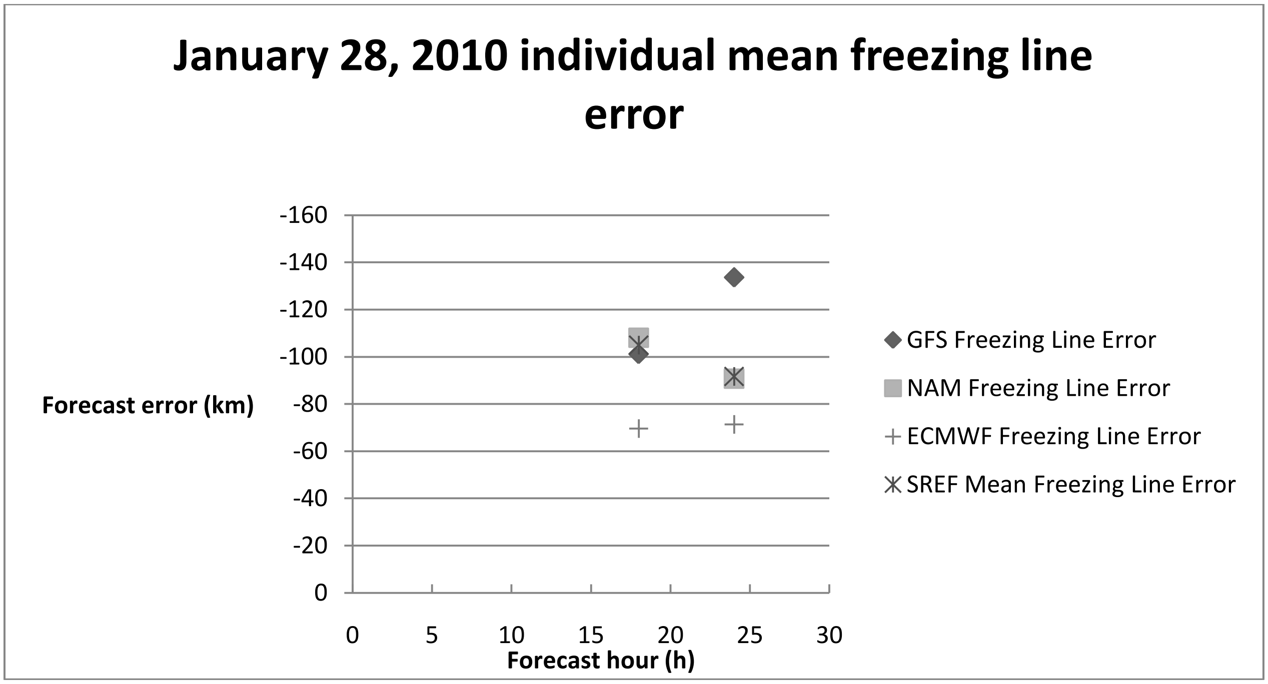

Fig. 7: Individual model average freezing line error on January 28, 2010 for the specified forecast hour.

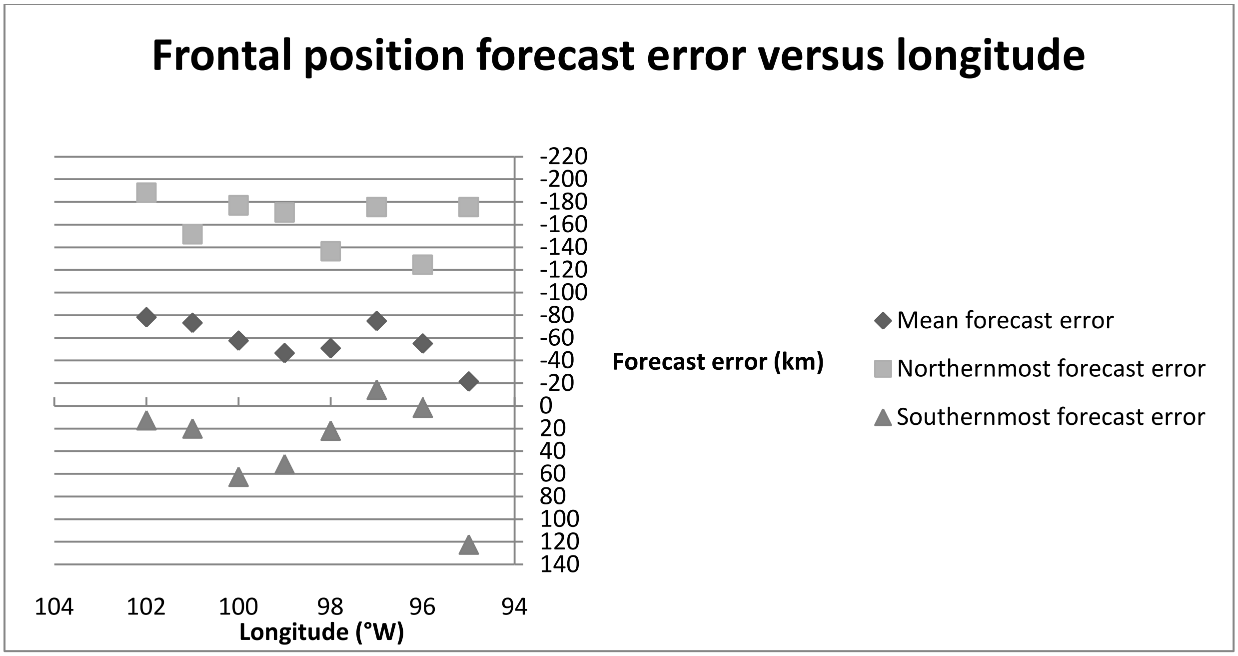

Fig. 8: Average longitudinal frontal error in kilometers with all models.

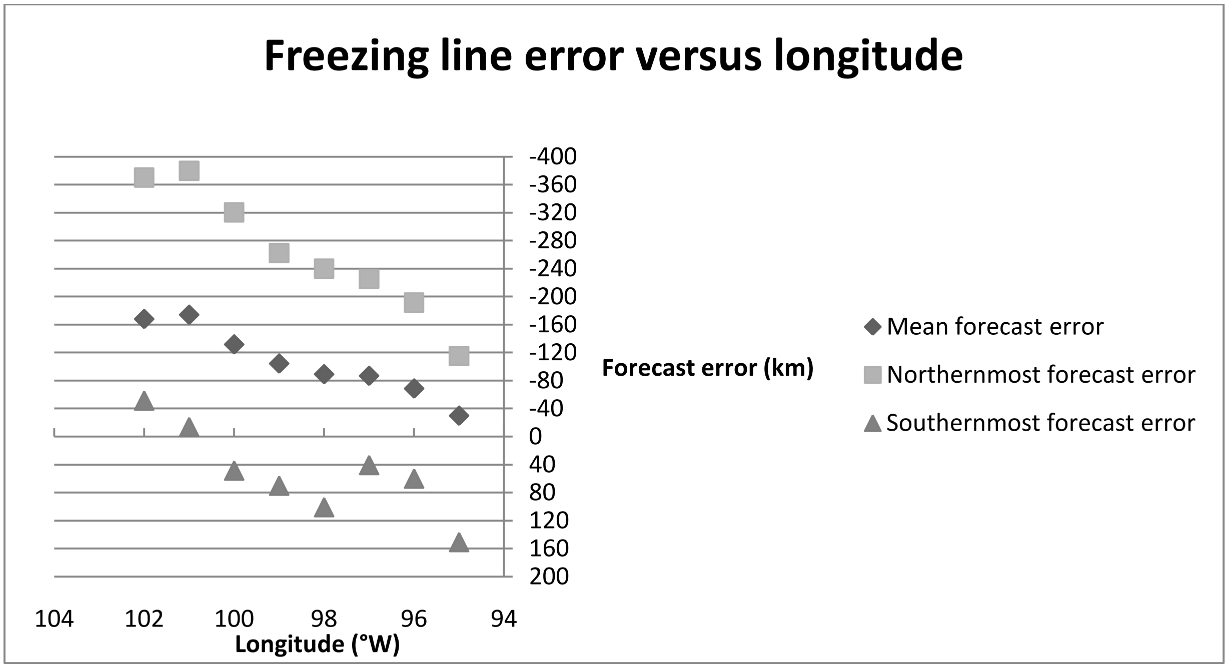

Fig. 9: Average longitudinal freezing line error in kilometers with all models.

4.4 Results from the SREF

In the January 28, 2010 case, at 21 hours into the SREF forecast, and at the time when freezing rain began, the SREF probabilities of temperatures below freezing yielded an intriguing result. Fig. 10 shows the observed freezing line plotted against the SREF forecast of the probability of freezing temperatures reaching a particular latitude at 21 hours from the model initial time, during the onset of the freezing rain. We see that from the 98° longitude to 102° degrees longitude, *the observed freezing line falls entirely outside of the probabilistic envelope (farther south), and lies in an area where the probability of freezing temperatures was forecast at zero percent*. Farther east the freezing line was observed in an area where the probability ranged from zero to about 50 percent. This finding is similar to that of Colucci et al. (1999), who found that their ensemble model had a northerly forecast error during a cold air outbreak. At 12 UTC on January, 28 2010 there was precipitation occurring in the southwestern portion of the domain. This is important because this is where the most substantial ice accumulations occurred. Fig. 10 shows that if the SREF model were used to prepare a forecast prior to the event, the forecast precipitation type in the southwestern portion of the domain would be rain. The ensemble not containing any probability of sub-freezing air along the western portion of the observed freezing line indicates that none of the constituent members of this ensemble predicted a temperature less than freezing this far south. In the eastern portion of Oklahoma the model did at least have the observed freezing line within the probabilistic envelope. Although this was only one case, one would not expect this result with a robust ensemble model, unless there is some systematic error in the way its constituent members handle the movement of shallow cold air. One must ask, does the ensemble have too few members, and are too many of the members similar in their principal makeup? The number of ensemble members within the SREF is twenty-two.

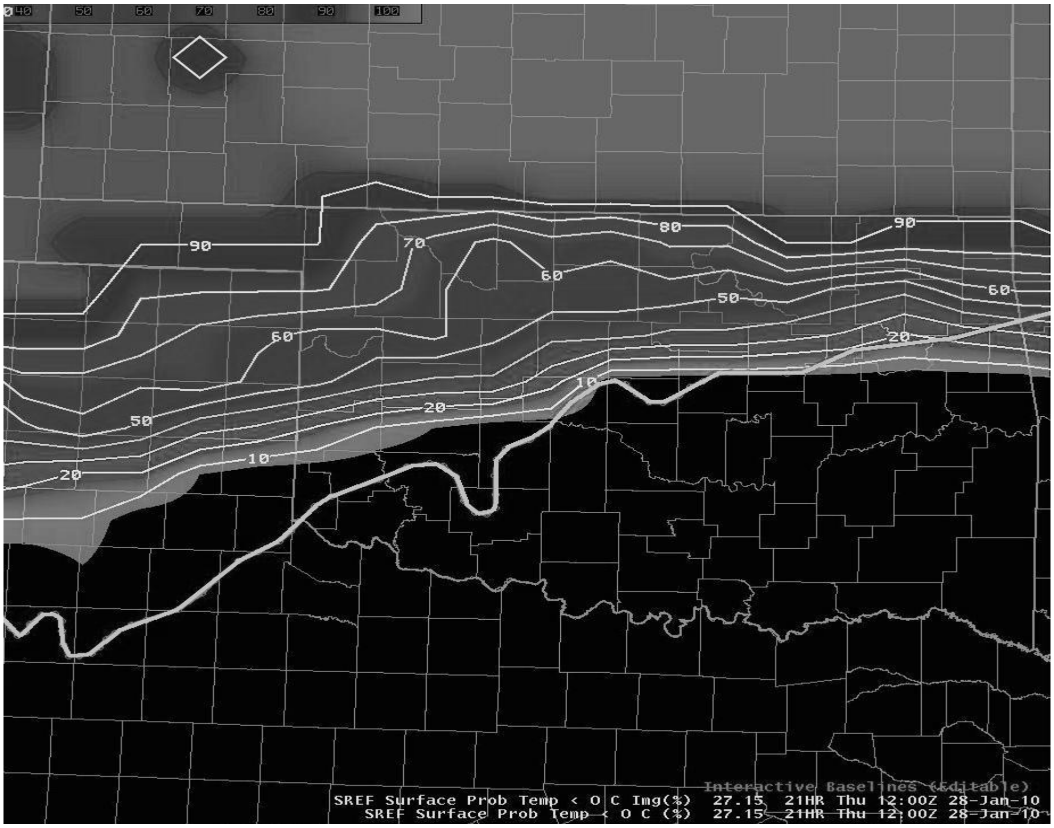

Fig. 10: SREF probability of temperature less than 0° C. 21 h forecast valid 12 UTC January, 28 2010 (white labeled contours), along with the image of the percentage (shaded) and the observed freezing line (grey unlabeled).

5. DISCUSSION

Based upon the results of this study, forecasters should be aware of the models' predisposition to forecast a slower southward progression of arctic fronts and associated freezing line than observed. Unfortunately, identifying possible sources of model error in these situations is not straightforward. In this discussion we focus on the freezing line, which is more important than the frontal position in predicting precipitation type. The change of temperature at a point is governed by the thermodynamic energy equation:

$$\frac{\partial T}{\partial t} = -\mathrm{v} \cdot \nabla_{\mathrm{p}} \mathrm{T} + \omega \left(\frac{\alpha}{C_p} - \frac{\partial \mathrm{T}}{\partial \mathrm{p}} \right) + \frac{1}{C_p} \frac{dQ}{dt} \qquad (1)$$

where $-v \cdot \nabla_p T$ is the local temperature change due to quasihorizontal temperature advection, $\omega\alpha C_p^{-1}$ is the adiabatic temperature change associated with work done on or by the air parcel by the environment during vertical displacements, $-\omega\partial T\partial p^{-1}$ is vertical temperature advection, and $C_p^{-1}dQdt^{-1}$ is diabatic heating. Latent heating (associated with precipitation processes) and solar heating both contribute to the diabatic term. In a qualitative sense for the four cases studied here, the model winds and orientation of the temperature fields suggested that temperature advection is fairly well represented by the models to the north of the cold front, while the modeled cold front was most often slower to reach a given point than was the observed front. Also, it should be expected that adiabatic processes should be well represented by numerical models. We therefore hypothesize that the diabatic term may contribute strongly to the model forecast error related to the freezing line movement.

5.1 Precipitation processes

In each case the 24 h forecast of precipitation was examined to consider some possible reasons for faults with the model surface temperature forecast. In general, the models forecast the placement of precipitation well. Using the January 12, 2007 case as an example, the GFS only slightly overestimated the observed amount of precipitation (Fig. 11). In central and southwestern Oklahoma, liquid equivalent of around .25 mm to 2.5 mm (.01-.1 in) was observed. Fig. 12 shows GFS model forecast values between 2.5 mm and 6.5 mm (.1-.25 in) of precipitation within the same region. The orientation and magnitude of the model output is similar to the observed precipitation field. At the Norman, Oklahoma (KOUN) sounding site, the GFS forecast of precipitation amount was about 1.25 cm (.5 in) and the observed amount was 6.5 mm (.25 in). As shown in the KOUN soundings and GFS forecast soundings in Fig. 13a to Fig.13b, and Fig. 14a to Fig. 14b, the GFS model shows a slow progression of the front and cold air at this location This results in a much different precipitation type than what is later observed

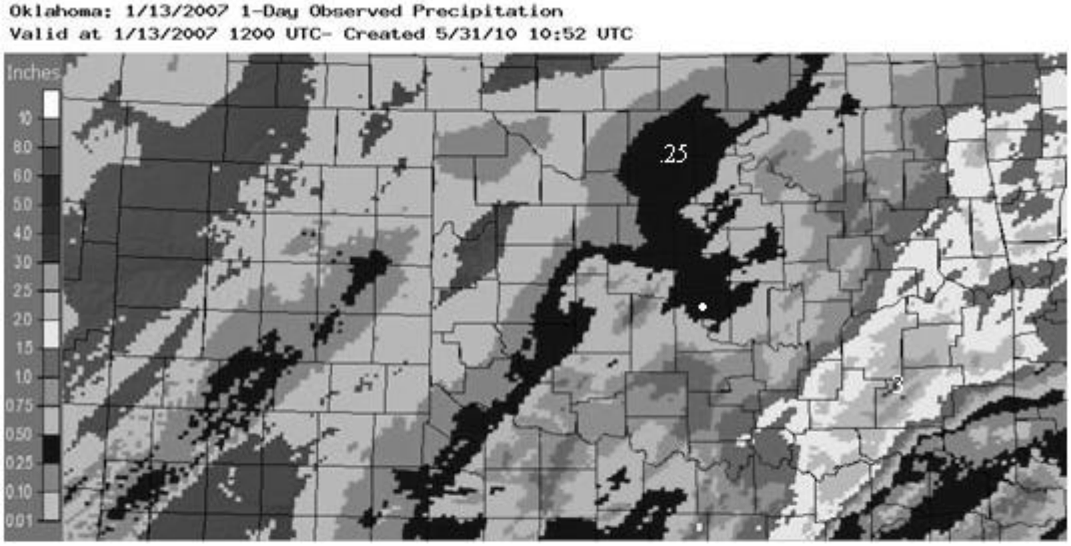

Fig. 11: Twenty-four hour observed liquid equivalent precipitation amount in inches valid from 12 UTC to 12 UTC January 13, 2007. Highest amount observed is 3 inches indicated in the southeast portion of the image. Norman, Oklahoma (KOUN) is indicated (white dot) within the .25 inches of precipitation. Map from the Advanced Hydrologic Prediction Service. Please note that the values indicated are in English units due to the model output being in inches of precipitation forecast.

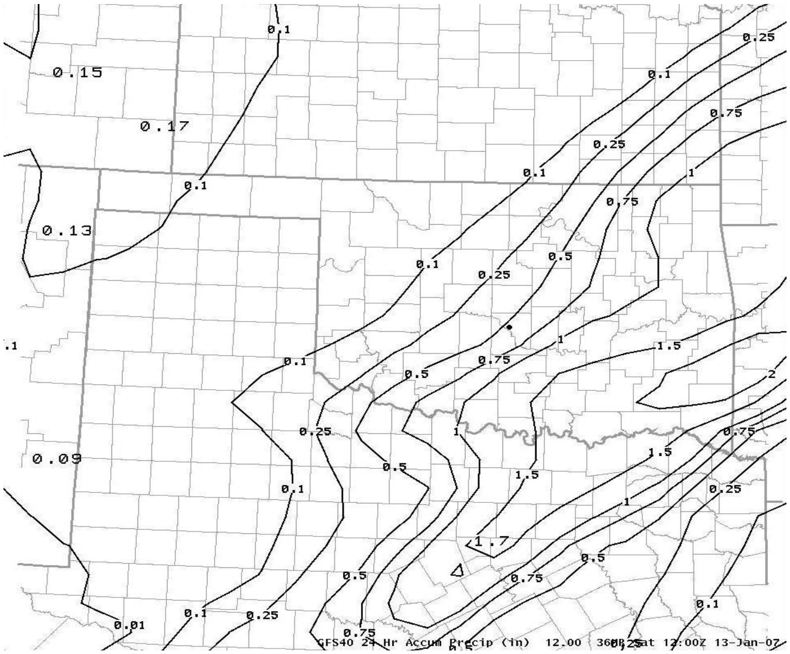

Fig. 12: GFS 24 hour liquid equivalent accumulated precipitation forecast in inches valid 12 UTC January, 13 2007. The black dot indicates the location of Norman, Oklahoma (KOUN).

(Fig. 14). It appears that the models have a good orientation of where precipitation is going to happen. As shown in the KOUN soundings in comparing Fig. 13b to 14b, the model decreases the temperatures.

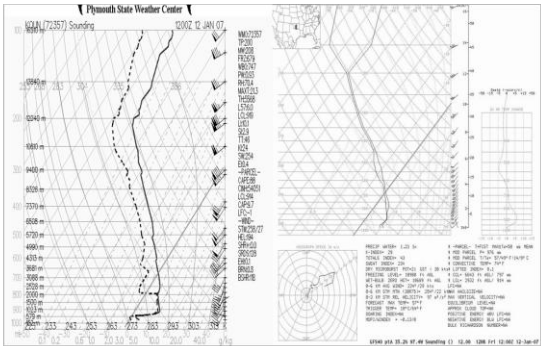

Fig. 13: Norman, Oklahoma (KOUN) sounding valid 12 UTC January 12, 2007 (a) left, observed from the Plymouth State Weather Center (b) right, GFS forecast sounding

With the model temperatures being too warm prior to and during the onset of precipitation, the GFS does not adequately cool surface temperatures, resulting in a precipitation type of rain.

5.2 Diurnal Heating

Upon examining temporal trends in the freezing line position, it appears that the models may potentially have error associated with radiative processes or the diurnal heating cycle.

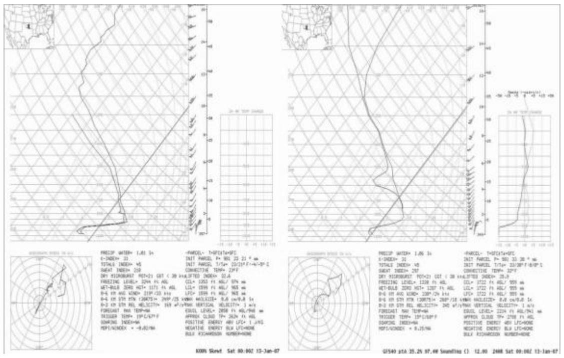

Fig. 14: Norman, Oklahoma (KOUN) sounding (a) left, 12 hour forecast valid 12 UTC January 12, 2007 (b) bottom, 24 hour forecast valid 00 UTC January 13, 2007.

Looking specifically at the freezing line error in the November 29, 2006 case, the GFS and NAM (not shown) models warm the surface over western Oklahoma, the Oklahoma panhandle, and the northern Texas panhandle. The modeled freezing line retreated northward from 12 to 18 UTC, while, the observed freezing line continued to proceed southward. This can clearly be seen when comparing Fig. 15a to 15b. The models heated the boundary layer more than was observed, and being the daytime hours, the likely source is solar radiation. The models may not have accurately estimated the effects of low cloud cover that was observed. The false heat input by the models at this time affects their output later in the forecast period.

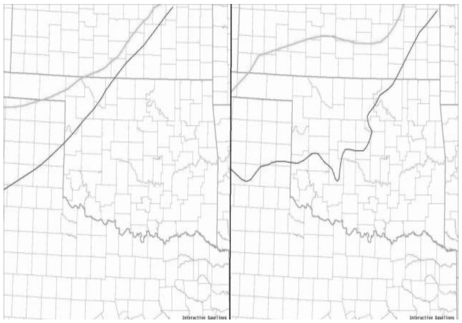

Fig. 15: Image of the 12 and 18 hour, GFS model freezing line forecast (grey) and the observed freezing line (black) (a) left, valid 12 UTC November 29, 2006 (b) right, valid 18 UTC November 29, 2006.

6. CONCLUSIONS

This study verified eleven model forecasts runs associated with four winter storm events that occurred in the southern Great Plains of the United States. Arctic cold fronts, arriving in advance of the onset of precipitation, were the source of cold air in all four cases. The models tended to keep both the freezing line and cold front north of the observed features. This result was consistent along the length of the front at forecast times of 12, 18 and 24 hours. On the January 28, 2010 case, the observed freezing line progressed southward outside the envelope SREF probabilities of sub-freezing temperatures. One would not expect this within a robust ensemble model. Forecasters relying on the SREF would have produced zero lead time for winter storm warnings in southwest Oklahoma, where a devastating ice storm took place. Scientists should work to ensure ensemble systems achieve a diversity of solutions, and are not affected by systematic bias -in particular with the movement of shallow cold air. More winter storm cases are needed for better identification of this northerly model error. It may also be enlightening to see if these results hold for non-precipitating arctic fronts. Arctic fronts passing through other regions would be of particular interest, to see if this error occurs in other locations as well.

7. ACKNOWLEDGEMENTS

This material is based on research done through the funding provided by National Science Foundation Grant No. ATM-0648566, and NOAA/Office of Oceanic and Atmospheric Research under NOAA-University of Oklahoma Cooperative Agreement #NA17RJ1227, U.S. Department of Commerce. supported by the National Science Foundation (NSF) under Grant No. ATM-0648566. The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of the National Science Foundation, NOAA, or the U.S. Department of Commerce. The authors would also like to thank the NOAA National Weather Service Forecast Office in Norman, Oklahoma for access to archived data and guidance throughout this program, along with the Advanced Hydrologic Prediction Service for access to their online observed precipitation archive.

8. REFERENCES

Bryan, G.H., and J.M. Fritsch, 2000a: Discrete propagation of surface fronts in a convective environment: observations and theory. *J. Atmos. Sci.*, **57,** 2041-2060.

———,2000b: Diabatically driven discrete propagation of surface fronts: a numerical analysis. *J. Atmos. Sci.,* **57,** 2061- 2079.

Colle, B.A., and C.F. Mass, 1995: The structure and evolution of cold surges east of the Rocky Mountains. *Mon. Wea. Rev.,* **123,** 2577-2610.

Colucci, S.J., D.P. Baumhefner, and C.E. Konrad II, 1998: Numerical prediction of a cold-air outbreak: a case study with ensemble forecasts. . *Mon. Wea. Rev.,* **127,** 1538-1550.

Oklahoma Department of Emergency Management, 2010: January 28-29, 2010: Winter weather event. Available at http://www.ok.gov/OEM/Emergencies_&_Disasters/2009/Winter_Weather_Event_20100128_Master/

Smith, S.K., and M.J. Reeder, 1988: On the movement and low-level sructure of cold fronts. *Mon.Wea. Rev.,* **116,** 1927-1944.

Miller, L.J., M.A. LeMone, W. Blumen, R.L. Grossman, N. Gamage, and R.J. Zamora, 1996: The low-level structure and evolution of a dry arctic front over the Central United States. part I: Mesoscale Observations. *Mon. Wea. Rev.,* **124,** 1648-1675