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Analysis of a Sharp Gradient Snow Event in the Upper Midwest

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ABSTRACT

In this study, the 23-24 March 2016 snow event across west central Wisconsin, south central Minnesota, tapering off into northwest Iowa and extreme southeast South Dakota was analyzed to better understand sharp gradient snow events. The focus of this study was to understand why this snow event occurred and what contributed to the sharp contrast in snow accumulations in such a densely populated area of the Minneapolis/St. Paul region. Analyses confirm that the warm, moist air from the south and east at low levels combined with the cold, dry air from the north and west at the upper levels enhanced lift, moisture and instability, constituting to the impressive snowfall gradient across the Upper Midwest. Additionally, the study looked to analyze both the model outputs from the North American Mesoscale and Global Forecasting System and compare atmospheric variables to what was actually observed as the snow event began on the 23 March at 12 UTC at certain locations affected by the snow band. Locations that saw the most snowfall also saw the highest values of omega, moisture, and instability, which agreed with what was hypothesized. Both models handled the event similarly, forecasting snowfall in locations within the dry slot best, but showed uncertainty within locations in the snow gradient. The greatest model disagreement in wind direction came from forecasts at 700 hPa.

1. Introduction

In late March 2016 a developing low-pressure center made its way from the Rockies and moved into the Midwest bringing high amounts of relative humidity and warm temperatures from the South Central U.S., and dry and cold air from the North Central U.S. The low continued to strengthen as it moved into the Upper Midwest (Figure 1). High dew point values along the cold front in areas of the Central U.S. helped develop severe thunderstorms late on the 23rd of March, with an impressive snowfall event set up north of the warm
front. The snowfall encompassed northwest Iowa, stretched to the north and east through south central Minnesota on into west central Wisconsin.

![Image of surface analysis]

FIG. 1. Surface Analysis valid 15 UTC 23 March 2016 formatted by the Weather Prediction Center (WPC).

The most significant aspect of the event was marked by the northern edge of the total snowfall accumulation having a sharper drop off than that of the southern edge of the snowfall accumulation. The main points of interest in the atmosphere where most of these meteorological parameters need to be analyzed are in the mesoscale region of the atmosphere. In this event, mesoscale processes were most impactful in lower portions of the troposphere.

Market and Cissell (2002) looked at a similar study of a sharp snowfall gradient in southern and central Missouri as the southern edge of the snowfall was more tapered off than the northern edge, which saw the sharper gradient in snow depth. This was mainly due in part to a sharp contrast in relative humidity values along the gradient boundary. Additionally, conditional instability was found to be greatest between 850-687 hPa levels in a similar study in the Midwest (Pettegrew et al. 2009).

Another main factor included in the analysis of these impressive gradient snowfall events is the presence of warm, moist air transported in the low-levels, interacting with the cold, dry air from the north (Graves et al. 2003). This interaction is also due in part to CSI (conditional symmetric instability.) Regions of CSI result in precipitation bands that are parallel to the field of snowfall. CSI is the result of high levels of moisture and strong vertical motion (Moore and Lambert 1993). Kinematic omegas (lift) are also important to compute and understand as this is where upward and downward motions are present at certain levels of the atmosphere (Moore and Blakley, 1988). Omega values are most critical in the saturated levels and snow growth zone (SGZ) of the atmosphere.

A fair amount of knowledge has been obtained in how the impressive snow bands develop and impact the world we live in. What can be learned from this snowfall gradient event and what can be concluded from atmospheric model output compared to atmospheric observations? The North American Mesoscale (NAM) and Global Forecasting System (GFS) atmospheric models were used to compare its forecasting of total snow accumulations, direction of vector winds and omega and other variables at different levels of the atmosphere.

2. Data and Analysis Methods

The research focused on analyzing the snow event as well as which atmospheric model forecasted the event best. There were
six cities chosen that were affected by the significant snowfall gradient. City name, location with respect to the snowfall gradient, and snow totals from the storm are listed to compare every city (Table 1). Several thermodynamic and kinematic features were studied in each city. Of the six, one was taken from the dry region (St. Cloud, MN), two were taken from the sharp gradient region (Minneapolis, MN and Redwood Falls, MN), and three constituted for regions within the highest snowfall observations (La Crosse, WI, Rochester, MN, and Sioux City, IA) (Figure 2).

Table 1. City name, location from gradient and snow total depicted.

<table>
<thead>
<tr>
<th>City</th>
<th>Location</th>
<th>Snow Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. Cloud, MN</td>
<td>North of Gradient</td>
<td>0 inches</td>
</tr>
<tr>
<td>Minneapolis, MN</td>
<td>Edge of Gradient</td>
<td>3.7 inches</td>
</tr>
<tr>
<td>Redwood Falls, MN</td>
<td>Edge of Gradient</td>
<td>2.6 inches</td>
</tr>
<tr>
<td>La Crosse, WI</td>
<td>Within Gradient</td>
<td>6.3 inches</td>
</tr>
<tr>
<td>Rochester, MN</td>
<td>Within Gradient</td>
<td>10.6 inches</td>
</tr>
<tr>
<td>Sioux City, IA</td>
<td>Within Gradient</td>
<td>14.1 inches</td>
</tr>
</tbody>
</table>

Observations were taken from the North American Reanalysis Data (NARR) (NOAA NCDC) site. The compiled data used a 3-hourly frequency for each variable used. Omega, specific humidity and vector winds were used to display values at different pressure levels in the atmosphere. Omega was displayed at 500, 700, and 850 hPa, specific humidity was displayed at 700 and 850 hPa and vector winds were displayed at 500, 700, and 850 hPa.

The snowfall event used model data from both the NAM and the GFS. 60, 48, 36, 24, 12 and 0 hour forecasts were conducted from both models observing atmospheric conditions as well as forecasted snowfall at 12 UTC 23 March. These models ran at a 6-hour frequency but were used at a 12-hour frequency for the purpose of this study. Vector wind comparison at 500, 700, and 850 hPa for each city were also taken into account.

Model data was acquired from the Iowa Environmental Mesonet and was computed through a forecasting program, BUFKIT. BUFKIT was used to collect forecasted values of omega, snowfall accumulations, vector winds, relative humidity, and snow growth. Cross sections

FIG. 2. Observed snowfall map formatted by the National Weather Service.
and soundings were analyzed from the program as well. Cross sections of the forecasted atmospheric profile include omega values, the dendritic snow growth region, as well as relative humidity values. The cross sections used in this study compare and contrast GFS and NAM model outputs valid at 00z March 23, 2016.

Microsoft Excel was used to plot a graphical comparison of snowfall observations and vector winds between observations, NAM and GFS forecasts as the snowfall band formed at 12 UTC 23 March. Microsoft Excel was also used to complete graphical depictions of the quantitative proof of the overall differences in both NAM and GFS outputs over all six cities from 12 UTC 23 March to 12 UTC 24 March. Snowfall observations from the storm were collected from the National Weather Service from the six cities as well.

The graphical depictions of forecasted snowfall was a comparison of forecast time compared to snowfall difference that the city experienced after its observations were official. Forecasted wind directions from both the NAM and GFS were graphed on a scatter plot comparing the forecasts to what wind direction was observed at the given level.

3. Results and Discussion

Forecasted snowfall through the time period fluctuated depending on location in the snow gradient. The city the NAM and GFS forecasted snowfall most successfully was St. Cloud, MN. Since St. Cloud was in a region of very dry air in the low to mid-levels and did not receive any snow, both models predicted little, if any snow for the location. The highest amount of snow predicted was the GFS at forecast hours 60 and 48 with 0.4 inches predicted. Minneapolis, MN received 3.7 inches of snow and Redwood Falls, MN received 2.6 inches of snow. At these locations, along the sharp gradient of snow, the forecasted difference in snowfall overestimated and underestimated the snowfall forecast. As the event neared, both had underestimated snowfall totals at the 12-hour forecast but then rebounded to accurate snowfall forecasts. In locations within the strongest gradient of snowfall, the overall difference between forecasted snowfall and observed snowfall varied the most. La Crosse, WI observed 6.3 inches, Rochester, MN saw 10.6 inches, and Sioux City, IA witnessed 14.1 inches. Throughout the forecast hours, both atmospheric models underestimated the forecasted snowfall in Sioux City, IA (Figure 3). The forecasted snowfall showed the greatest difference on average in locations that received the most amount of snow.

In this case study it was seen that the 500 hPa winds experienced the smallest difference in forecasts at each location. Throughout most of the pressure level, winds were observed from the west. In cities such as St. Cloud, that saw no snowfall, the 700 hPa winds were consistently out of the NW, bringing in the dry air at the mid-levels, giving way to insufficient moisture. In locations deep into the snow band, such as Rochester, 700 hPa winds were mainly out of the south and east, bringing in sufficient humidity values from the Gulf of
FIG. 3. Forecasts starting 60 hours in advance using 12-hour increments of forecasted snowfall and its difference in snowfall observations at six cities within the snowstorm from 12 UTC 23 March to 12 UTC 24 March 2016. Note that the y-axis range differs due to different snowfall values.

Mexico. The 850 hPa level featured observed winds from the north and east at most locations.

At 700 hPa, the NAM and GFS showed the most fluctuation in forecasted wind direction, as there was much uncertainty of where the sharp gradient of snowfall was forecasted to set up. Throughout the atmospheric models’ outputs, it was noted that the region of the atmosphere that saw the right conditions unfold for the development of clouds and snowfall was in the 500-700 hPa regions, as wind direction was an important factor in the role of moisture and instability. Using the 700 hPa wind vector plot, it “mirrored” where the snowfall gradient took place. Regions following the trend of NW winds at the 700 hPa pressure level saw little to no snowfall, while regions within the southerly winds saw sufficient amounts of snowfall (Figure 4).

FIG. 4. Observed vector wind direction at 500 hPa (a.), 700 hPa (b.), and 850 hPa (c.) 12 UTC March 23.
Forecast model output from both the NAM and GFS consistently showed the largest difference between forecasts and what was observed at 700 hPa. Wind direction was forecasted fairly accurately at most cities around the 850 hPa level, but differed the least at the 500 hPa level. Redwood Falls, MN is a good depiction of how wind direction differed as models were in disagreement on where the convective snowfall band would set up. Northerly wind direction is marked by 0°, easterly wind direction is represented by 90°, southerly wind direction is noted from 180°, and westerly winds are displayed by 270° (Figure 5).

FIG. 5. Forecasts starting 60 hours in advance using 12-hour increments of NAM and GFS forecasted vector wind direction and its difference with observations at Redwood Falls, MN within the snowstorm. Valid 12z 23 March. Note that the y-axis range differs due to different wind direction values. Observed wind direction is denoted by the red highlighted point.

Kinematic omega was also an important aspect of this case study. Strong values of omega are where the most amount of lift is available in the atmosphere to aid in the development of clouds and thus, enhancing the production of snow. The most negative values in the plots represent the strongest values of upward vertical motion. Throughout the atmosphere, the most amount of lift was observed in regions that experienced the most amount of snowfall. Regions outlined in the strongest values of omega are located in south central Minnesota and west central Wisconsin. At Rochester, MN and La Crosse, WI omega was consistently strong throughout the atmosphere ranging between -20 μbars/sec and -40 μbars/sec. In locations along the sharp snowfall gradient such as Minneapolis, MN and Redwood Falls, MN,
omega values were sufficient enough 0 \( \mu \text{bars/sec} \) to -20 \( \mu \text{bars/sec} \) to provide lift, but not as strong as they were in Rochester and La Crosse. St. Cloud, MN was presented with strong omega values at upper levels but the lack of moisture values prohibited them from experiencing any precipitation (Figure 6).

![Image](https://example.com/image.png)

**FIG. 6.** Observed kinematic omega values plotted at 500hPa (a.), 700hPa (b.), and 850hPa (c.) respectively. Note: 1 Pascal/second = 10 \( \mu \text{bars/second} \).

There was a definite difference in how both the NAM and GFS handled the snow event in St. Cloud, Minneapolis, and Rochester, MN. In St. Cloud, the NAM and GFS both predicted low values of omega to be affecting the snow growth zone (SGZ) (marked in yellow). The GFS predicted lower values of humidity in this important zone for snow growth as values ranged between 70-80%. The NAM hinted at slightly higher humidity values in the SGZ than the GFS, but counteracted it with the stronger values of omega forecasted within the SGZ. There were also moderate values of omega (between 5-15 \( \mu \text{bars/sec} \)) included in the SGZ for the NAM forecast as values were strongest at -10 \( \mu \text{bars/sec} \) (Figures 7a and 7b).

Minneapolis, MN showed higher chances of snowfall for a city directly on the sharp gradient. At this location, both the NAM and GFS forecasted saturated humidity levels throughout the low to mid levels of the atmosphere, aiding the SGZ in the development of large, dendritic snowflakes. Strong values of omega were also forecasted as the NAM topped out at -20 \( \mu \text{bars/sec} \) and the GFS with -15 \( \mu \text{bars/sec} \). Anything above -15 \( \mu \text{bars/sec} \) is considered “strong” omega. Snow growth and the highest omega values were found to originate within the 500-600 hPa layer of the atmosphere, forecasting snowfall in the region due to a saturated atmospheric profile (Figures 7c and 7d).

In Rochester, the main difference in this city’s forecast was the presence of both the NAM and GFS’ depiction of how saturated the profile is, as well as the gradient and strength of omega between the mid to upper levels. Both model outputs presented the low and mid levels of the atmosphere with a 100% saturated forecast. In the SGZ, omega values ranged from -5 \( \mu \text{bars/sec} \) to -40 \( \mu \text{bars/sec} \). This forecast is double the amount of lift forecasted in the Minneapolis atmospheric profile. Both the NAM and GFS presented a broad, strong area of omega between 300-700 hPa. The
onset of the broad amount of omega values in the atmosphere helped form the high amounts of observed snowfall in Rochester in the later stages of the snowfall event (Figures 7e and 7f).

Specific humidity is another key ingredient required for the development and onset of a snowfall band. Persistent, high values of specific humidity at 700hPa and 850hPa, interacting with omega to form clouds and precipitation, results in a strong gradient of snowfall for a region. In St. Cloud, both 700hPa and 850hPa levels indicated that there was not enough moisture to support precipitation there. Specific humidity values ranged from 1.0-1.5 g/kg at 18z on March 23 and 0z on March 24. Meanwhile, cities along the sharp gradient experienced specific humidity between 2.5-4.0 g/kg at both pressure levels, providing enough moisture for snowfall. Much of the cities within the highest values of observed snowfall experienced specific humidity values between 3.0-4.5 g/kg at both 700hPa and 850hPa. The 850hPa level was the driest level of the atmosphere, especially seen at 0 UTC 24 March as most locations saw specific humidity values below 3.0 g/kg. The specific humidity gradient evolved between the 12 hours as

FIG. 7. a.-b. St. Cloud, MN: Cross Sections of the atmosphere displaying forecasted values of omega (Red), relative humidity (Green & Purple) and snow growth zone (Yellow). Green = Relative humidity < 100%, while Purple = Relative humidity > 100%. (a.) is the GFS and (b.) is the NAM.


FIG. 7. e.-f. Rochester, MN: continued.
the gradient looked to mirror the snowfall gradient, resulting in a sharp gradient of moisture at the surface (Figure 8).

![Image of Specific Humidity](image)

**FIG. 8.** Specific humidity (g/kg).
- a. 700 hPa 18 UTC 23 March
- b. 850 hPa 18 UTC 23 March
- c. 700 hPa 0 UTC 24 March
- d. 850 hPa 0 UTC 24 March

4. Conclusion

Both the NAM and GFS models showed marginal and also extreme differences in snowfall forecasting compared to observations. In regions such as St. Cloud, the difference between observed snowfall and atmospheric model forecasts was marginal, while locations on the snowfall band saw the most uncertainty on where the sharp snow gradient would set up. On the other hand, locations in the heavy snowfall regions saw the largest differences, as models consistently overestimated and even underestimated snowfall at these locations.

The forecast of winds with height showed some differences compared to observations as well. Both models generally agreed throughout their time evolution of the 500 hPa wind direction. Some differences were seen with the forecasting of the 850 hPa winds. The 700 hPa forecasted time evolution differed in most due to the uncertainty of where the mesoscale snow band was poised to set up, along with the track of the surface low and the warm front. When both the 700 hPa and 850 hPa vector winds were out of the south and east, the warm, moist air was in place, adding enough moisture to strong omega values for the development of moderate to heavy snowfall.

Both the NAM and GFS were in agreement with omega and relative humidity values in and near the snow growth region of the atmosphere. At times, the GFS forecasted a smaller, more intense region of omega (near -40 µbars/sec), but omega and relative humidity values were conducive for precipitation (at times heavy), along the edge of the snowfall gradient, and even in Rochester, a city clearly in the heaviest gradient of snowfall.

The most critical levels of the atmosphere that shaped how the snowfall band evolved were between 500-700 hPa. This is the region that saw the largest wind shift direction, largest differences in omega values, and largest differences in relative and specific humidity. Another reason why
this area of the atmosphere was important is because both the NAM and GFS consistently had the snow growth zone developed in that region of the atmosphere.

Further research can be done to compare the two atmospheric models on their forecasts of additional heavy and sharp snowfall gradients. Comparison of additional models would further aid in the analysis of atmospheric model forecasting these phenomena in the future.

5. References


