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A CASE STUDY ANALYSIS OF TWO HEAVY SNOWFALL EVENTS AND ROAD WEATHER IMPLICATIONS IN 2018 FOR NEBRASKA

Nancy Barnhardt
University of Nebraska - Lincoln, nbarnhardt2@unl.edu

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A CASE STUDY ANALYSIS OF TWO HEAVY SNOWFALL EVENTS AND ROAD WEATHER IMPLICATIONS IN 2018 FOR NEBRASKA

by

Nancy Barnhardt

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Nancy Barnhardt, M.S.

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Advisor: Mark R. Anderson

Weather-related car accidents make up approximately a quarter of all crashes even though the amount of time during the year in which they can occur is minimal in comparison to fair weather day crashes. Maintenance Decision Support Systems (MDSS) were developed to help mitigate the number of crashes that occur during winter weather through improved operations along with reducing chemical usage. An MDSS uses weather information to recommend road treatments based on current and future weather conditions. To evaluate the limitations and capabilities of the Nebraska Department of Transportation Maintenance Decision Support System (NDOT-MDSS), case study analysis was performed on two 2018 winter storms, 20-22 January and 13-15 April which occurred over the state of Nebraska. These storms were chosen because they produced heavy snowfall totals across the state and travel delays and road closures were recorded for both events. A comparison of the NDOT-MDSS analysis and the observations from archived meteorological sources for each storm was done to investigate the timing and the total snowfall accumulations, pavement temperatures, air temperatures, and the winds, highlighting both the differences and similarities between the two observation data sets. A synoptic analysis of both winter storms was done to understand the atmospheric conditions and to illustrate how the NDOT-MDSS handled each situation. Understanding how well the NDOT-MDSS handled each storm is a key component in helping

maintenance crews be more efficient utilizing the maintenance recommendations. This research will provide the Nebraska Department of Transportation (NDOT) information on the NDOT-MDSS that will lead to a reduction of chemicals used to treat the roads.

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Chapter 1: INTRODUCTION

With more people on the road in recent years than ever before, the impacts of weather have increasing potential to impact drivers. According to the Federal Highway Administration (FHWA), weather-related crashes are defined as any crash that involves precipitation, fog or when there is precipitation on the roadway that causes it not to be dry or clear (U.S. Department of Transportation 2017). These types of crashes make up approximately a quarter of the total number of crashes every year. Over 7,400 people are killed in these crashes and another 673,000 are injured (Pisano et al. 2008). In the United States, 70% of the roadways receive more than 13 cm (5 in) of snow annually, the criteria to be considered a snowy region. With the substantial amount of roadways located in snowy regions, 21% of the weather-related crashes occur due to winter weather causing dangerous pavement conditions. During these winter-weather-related crashes, 1,300 people are killed per year and 139,800 are injured (U.S. Department of Transportation 2017).

It is critical for roadways to be kept clear or drivable during and after these winter weather events to help prevent accidents. Unfortunately, unlimited use of resources or chemicals cannot ensure driver safety due to cost and environmental impacts. A Maintenance Decision Support System (MDSS) can be used to help road maintenance crews determine the best road treatment based on the weather conditions. These systems use the weather conditions and forecasts to provide road treatment recommendations, so accurate weather and road condition information is vital to have. Some of the weather forecasts that are provided by MDSS are precipitation types and rates, insolation values, wind speeds and directions, and air and dew point temperatures (Mahoney and Myers

2003). The Nebraska Department of Transportation (NDOT) recently implemented an MDSS to help cut down maintenance costs and provide weather information to maintenance crews. The accuracy of the weather variables in the new NDOT-MDSS system in Nebraska is untested, so it is not clear how useful the system or the recommendations actually are for the roadways in Nebraska. NDOT maintenance crews are told to use the NDOT-MDSS during winter storm events; however, if the meteorological variables are inaccurate, then the treatment recommendations will be affected and this could lead to over- or under-use of materials and icy roadways. By understanding how accurate the meteorological variables are from the NDOT-MDSS, NDOT will have a better working knowledge of the limitations and capabilities of the system.

This study will investigate the accuracy of total snowfall accumulation, pavement temperatures, air temperatures, start and end times of precipitation, and wind variables from the NDOT-MDSS. Two winter storms were chosen for this study: 21-23 January 2018 and 13-15 April 2018. Both storms had major impacts on the roadways within Nebraska. A synoptic analysis will be completed to determine the similarities and differences in the weather systems to determine how the NDOT-MDSS handled them. This will help determine the strengths and weaknesses of the NDOT-MDSS during these heavy snowfall events. The main research objective is finding the limitations and capabilities of the NDOT-MDSS for two Colorado type low pressure systems to help NDOT understand how well the system works in certain storm types.

All of the data used will provide insight into the evolution of each storm and be useful for understanding the path and timing each storm took. Using the characteristics of each storm, data from the NDOT-MDSS will be examined to find how differences and similarities are handled and if there was a significant discrepancy in the forecasting ability or data output between each storm. Knowing how well NDOT-MDSS performed with each storm is important in understanding how well it will perform in the future with storms of similar nature.

Chapter 2: BACKGROUND

2.1 Road Weather

Adverse weather conditions can cause both traffic speed and volume reductions. During heavy snow, the FHWA found that there are an average speed reductions of anywhere between 5%-40% and an average volume reduction of 30%-44% on highways (U.S. Department of Transportation 2018). During light rain or snow, there are also reductions of both speed and volume with speed reducing by 3%-13% and volume decreasing by 5%-10%. Shah et al. (2003) looked at weather impacts on traffic flow in Washington D.C.. Travel time data were collected in 5 minute intervals throughout the day without any impacts that would cause a problem for commuters such as weather. This was used as their “base travel time” for daily commutes. The surface hourly weather data used by Shah et al. were from the Automated Surface Observing System (ASOS) network. Radar data were also used to connect the ASOS data to current conditions. The time that was found to be most representative of the weather impacts on traffic was the non-peak hours of traffic where precipitation caused travel time to increase by 11%. The study shows that weather events impact travel conditions, which slow down traffic patterns.

Using weather information during maintenance operations can help keep the roads safer and keep the cost of maintenance down. Shi et al. (2009) investigated the cost benefits of relaying weather information, such as the forecast and current conditions, to maintenance crews during wintertime events and found that using the information was more beneficial than costly. Both free and paid weather forecast data were investigated. It was found that both sources of data had their pros and cons. Free weather forecast data were available and were widely used by many people wanting weather information; however, free forecast data were less detailed and slightly less accurate. The paid forecast data were more accurate although, a lot of people are not willing to pay for forecasts when they can get them for free. It was noted that the biggest barrier preventing the use of weather forecast data by the winter maintenance professionals was the overall accuracy which goes back to if paying for the data is cost-effective. The study did come to the conclusion that the greatest benefit of using weather data during winter maintenance was the reduction in maintenance costs which means that paying for the more accurate data would actually save money, rather than getting the less accurate weather forecast data for free.

Shi et al. (2009) conducted a series of case studies in Michigan, Iowa, and Nevada to decipher how weather information before and during maintenance operations affected maintenance costs. In every state, a positive outcome occurred in reducing maintenance costs by incorporating weather information into their decision-making. The potential causes in the reduction of costs were both the frequency the weather data and the accuracy of the weather source. It was noted that, accuracy is more important than frequency, because maintenance operators need to have accurate real time forecasts to help them make cost-effective decisions.

2.2 Maintenance Decision Support System

An MDSS is a system that uses current and forecasted weather data along with road surface modeling to recommend treatment options for materials or actions needed to treat specific roads. The development of an MDSS by the FHWA began in 2001 due to the need for the integration of weather forecasts and treatment of the roads during events (Mahoney and Myers 2003). Five research labs were part of the development of FHWA MDSS: Army Cold Regions Research and Engineering Laboratory (CRREL), National Center for Atmospheric Research (NCAR), Massachusetts Institute of Technology-Lincoln Laboratory (MIT/LL), National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory (NSSL), and NOAA Forecast Systems Laboratory (FSL) (Andrle et al. 2003). This MDSS was set up as a modular system with different individual parts. The reasoning behind the modular design was so that if improvements needed to be made, individual parts could be improved without changing the entire system (Mahoney and Myers 2003).

Mahoney and Myers (2003) noted that there were a few different components that were implemented into MDSS. One of the main modular components is the Road Weather Forecast System (RWFS) This component of MDSS uses data from various sources such as the National Center for Environmental Prediction (NCEP) mesoscale models, Road Weather Information System (RWIS), and ASOS. The RWFS takes in the weather data from the various NCEP models and ASOS stations to give current conditions and forecasts.

The Road Condition and Treatment Module (RCTM) determines the road conditions which include road temperature and snow coverage and appropriate treatments for each segment of the road system. Hallowell and Blaisdell (2003) explained that the RCTM in an MDSS functional prototype used a land-surface model known as SNTHERM-RT to retrieve temperatures for the road surface and subsurface. The RCTM is also the module in MDSS where weather variables and road conditions are integrated to get the chemical recommendations for road segments. The module is responsible for the updates in road conditions after a treatment has been applied. The RCTM has a set snow-to-liquid equivalent ratio (SLR) of 10:1 for every event that occurs. The set SLR in MDSS makes the model easier to set up and for winter storms to be more generalized in terms of predicted snowfall. However, within an individual storm, the SLR can vary as the storm progresses due to varying temperatures as well as varying liquid water contents. SLR is influenced by the measure of air that is captured in the gaps within the ice crystals of the snow, lower-level temperatures, and the surrounding environment. Changes in these factors will lead to SLRs different from the mean SLR of 10:1 (Baxter et al. 2005). Since MDSS uses a mean SLR, the forecasted and observed amounts could be flawed due to potential inconsistencies depending on location and weather conditions. The pavement model that is in use inputs the thermal properties of the road into the system, which then determines the amount of compaction and melting taking place.

All of these components and modules make up the complex system of an MDSS. Without one part, the data flow would be interrupted and the integration of the meteorological variables, road weather conditions, or recommendations would be unattainable. Issues with any of the components might affect other components in an MDSS which could cause inconsistencies or errors in the analyses that are being put into the system.

The Iowa Department of Transportation (IDOT) was one of the states chosen to implement an MDSS when it was still a prototype (Andrle et al. 2003). Evaluations of the different parts of MDSS took place including the weather forecasting tools, the different treatment recommendations that were given, and the potential benefits and limitations of the system. Fifteen test routes were selected in the Ames and Des Moines, IA vicinities. The evaluations occurred between 3 February-7 April 2003. During this time period, there were three heavy snow events, five light snow events and one mixed precipitation event. There were various weather data sources, real-time and archived, which were used to verify MDSS weather data during these nine events. The recommendations given by IDOT after the evaluations were completed, showed the accuracy of the weather forecasts, especially the timing of the event, needed improvement and MDSS display and data collection portion were both difficult to use.

One of the main areas of focus during the development of MDSS was to increase the benefits or the savings for maintenance operations during winter weather events by reducing chemical usage (Mahoney and Myers 2003). Up to 33% of state highway budgets are used in winter road maintenance during snow and ice events even though these events occur very rarely throughout the year (Hanbali 1994). With new technology and more accurate weather forecasts, maintenance crews can become more proactive than reactive when it comes to applying chemicals to treat the roads. Treating roads earlier may help weaken the bond that snow or ice forms with the roadway. With the bond being weaker, there is less of a need to use chemicals to clear the roadways which leads to lower maintenance costs and less human power hours needed during an event (Shi 2009). MDSS recommends various solid and liquid road treatments during winter events.

2.3 Road Chemicals

Having an accurate forecast prior to a storm is vital to maintenance crews to better help treat the roads. Keeping the roads clear during the winter besides plowing involves many different materials including anti-icing and deicing materials (NDOR 2010). Anti-icing materials are a preventative measure taken by maintenance crews and are applied before or at the onset of the winter precipitation. The purpose of putting these chemicals down before the event is to help prevent the bond between snow or ice and the road surface. Having current weather conditions along with accurate forecasts is critical in the application of anti-icers because they rely so much on the timing of events. If the forecast is incorrect about the timing and onset of an event, anti-icing materials may be wasted by applying them too early or not applying them early enough. In some states, such as Virginia, anti-icing chemicals are only applied on roads with high levels of service because it has to be applied so early on in the maintenance process (Roosevelt 1997). Liquid chemicals are much more effective than solids, for anti-icing. When applying these chemicals, it is also important to look at the temperatures because different chemicals can be used for colder, below freezing temperatures (Table 2.1). A eutectic mixture, is a mixture where the combination of substances has a lower freezing point than any of the individual components. The eutectic temperature is the temperature where a eutectic mixture freezes (Ketcham et al. 1996). The eutectic temperature is not equivalent to the effective temperature of a material. The effective temperature of a material is the temperature at which that material freezes, and is no longer useful because it does not have any melting effect on snow or ice. An important aspect of anti-icing is that when

Table 2.1: Eutectic Temperatures for Commonly Used Anti-icing and Deicing Materials (Ketcham et al. 1996, Fischel 2001)

Anti-icing/Deicing Material	Eutectic Temperature	Effective Temperature
Sodium Chloride	-21.0 °C (-6 °F)	-9.0 °C (16 °F)
Calcium Chloride	-51.0 °C (-60 °F)	-32.0 °C (-26 °F)
Magnesium Chloride	-33.0 °C (-28 °F)	-32.0 °C (-26 °F)
Potassium Acetate	-60.0 °C (-76 °F)	-26.0 °C (-15 °F)
Calcium Magnesium Acetate	-27.5 °C (-17.7 °F)	-7.0 °C (20 °F)

used correctly, anti-icers can decrease the overall uses of chemicals throughout an event which will decrease costs of maintenance (Shi et al. 2009).

Deicing chemicals are applied to areas of the road that already have accumulation of snow or ice. This may occur at any point after the beginning of the event. The purpose of deicers is to penetrate the accumulated snow or ice to weaken or break the bond it has with the road. Weakening the bond will make plowing the snow or even displacing by traffic much easier. Some examples of commonly used deicers used by maintenance crews are calcium chloride, sodium chloride, potassium acetate, and calcium magnesium acetate, which are very similar to the popular anti-icing materials (Fischel 2001).

Solid ice control materials, such as sand and gravel, have various uses such as increasing traction for vehicles and preventing and removing ice and snow. Aggregates and abrasives are placed on the road surface before and during the storm. They are pre-wet before being applied to help them stick to the road more efficiently (Albers and Tuan 2015). Pre-wetting is also done for deicing materials. Aggregates should be put down on problem areas where sliding occurs more easily such as curves and places where stopping quickly may become an issue such as intersections. Sand and gravel are also used when deicing materials become ineffective due to extremely low temperatures.

2.4 Mid Latitude Cyclones/Colorado Lows

Mid-latitude cyclones usually bring in a wide variety of weather conditions, including snowfall in the winter. The snowfall can often be heavy in areas, causing poor road conditions. Understanding the development and conditions that accompany these systems can help road maintenance crews better prepare for an event. There are various locations that mid-latitude cyclones can form; however, the focus area for this study is over eastern Colorado since these events influence the weather over Nebraska.

A typical environment prior to the development of a cyclone is warm, moist air to the southeast, warmer, drier air to the west of the mountains, and colder, drier air is usually located to the north. The warm moist air to the southeast helps to provide a moisture source for the system. The cold, dry air from the north advects southward and the warmer air advects northward which produces fronts, a necessary situation with the development of a mid-latitude cyclone. Intensification is caused by the tightening of the pressure gradient and when divergence aloft surpasses the convergence at the surface. The tightening of the pressure gradient causes stronger winds which can advect more moisture and temperature. The additional advection can cause heavier precipitation to occur. Once the cyclone has reached the occlusion stage of development, it is mostly or fully matured. As the storm occludes, the warm sector shrinks and the energy for the storm dissipates, causing its demise. Cold air then fully overtakes the warm air and stabilizes the surface (Lackmann 2015).

Colorado Lows, or lee-side cyclones, are known for a wide variety of weather as well as their intensity. These systems can potentially lead to severe storms along the southern portion of the cold front and snow, rain, sleet or freezing rain in the warm sector, depending on temperatures. In addition, if ample moisture is present, heavy precipitation can fall. In the wintertime with appropriate temperatures, the northwestern part of Colorado Lows can produce snow with blizzard conditions possible. The National Weather Service (NWS) criteria for a storm to be a blizzard is a minimum of 3 hours of winds over 15.6 $m\ s^{-1}$ (30.4 kts) and 0.22 km (¼ mile) of visibility. There are three meteorological ingredients that are needed to produce blizzard conditions: cold air, moisture and warm, rising air. A Colorado low pressure system follows the structure and development of a classic Norwegian mid-latitude cyclone. Some of the characteristics are its distinctive comma cloud shape and how the low forms along frontal boundaries. Carlson (1980) noted that the comma cloud shape is potentially caused by an occluded front when the storm is mature. This is the first step in the dissipation of the storm. Mid-latitude cyclones usually take place at latitudes between 35°-55° N (Ferreira et al. 2013). The approximate size of a mid-latitude cyclone is 1500-5000 km in diameter, which surpasses the size of a smaller tropical cyclone (200-1000 km). One of the main purposes of mid-latitude cyclones is global heat transport. In a mid-latitude cyclone, the counter-clockwise rotation allows warmer air to be advected northward and colder air to be advected southward. The warmer air rises over the colder air, causing upward motion which will help deepen the low pressure system.

Prior to the development of a mid-latitude cyclone, an upper level shortwave usually forms, which also represents instability. Shortwaves at 500 hPa surfaces, which are also known as upper level disturbances, are usually embedded within long waves. Shortwaves are able to move at a faster speed than long waves and usually are associated with areas of precipitation. In the winter season, locations to the northwest of the surface low typically observe frozen precipitation. Shortwaves are a very important part of the development of a cyclone because it helps initiate the counter-clockwise rotation through cold air and warm air advections in the trough. Stronger advections of moisture and temperature intensify the storm. Another important ingredient for cyclones are jet streaks.

Jet streaks have areas of divergence in their left exit region and their right entrance region (Ahrens and Samson 2011).

Determining where the rain/snow line will be in a Colorado cyclone can be difficult at times. The meteorological variable known as thickness refers to the vertical distance between two pressure levels. The thickness can be used as a way to tell the mean layer temperature (Venne et al. 1997). The critical thickness of a layer helps identify where the rain-snow line will occur. In winter weather forecasting, critical thicknesses are used to help the forecaster determine the type of precipitation that is going to fall at a given time and location. There are various critical thickness lines within the atmosphere for different layers (Table 2.2). These critical thicknesses are “rules-of-thumb” that indicate where the thickness of a layer corresponds to an appropriate mean layer temperature of 0 °C. Layers with mean temperatures above 0 °C allow for melting of the ice crystals. Melting will lead to different types of precipitation such as sleet, freezing rain, or rain. Critical thicknesses are not always an accurate measure though, especially at higher elevations. The critical thickness of a layer also may not always represent the rain-snow line at areas that are at sea level because of the potential for shallow layers of warm air that are near the surface.

Varying temperatures and saturation of a dendritic growth zone (DGZ) will cause different shapes and sizes of snowflakes to form. A DGZ is a saturated section of the atmosphere that has temperatures ranging from -12 °C to -18 °C where dendritic crystals are formed. Different temperatures and saturation ratios will mean that the ice crystals can form into shapes such as needles which include pyramids, bullets, and columns or plates which include dendrites, stellar crystals, sectored hexagons, and hexagonal

Table 2.2: Critical thickness values used to determine where the rain-snow line is located and their corresponding thickness layers (Venne et al. 1997).

Thickness (hPa)	Critical Thickness (m)
1000-850	1300
1000-700	2840
1000-500	5400
850-700	1540
850-500	4100
700-500	2560

plates. Temperatures between -10 °C and -20 °C will form a variety of plate shapes depending on the saturation of the atmosphere. Needle-shaped ice crystals are more likely to form when there is lower saturation excess (Curry and Webster 1999). When looking at the atmospheric profile during a winter event, it is important to determine whether the DGZ is mostly or completely saturated. If any part of the temperature profile exceeds 0 °C (32 °F), this can lead to other types of precipitation such as sleet or freezing rain due to melting.

Atmospheric moisture is also important to the development and overall precipitation patterns of a mid-latitude cyclone. Precipitable water is the total amount of water in a column of air if all the water in that column fell as rain over an area. It is an indicator of places where greater amounts of precipitation may fall. Areas where snow is falling, usually to the northwest of the low pressure center, do not have as much precipitable water as areas where heavy rain is falling, which is usually along the cold front.

Another component of the atmosphere that is important in the forecasting of mid-latitude cyclones is the change in slope of a temperature gradient between levels. If there is an increase in the horizontal temperature gradient over time, this indicates that frontogenesis is occurring (Sawyer 1956). Two processes that are major contributors of frontogenesis are divergence and deformation. These processes are significant contributors to the overall formation of winter storms as well. Frontogenesis can occur between 850 hPa and 500 hPa and can take place during the developing or mature stages of a mid-latitude cyclone. One of the areas of snowfall is commonly located is on the northwestern side of the storm where the deformation zone is located. The deformation zone is produced by frontogenesis. In addition to frontogenesis, equivalent potential vorticity in term of the geopotential wind (EPVg*) is another important ingredient in producing heavy snow. Evans and Jurewicz Sr. (2009) found that there is a correlation between the heaviest snowfall accumulation and the minimum value along with the depth and persistence of negative EPVg*. The findings show that the lowest values of EPVg* were present just before the start of the heaviest snowfall of the event. Another correlation that was found in the same study was between depth and persistence of rising motion less than -8 μb s^{-1}. The correlation usually occurs in the dendrite zone and where the maximum snowfall fell. Understanding how the various ingredients within a lee side cyclone are important in finding areas where heavy snow can fall which will be beneficial for a synoptic analysis of a major winter storm.

Chapter 3: DATA AND METHODS

NDOT divides the state of Nebraska into eight different maintenance districts (Figure 3.1). In the NDOT-MDSS, each NDOT road within a district is partitioned into individual road segments or "routes". To determine how the NDOT-MDSS varies across a district or regions within the state, several routes have been chosen to be investigated. The routes were selected by location and from discussions with NDOT. Routes within each district were chosen to best represent that district based on the proximity to ASOS, RWIS stations, and roadside cameras and the route cardinal orientation (e.g., north/south or east/west directions). While choosing these routes, the type of road (i.e., 2-lane or 4-lane) was also taken into consideration to make sure that there are variations in the level of service (LOS) determined by NDOT (Table 3.1). The LOS is based on a daily average traffic flow, as well as the amount of time it should take each route to regain bare pavement after a snow event (NDOR 2010).

Two storms were chosen for the case study analysis: 21-23 January 2018 and 13-15 April 2018. These storms were chosen because blizzard conditions occurred throughout the state and had major impacts on travel, including many road closures. Both of the storms would be classified as Colorado lows. The storms are very similar in terms of strength and snowfall. Eight routes (Table 3.2, Figure 3.2) were chosen in total representing Districts 3, 6, and 8 based on the impacts of the storms. The NDOT-MDSS data for both archived storms were extracted from the web interface of NDOT-MDSS (2018). Since the NDOT-MDSS archive is a proprietary entity, control of the data within the archive is not set by the author and may limit analyses with the case studies. Three-

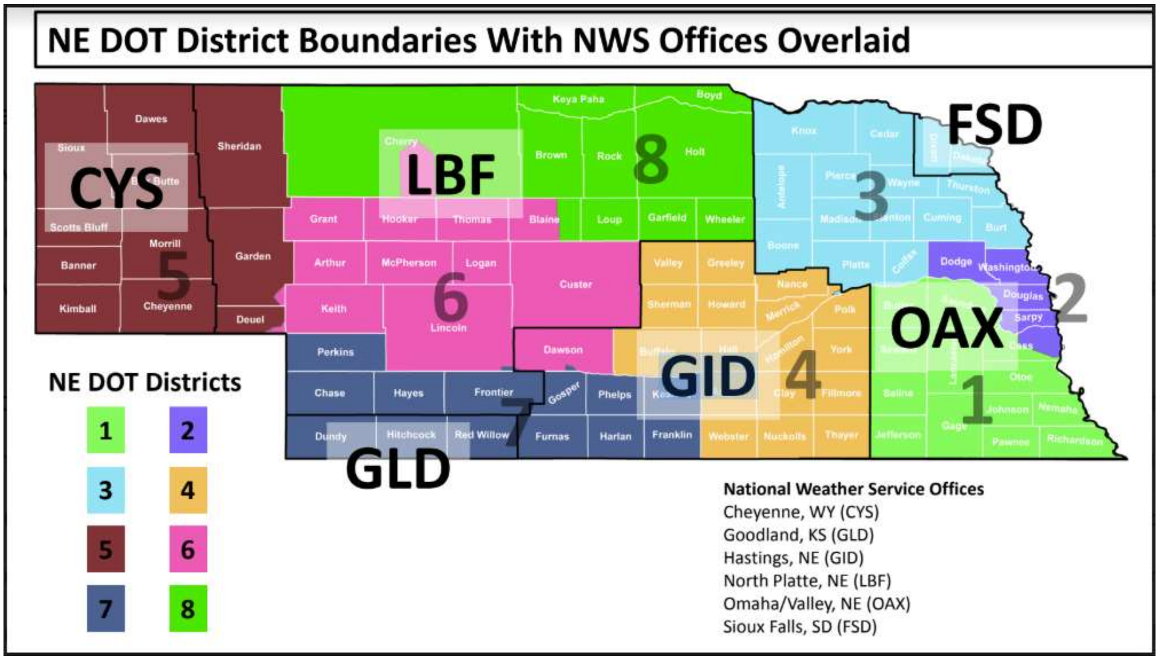


Figure 3.1: County Warning Areas for NWS Weather Forecast Offices serving Nebraska overlaid onto the 8 NDOT maintenance divisions (Adapted from NDOT 2019).

Table 3.1: NDOT level of service for different road types. (NDOR, 2010)

Route Designation	Traffic level (Average Daily Traffic Count)	Regain time (bare lane) (hrs)
Super Commuter	>50,000	4
Urban Commuter	20,000-50,000	6
Rural Commuter	7,000-20,000	8
Primary	2,500-7,000	12
Secondary	1,000-2,500	24
Low Volume	<1,000	48

Table 3.2: Selected Test Routes from the NDOT-MDSS

Route	District	Route Description	Route Cardinal Orientation	Daily Traffic Count	RWIS site	ASOS site
1	3	330-US 81 Jct. 275 to Jct. 91 at Humphrey RP 133.28-158.42	North-South	8425	Scribner	KLCG
2	3	340-US 75, from Jct. 77 at Winnebago to Jct. 129 just south of south Sioux City RP 168.76-184.87	North-South	7875	Scribner	KLCG
3	3	350-NE 35, Wayne West to Jct. 35&98, MP 29.69 to MP 21.68	East-West	4415	Scribner	KLCG
4	6	620-US 30 North Platte to Brady	East-West	1630	Wellfleet	KLBF
5	6	620-I-80 North Platte to Brady	East-West	15420	Wellfleet	KLBF
6	6	650-US83, Dismal River to Thedford	North-South	418	North Thedford	KANW
7	8	810-N12, N Jct. US 183 to N Jct. NE 137	East-West	230	North Thedford	KANW
8	3	310-Hwy 56, Greeley/Boone Co. Line to Jct. 56&14	East-West	615	Cedar Rapids	KBVN

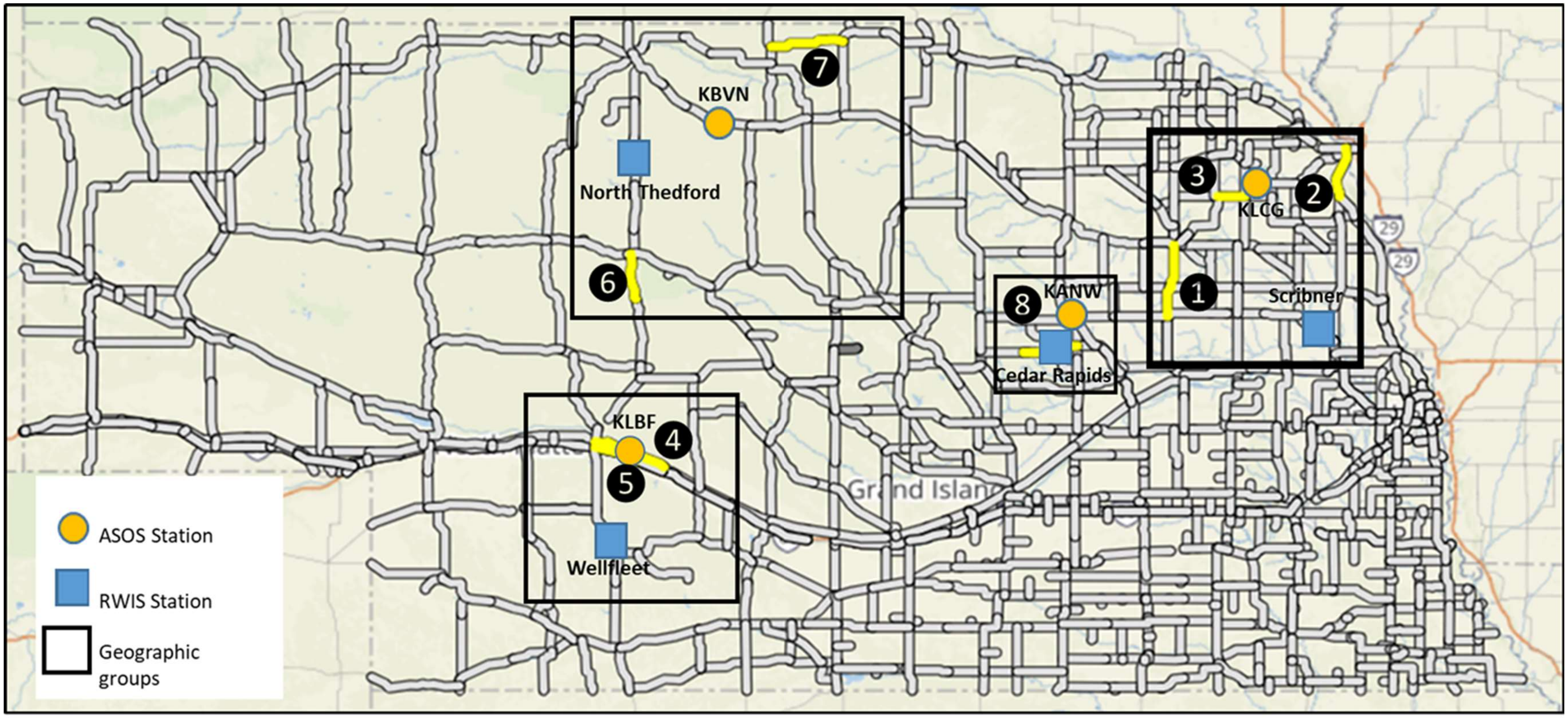


Figure 3.2: Locations of ASOS and RWIS stations used for comparison against the MDSS routes (yellow, route # in black)

hourly increments were chosen for each storm, starting from the beginning of the saved storm within the NDOT-MDSS system, which is up to 24 hours prior to the onset of the storm, to the end of the precipitation for that route. Images of the analysis of the conditions for every route provided by NDOT-MDSS were also taken at three-hourly increments to show how the storm progressed as well as how well the system identified heavy precipitation and the location of the rain-snow line. The placement of the rain-snow line within the NDOT-MDSS will be compared to known critical thicknesses of different layers in the atmosphere. In addition, the surface freezing level from ASOS observations will be used to determine variations within NDOT-MDSS.

Two of the routes, Routes 4 and 5 (Figure 3.3), were selected because they run parallel to each other as well as their close proximity to each other (< 4 km). A comparison will be done between these two routes within NDOT-MDSS to see how their snowfall accumulations and start and end times varied from one another. This will show if any major deviations occurred in the forecasts for locations that are in the same area. If there are differences, reasons explaining them will be investigated. Routes that have different route cardinal orientation will also be investigated to identify any differences in treatment or NDOT-MDSS's forecast ability.

To help determine the accuracy of the NDOT-MDSS forecasts, the start and end times of the precipitation for each route were determined in three separate ways. First, the precipitation start and end times from the NDOT-MDSS forecast are found. Then, the start and end times are obtained from the analysis within NDOT-MDSS. Finally the start and end times of precipitation are determined from local NWS radar data. The radar data are considered independent observations to the NDOT-MDSS, even though the

Figure 3.3: Location of Routes 4 and 5 in respect to each other and to the KLBF ASOS station

NDOT-MDSS could be incorporating radar data. The forecasted precipitation start and end times were taken 6 hours prior to the NDOT-MDSS analysis of the start and end times because maintenance crews need to know approximately 6 hours before the storm starts or ends to be able to put down chemicals, if necessary. The differences in start and end times of precipitation can be used as a verification for the efficiency of the NDOT-MDSS as both a forecasting and analysis tool. When the forecasted start time is different from the analysis of the start time within the NDOT-MDSS, the positive (negative) values indicate that the forecasted start time was later (earlier) than the analysis of the start time. Positive (negative) values also indicate that the NDOT-MDSS forecasted or analysis values start later (earlier) than the radar observed values. Western routes have shorter forecast lead times due to the way NDOT archives data within NDOT-MDSS. Storms are saved for each event when the storm starts to impact western Nebraska. Generally, there is less than 24 hours of lead time in the western part of the state before the occurrence of precipitation. Eastern Nebraska has longer lead times than western Nebraska by 20 hours in the April storm and 30 hours in the January storm.

Similarly, total forecasted snow accumulation can be taken from within the NDOT-MDSS and compared to independent snow totals for each storm to determine similarities or differences in forecasts. The independent snow totals are comprised of individual observations from xmACIS (2019) which include observations from the Weather Bureau Army Navy (WBAN), Cooperative Observer (CO-OP) and the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS). The highest total snow accumulation within the NDOT-MDSS during the storm will be used because the system accounts for compaction, melt and treatments applied as the storm impacts the route. Compaction, melt and treatment application on the roads have the potential to lead to lower snow totals than what might actually have occurred. Comparisons of the total snowfall accumulations of xmACIS and the NDOT-MDSS will be completed. The comparison will serve as a verification for the accuracy and limitations of the NDOT-MDSS. Hourly wind and temperature analyses will be taken from the NDOT-MDSS and various ASOS stations (Plymouth State University 2019) located near the selected routes for comparison. The temperature analysis in the NDOT-MDSS is assumed to be 2 m temperatures. Hourly pavement temperature analyses will be taken from the NDOT-MDSS and various RWIS stations (WebMDSS™ 2018). Each route will be grouped based on their geographic location in respect to ASOS and RWIS stations (Figure 3.2). The temperatures obtained from the RWIS and ASOS stations in each geographic group will be compared to see how much they differ. Large differences could potentially indicate that there may also be a problem with the pavement temperature being reported and input into the NDOT-MDSS which may lead to issues with snowfall total accumulations and snow rates. The proximity of the routes to the ASOS station varies in the geographic locations so that may limit the accuracy of the data (Table 3.3). The geography of the routes were very similar to the geography of the area that the ASOS stations were located in. In general, they were both flat with minimal trees so to this will cut down on possibly differences, especially with the wind analysis.

A synoptic analysis will be done for each winter storm to identify key weather conditions associated with each event. The two storms will be compared and contrasted based on their meteorological characteristics. For this analysis, surface conditions, 850 hPa, 700 hPa, 500 hPa and 300 hPa upper air level data, along with radar

Table 3.3: Approximate Distance of each route to their respective ASOS station

Route	**Approximate Distance from ASOS station**
1	50.0 km
2	41.0 km
3	3.1 km
4	0.5 km
5	2.9 km
6	85.0 km
7	50.0 km
8	8.0 km

data will be used to describe the meteorological characteristics. Surface and upper air conditions will be acquired from the Storm Prediction Center (SPC) archive (SPC 2019). The radar imagery were obtained from NCAR (2018) and the SPC (2019). Radar images will also be used for verification of the start and end times of precipitation from each storm based on the route location. Upper air soundings from the archive at Plymouth State (2018) were obtained to show where the dendritic growth zone (DGZ) is located in the atmospheric column to determine snowfall characteristics. In addition, other aspects of the storm will be investigated using data and charts from SPC (2019), such as frontogenesis, EVPg*, vorticity, rising motion, precipitable water and divergence aloft.

The forecasted precipitation probabilities and the predicted location of the low pressure center for each of the storms were collected from WPC (2019). The low pressure tracks indicate the shifts that the forecast takes in days 7 through 3 prior to the event over Nebraska. The forecast tracks also show where there is a higher chance of precipitation. In addition, the forecasts tracks will be used as a visual aid to help understand the decisions made by the NWS in their forecasts.

The routes are located in 3 different NWS county warning areas (CWA): Sioux Falls, Omaha/Valley, and North Platte (Figure 3.1). Routes 1, 3, and 8 are in the CWA of the Omaha/Valley NWS office, Routes 4, 5, 6, and 7 are in the CWA of the North Platte NWS office, and Route 2 is the CWA of the Sioux Falls NWS. The Area Forecast Discussions (AFD), advisories, warnings and watches produced by the NWS were obtained from Iowa State University (2019). The products will be compiled to show how the NWS forecasts developed over time along with snow total predictions for each CWA. NWS Hastings was included due to their proximity to Route 8. Knowing the forecasts for the storms will provide insight into how well the models did in addition to the how the forecasts evolved alongside the forecasted location of the low.

Chapter 4: RESULTS

4.1 January Synoptic Results

The development of the January storm system began with a low pressure system that formed over southeastern Colorado. The system brought clouds and precipitation to the west coast then strengthened as it crossed the Rocky Mountains. The storm system took advantage of strong moisture advection from the Gulf of Mexico which aided in the development of rising motion. The large amount of moisture combined with the rising motion produced high amounts of wet snow throughout the central Great Plains, which commonly occurs with Colorado Lows. Strong to severe thunderstorms also occurred along the cold front in the Mississippi Valley. The effects of the storm in Nebraska started at 0000 UTC 21 January in the far western parts of the state. The storm had not fully matured, so areas in the western part of the state did not receive as much snow as the central and eastern parts of Nebraska. As the low moved into Kansas from southeastern Colorado, the low strengthened and areas in Nebraska to the northwest of the low received upwards of 25.4-30.48cm (10-12 in) of snow (Figure 4.1). Drifting caused road closures on both state and county roads (U.S. Department of Commerce 2018a).

At 0000 UTC 22 January, the North Platte, NE atmospheric sounding (Figure 4.2) showed that the atmosphere has the necessary ingredients to produce snowfall. There is saturation in the DGZ, which is located between 650 hPa and 550 hPa. There is also no melting taking place in this temperature profile due to the fact the temperature never goes above 0 °C (32 °F). The ASOS station located at KLBF in North Platte was reporting heavy snow at this time. At 0000 UTC 22 January, the NWS Omaha/Valley atmospheric

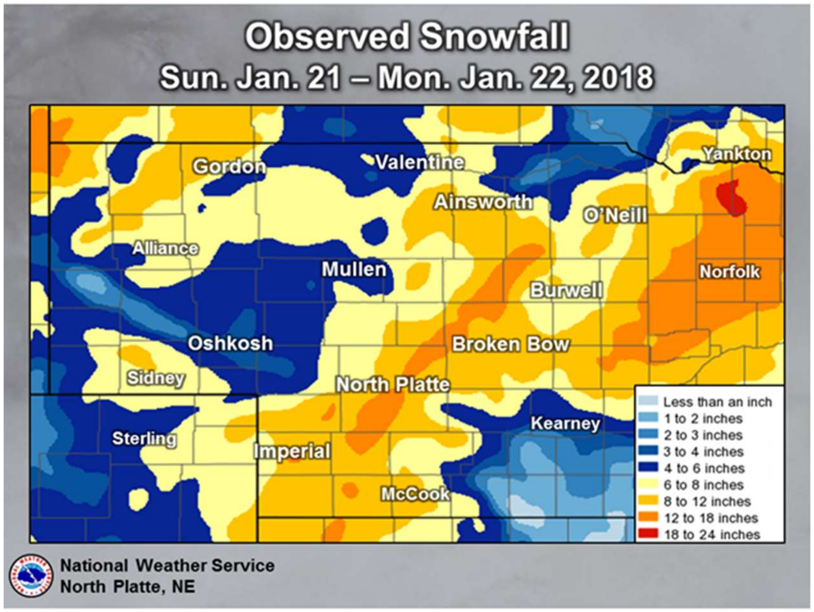


Figure 4.1: Snowfall totals throughout the state of Nebraska from the NWS for the January storm (U.S. Department of Commerce 2018a)

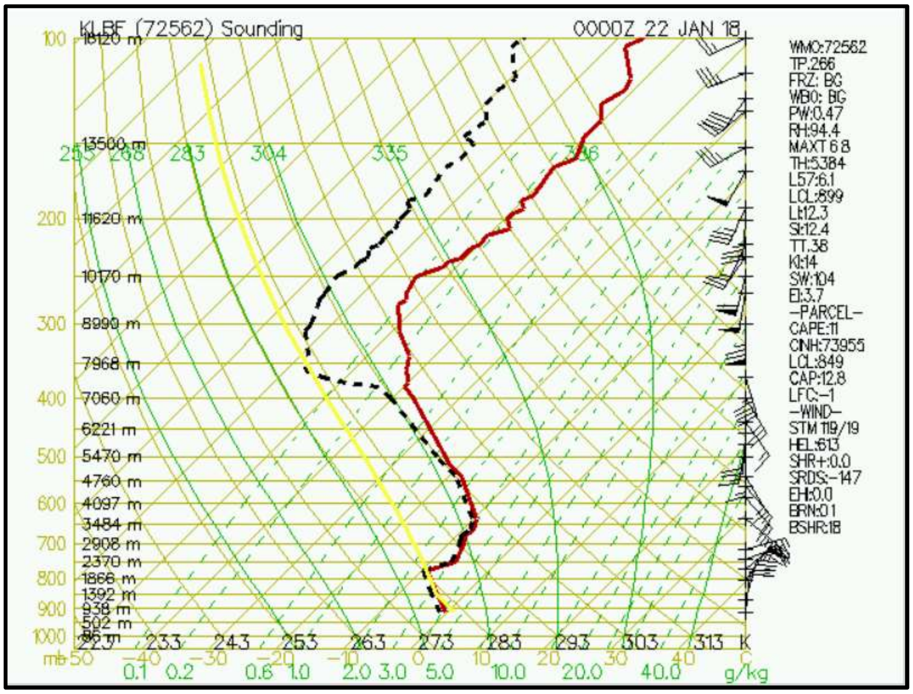


Figure 4.2: Profile of the atmosphere at 0000 UTC 22 January for North Platte, Nebraska (Plymouth State Archive 2019)

sounding (Figure 4.3) is showing complete saturation from 950-775 hPa. The temperatures in that part of the atmosphere are above 0 °C until 790 hPa. The DGZ is located between 600 hPa and 500 hPa and is not quite fully saturated; however, there is a pocket of dry air below the DGZ so any ice crystals that do form and fall will most likely sublimate or melt before reaching the surface. The ASOS station located at KOAX in Omaha is reporting haze. As the storm moves to the east, the North Platte atmospheric sounding at 1200 UTC 22 January (Figure 4.4) still shows that the atmosphere is mostly saturated and that the temperatures do not exceed 0 °C so the ingredients for snow are still present. Light snow was reported by the North Platte ASOS station. The Omaha atmospheric sounding at 1200 UTC 22 January 2018 (Figure 4.5), indicates that the temperatures never exceed 0 °C (32 °F) throughout the sounding. Even though there is an inversion from 850 hPa-750 hPa, the temperature never reaches above freezing, which implies that there was no melt of the ice crystals on the way to the surface. The DGZ is located between 650 hPa-550 hPa and is almost completely saturated which allows for the excellent dendrite ice crystal growth. The sounding can be compared with radar observations to show that precipitation was falling at 1225 UTC over eastern Nebraska (Figure 4.6). Since the temperatures in the sounding were all below freezing, snowfall can be considered the precipitation type. The saturated atmosphere also means that the precipitation can be tracked back to the DGZ. The Omaha ASOS station was reporting light rain at 1200 UTC. The light rain turned over to snow within 30 minutes of 1200 UTC.

Two days before Nebraska will feel any impacts from the storm at 0000 UTC 20 January, a shortwave at 500 hPa is found over northern California (Figure 4.7). By

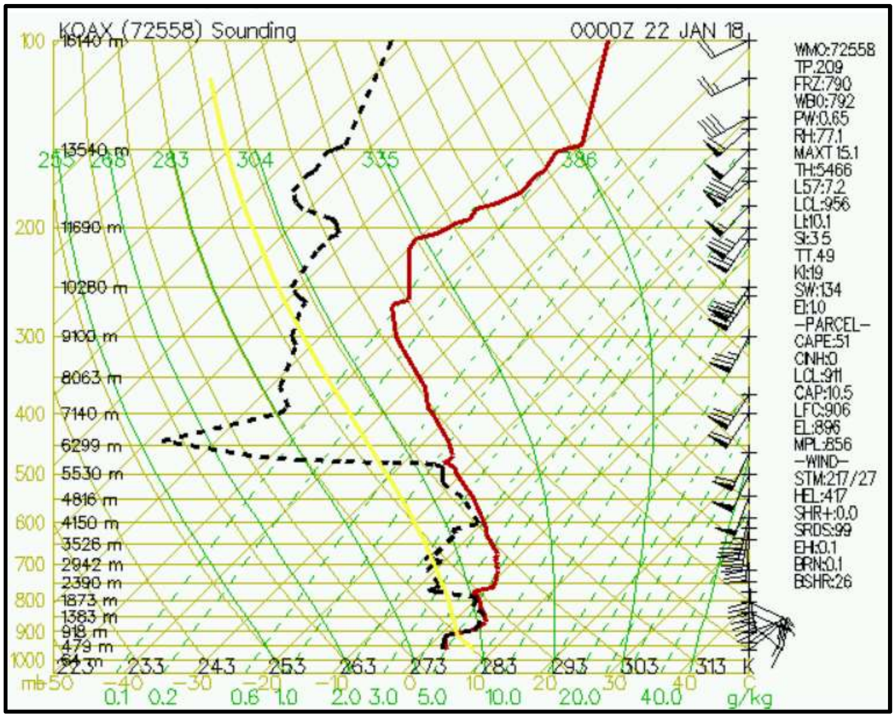


Figure 4.3: Profile of the atmosphere at 0000 UTC 22 January 2018 for Omaha, Nebraska (Plymouth State Archive 2019)

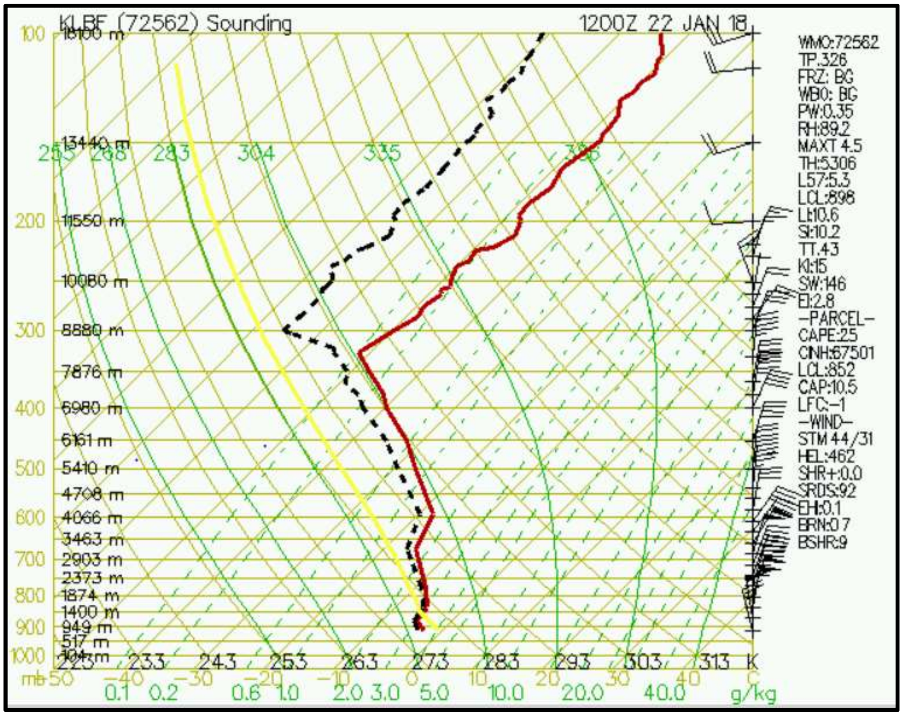


Figure 4.4: Profile of the atmosphere at 1200 UTC 22 January for North Platte, Nebraska (Plymouth State Archive 2019)

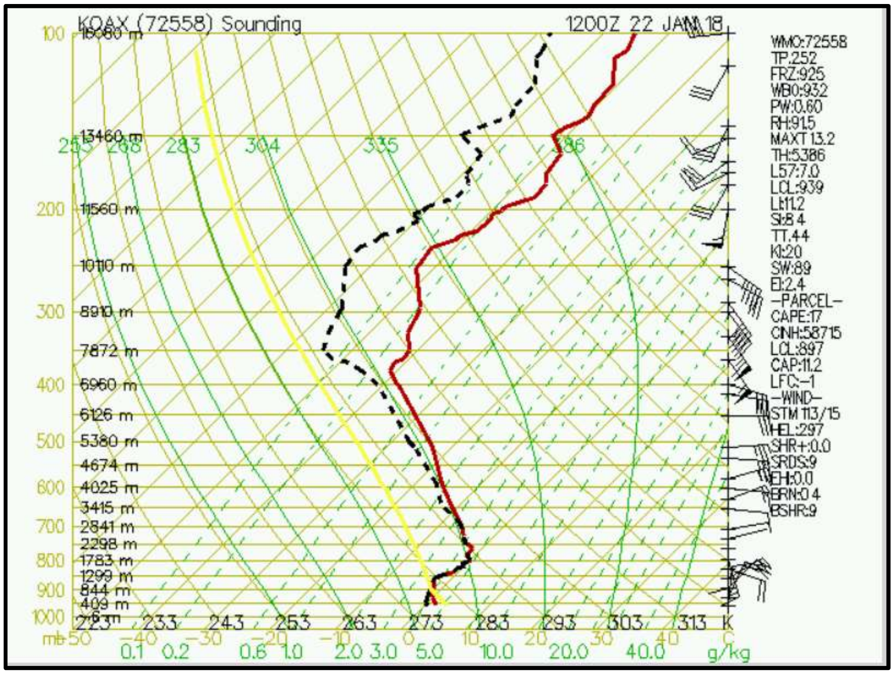


Figure 4.5: Profile of the atmosphere at 1200 UTC 22 January 2018 for Omaha, Nebraska (Plymouth State Archive 2019)

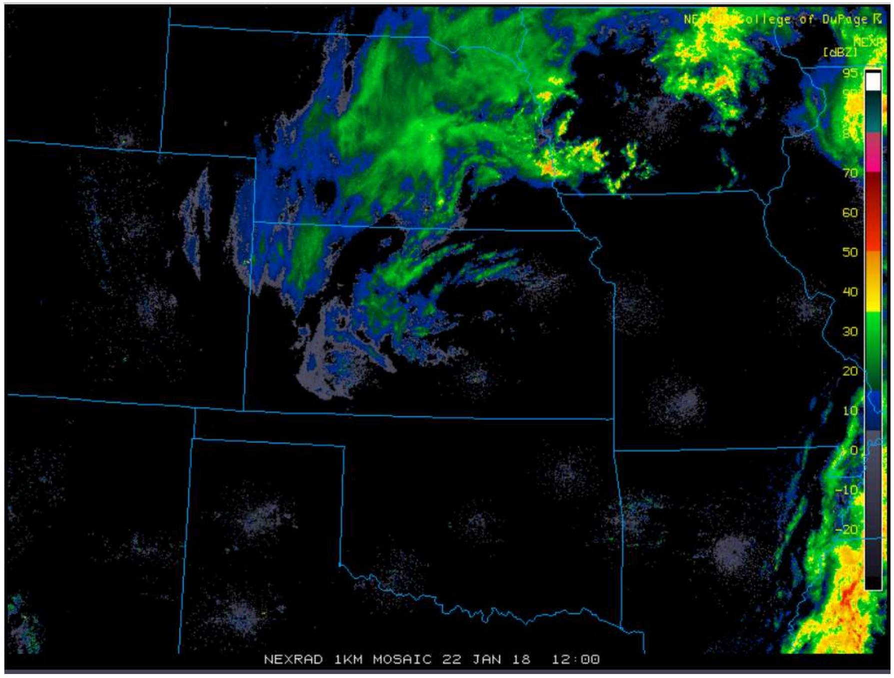


Figure 4.6: Radar image at 1200 UTC 22 January 2018 (NCAR 2018)

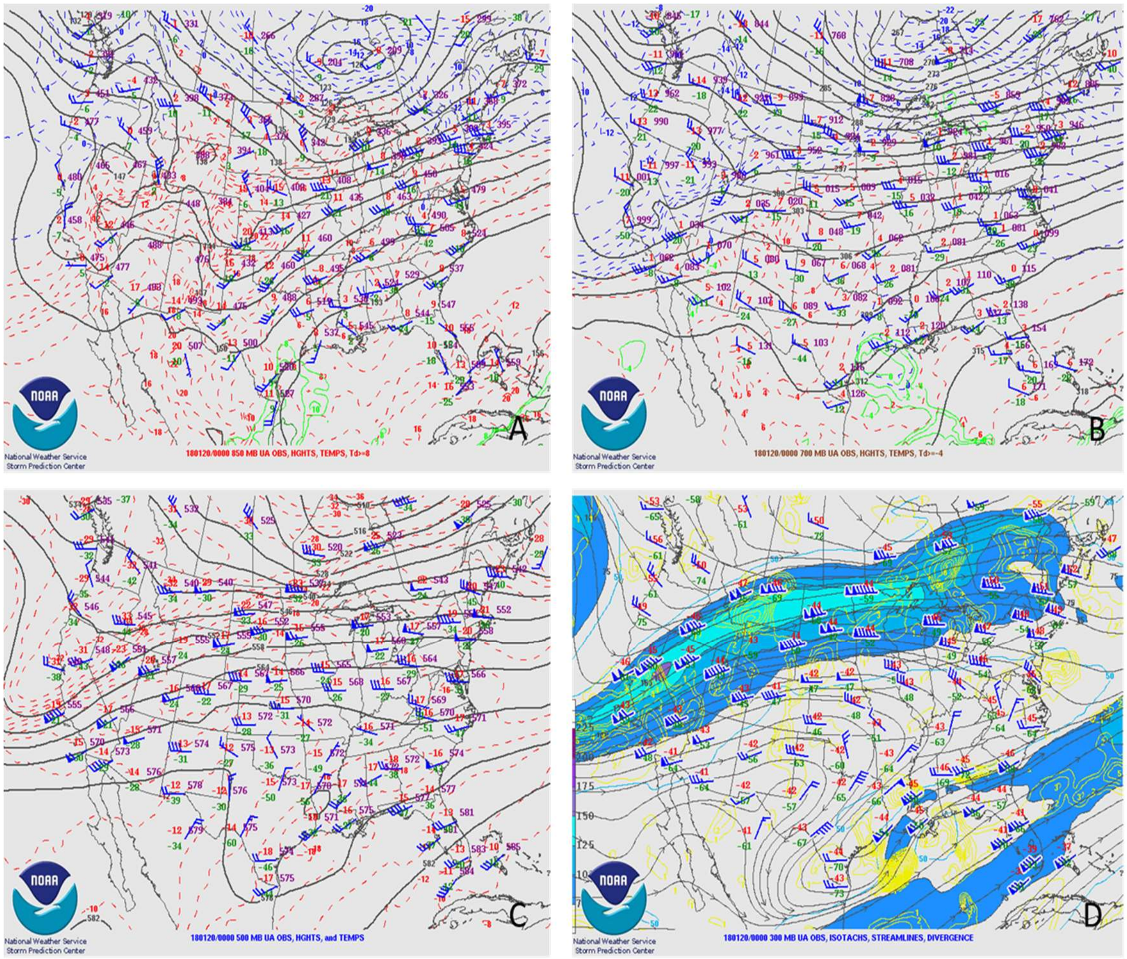


Figure 4.7: Different levels in the atmosphere at 0000 UTC 20 January 2018. a) 850 hPa b) 700 hPa. c) 500 hPa d) 300 hPa (SPC 2019)

1200 UTC 20 January (Figure 4.8), the 500 hPa shortwave moves southward to southern California where a closed low starts to develop. The 500 hPa trough is positively tilted, which is usually known as a building phase of a trough. The positive tilt of 500 hPa trough proceeds the neutral phase where the trough usually is completely vertical. At 1200 UTC 21 January (Figure 4.9), the 500 hPa trough closes off and a closed low is found over the Four Corners area. When the closed low forms, the system really starts to deepen. The system is intensifying and the height gradient is decreasing which leads to stronger winds throughout the area. Winds reaching 36 m s^{-1} (70 kts) were observed to the southeast of the closed low at 500 hPa. Twenty four hours later, at 1200 UTC 22 January, the trough has matured and is now neutrally tilted over the Great Plains and most of the central United States (Figure 4.10). The closed low is noticeably stronger and the impacts from the low are stronger winds and heavy precipitation which are being felt across Nebraska. Cold air advection (CAA) can be seen at 850 hPa (Figure 4.10a) to the northwest and west side of the low pressure center. The CAA stretches from North Dakota all the way down to Texas. CAA helps bring in the cold air necessary for producing snowfall as the dominant precipitation type. The low pressure center is in northeastern Kansas, shown by the circulation occurring at the surface at 0013 UTC 22 January (Figure 4.11).

At 1200 UTC 21 January, most of the critical thicknesses are still located to the north of eastern Nebraska though the western part of Nebraska would indicate snow (Figure 4.12). This indicates with moderate accuracy that if any precipitation is falling in central or eastern Nebraska, then it will most likely be rain. The NDOT-MDSS is showing that there is snow falling in northwestern Nebraska and a combination of rain

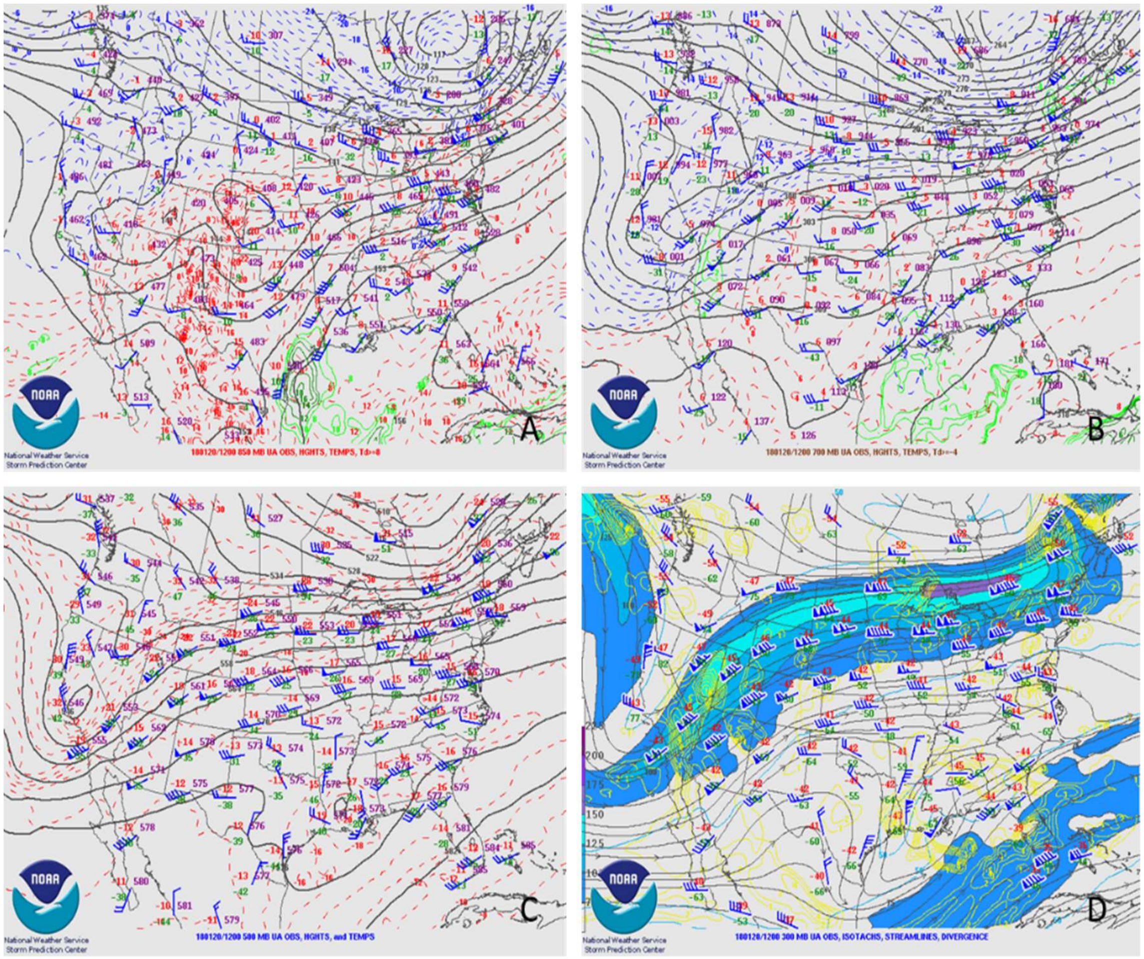


Figure 4.8: Different levels in the atmosphere at 1200 UTC 20 January 2018. a) 850 hPa. b) 700 hPa c) 500 hPa d) 300 hPa (SPC 2019)

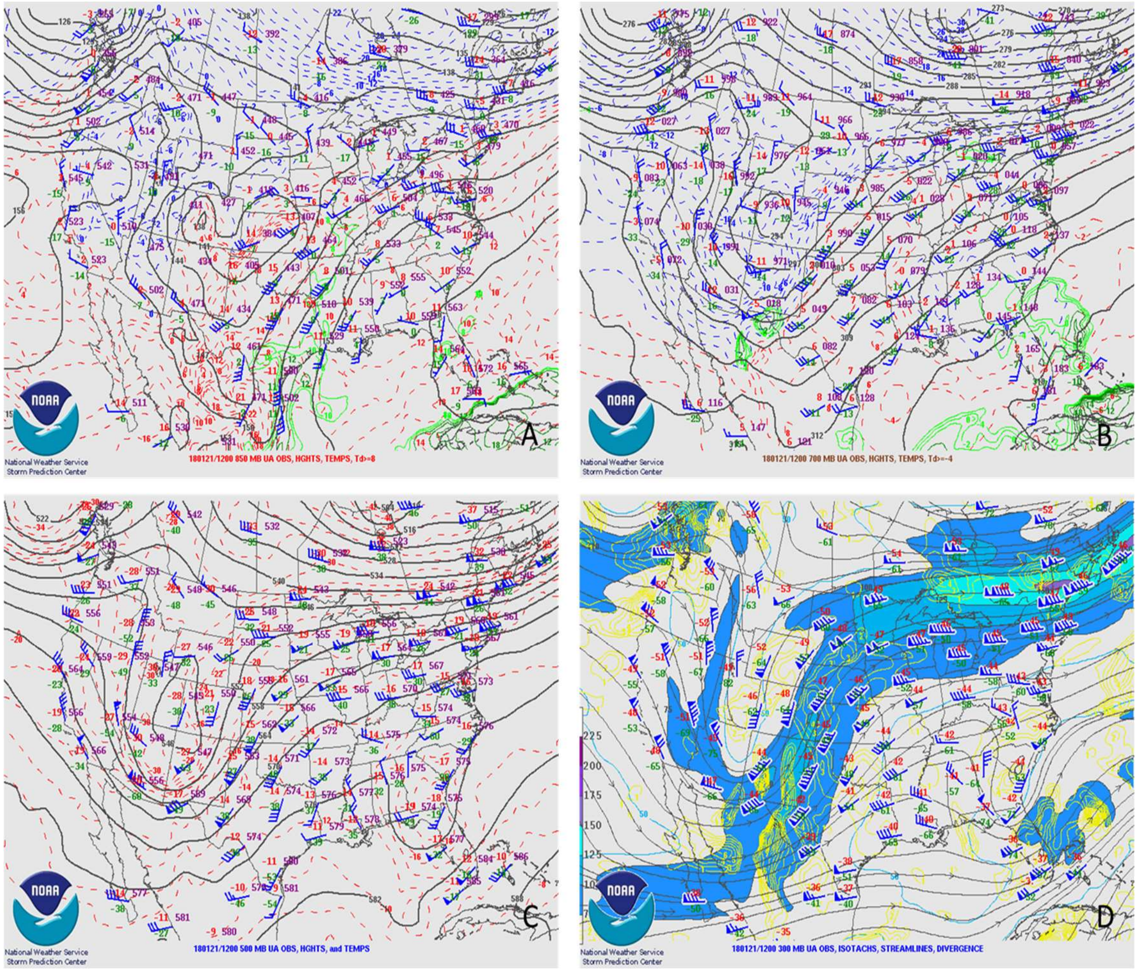


Figure 4.9: Different levels in the atmosphere at 1200 UTC 21 January 2018. a) 850 hPa b) 700 hPa c) 500 hPa d) 300 hPa (SPC 2019)

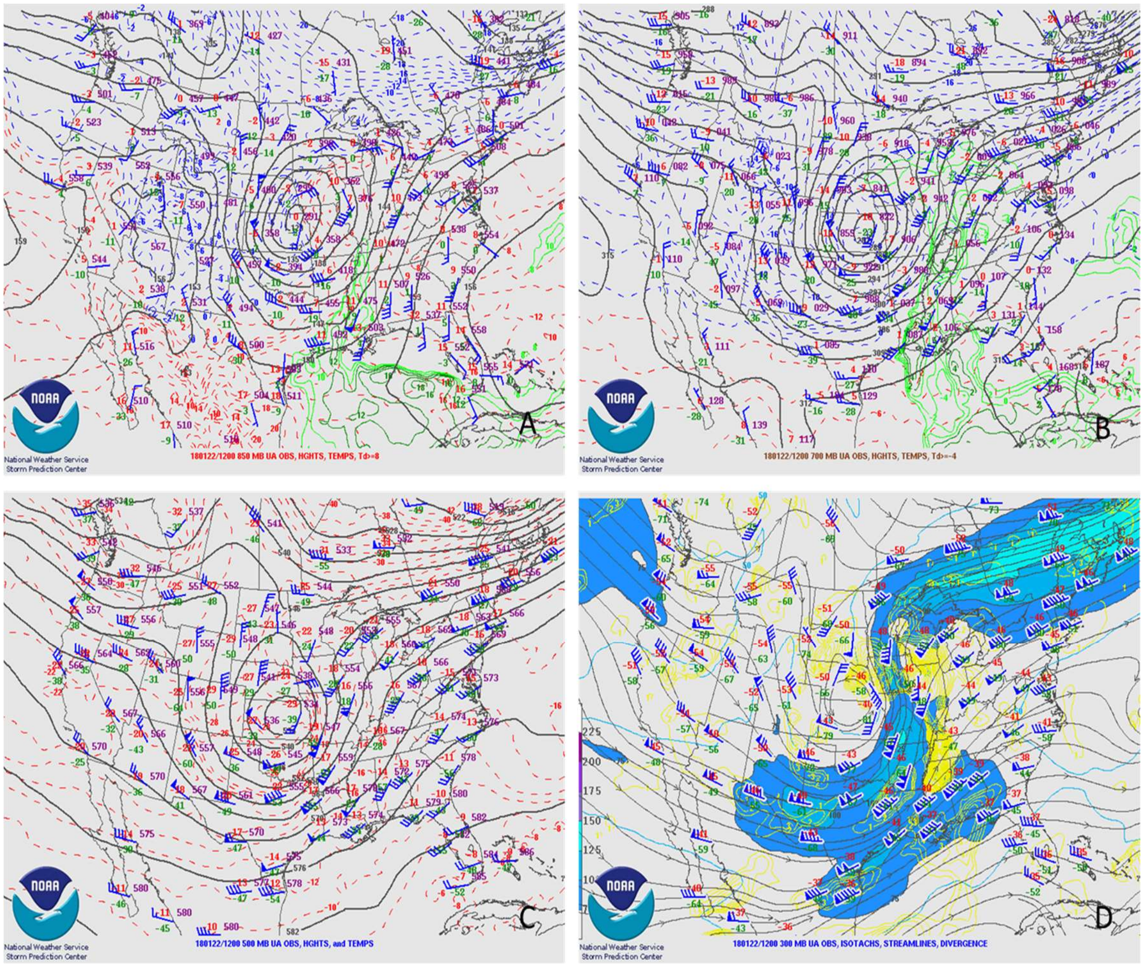


Figure 4.10: Different levels in the atmosphere at 1200 UTC 22 January 2018. a) 850 hPa b) 700 hPa c) 500 hPa d) 300 hPa (SPC 2019)

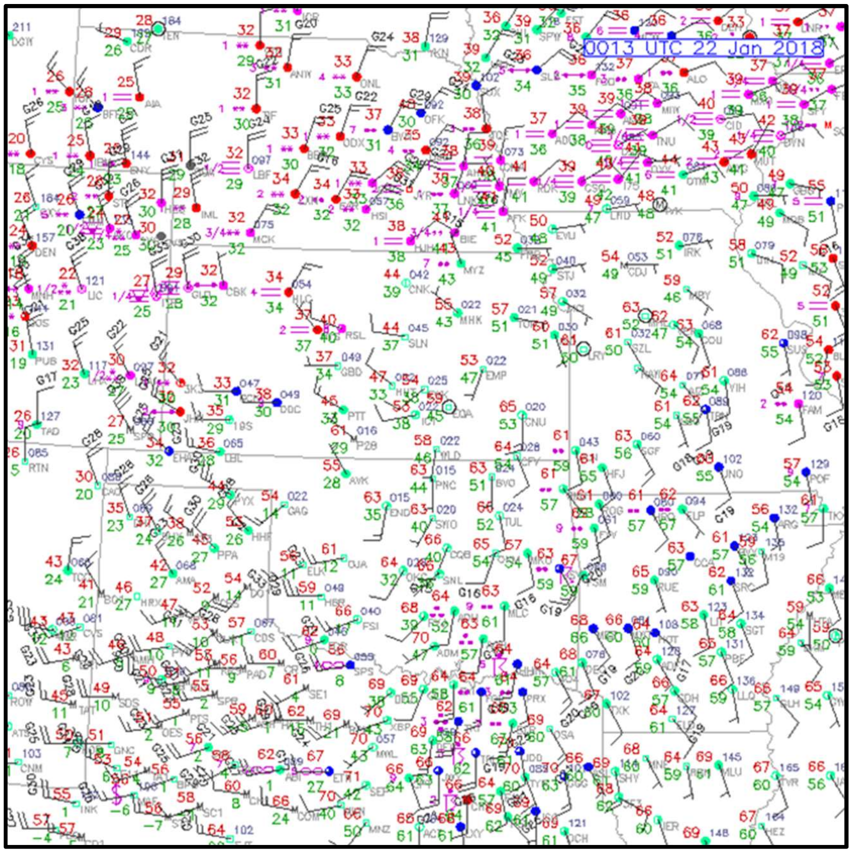


Figure 4.11: Surface observations at 0013 UTC 22 January 2018 for the Great Plains (SPC 2019)

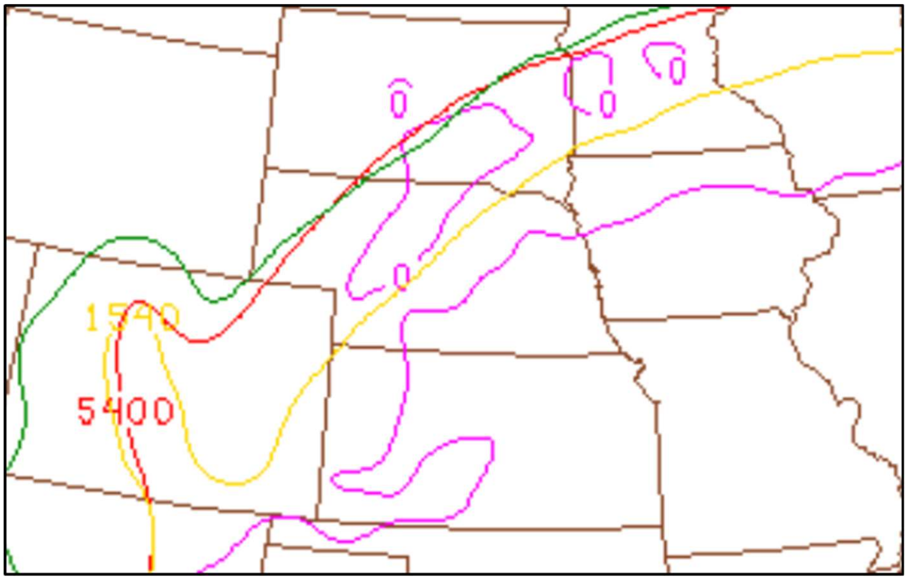


Figure 4.12: Critical thickness lines at 1200 UTC 21 January across 1000-500 hPa (red), 1000-700 hPa (green), 1000-850 hPa (blue), 850-700 hPa (yellow) and the surface 0° temperature (magenta) (SPC 2019).

and freezing rain is falling throughout southern Nebraska (Figure 4.13). Alliance airport ASOS station (KAIA) in northwestern Nebraska was reporting snow at 1200 UTC 21 January while McCook airport ASOS station (KMCK) in southwestern Nebraska was only reporting cloud cover. As the storm's effects move through Nebraska, the precipitable water content at 1800 UTC 21 January falls between 0.76-1.5 cm (0.3-0.6 in) in Nebraska (Figure 4.14). With this amount of moisture in the atmosphere, snow production is very possible if all other ingredients are present. According to the NDOT-MDSS, snow is falling in western Nebraska while rain is falling in eastern Nebraska (Figure 4.15). At 0000 UTC 22 January, the highest values of vorticity (Figure 4.16) are concentrated over western Kansas and stretch down through the panhandle of Texas. Vorticity values are reaching upwards of 30 $x10^{-5}$ s^{-1} in the area over western Kansas. At this time, the 850 hPa trough is extending from New Mexico through South Dakota with areas of rising motion over southwestern Nebraska, northeastern Colorado and northwestern Kansas (Figure 4.17).

At 0700 UTC 22 January at 300 hPa, there was a trough extending through most of the West and Midwest states with the jet streak positioned over eastern Nebraska down to Texas (Figure 4.18). The left exit region and the right entrance region of a jet streak is where the divergence in the upper levels occur. The rising motion is found in both of these areas, which is to be expected since rising motion is necessary for divergence aloft. There are large regions of divergence over eastern Nebraska and along the Mississippi Valley (Figure 4.18) where the cold front is located (Figure 4.19). Another source of divergence aloft is associated with positive vorticity, because positive vorticity aids rising motion. At 1200 UTC 22 January at 500 hPa (Figure 4.20), there is a region of

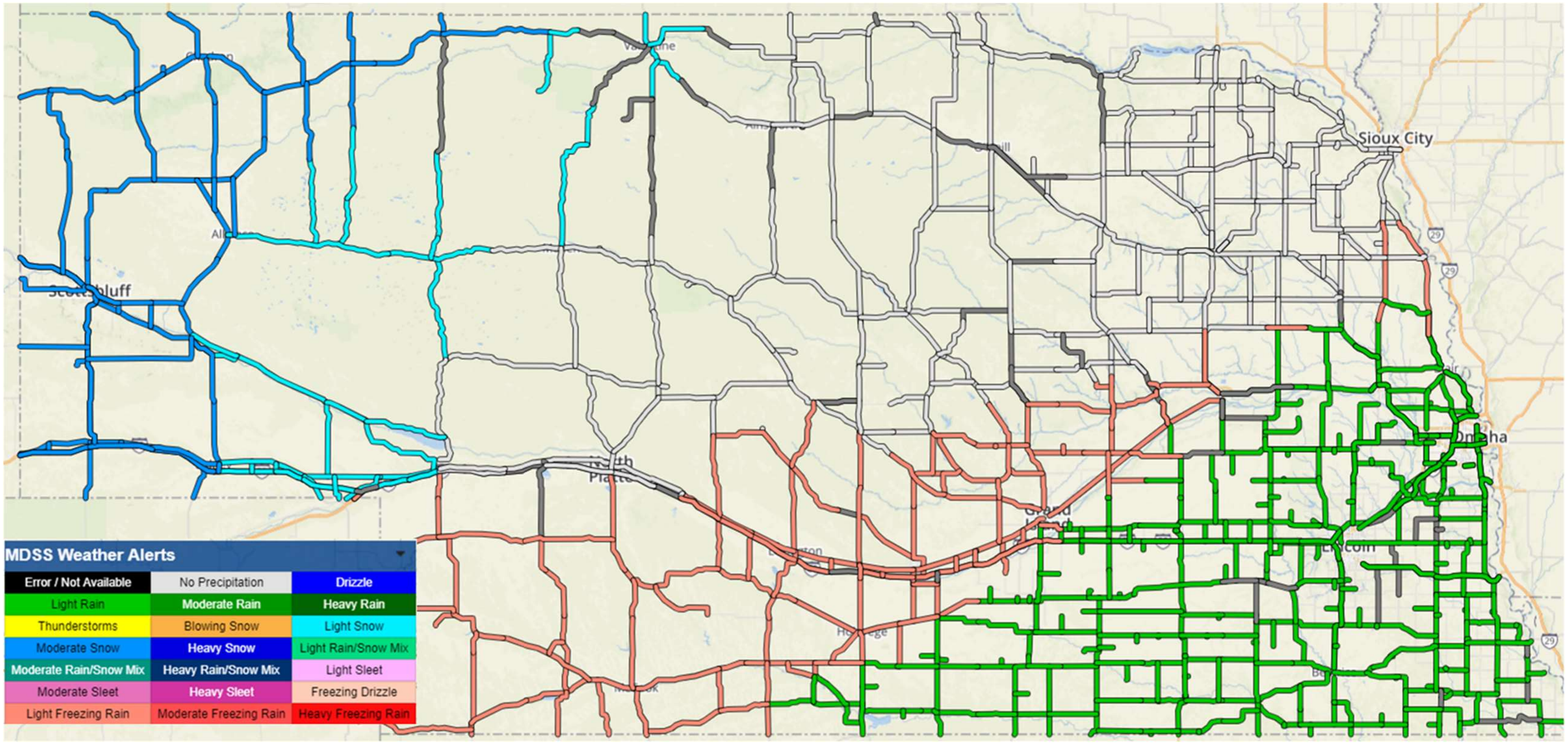


Figure 4.13: Analysis of the conditions for 1200 UTC 21 January (WebMDSS™ 2018)

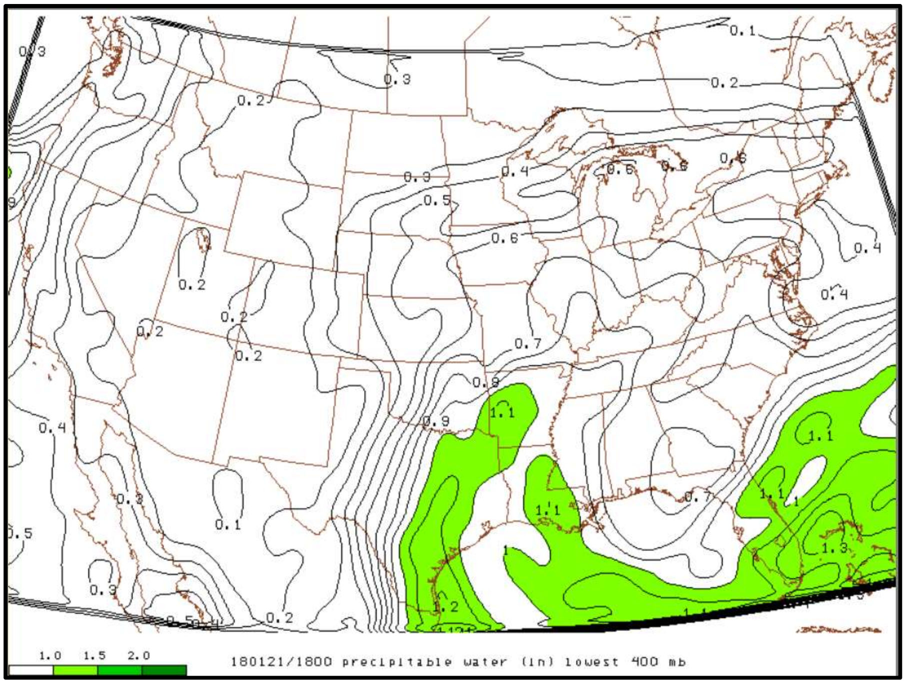


Figure 4.14: Precipitable water in the lowest 400 hPa at 1800 UTC 21 January (SPC 2019)

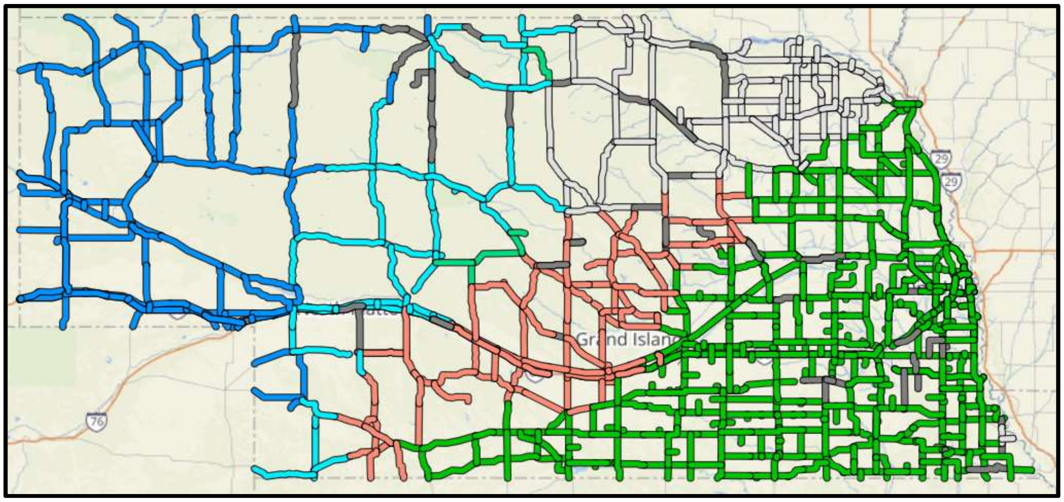


Figure 4.15: Analysis of conditions at 1800 UTC 21 January (Colors correspond to legend in Figure 4.13) (WebMDSS™ 2018)

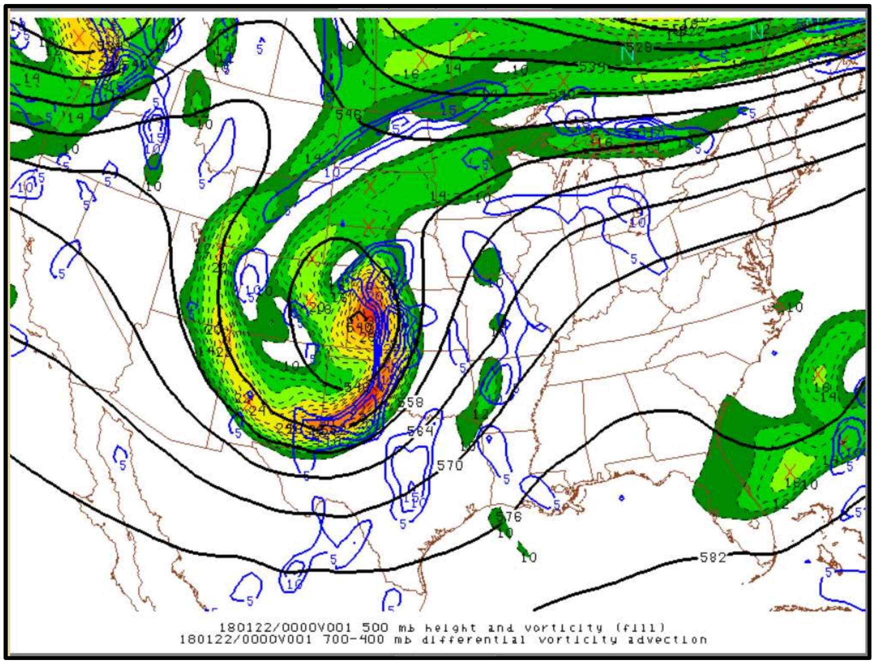


Figure 4.16: Vorticity and height at 500 hPa at 0000 UTC 22 January (SPC 2019)

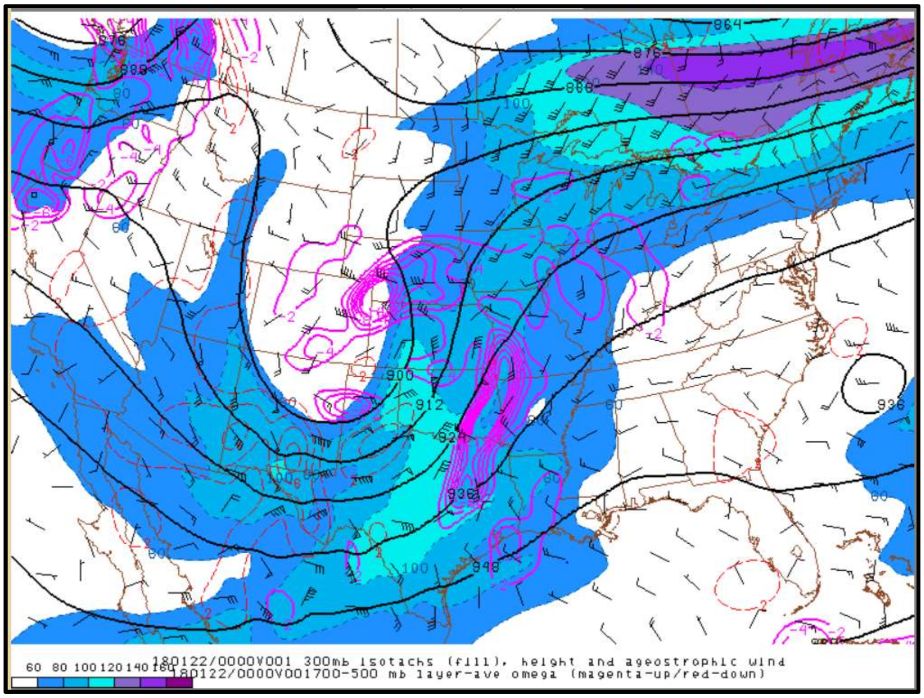


Figure 4.17: Average omega (850hPa) overlaid on the jet stream (300hPa) at 0000 UTC 22 January (SPC 2019)

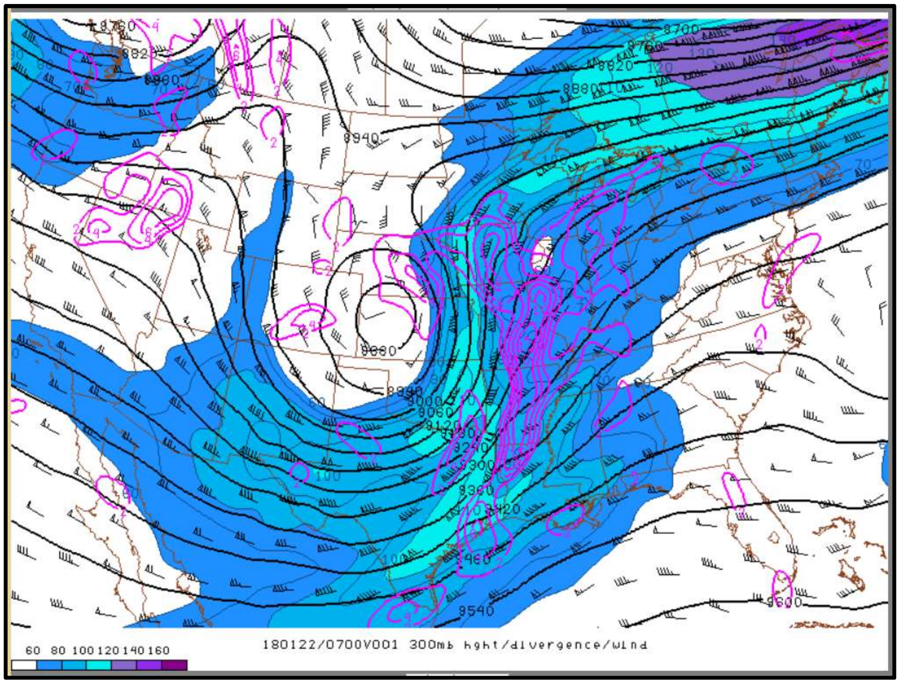


Figure 4.18: Average omega (850hPa) overlaid on the jet stream (300hPa) at 0700 UTC 22 January (SPC 2019)

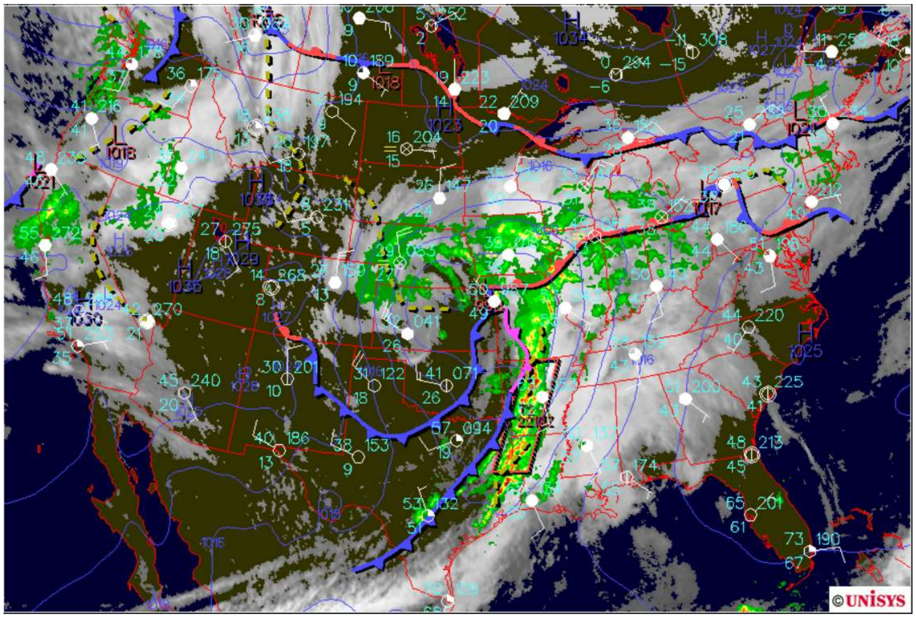


Figure 4.19: Satellite surface map of the United States at 0730 UTC 22 January (Unisys 2018)

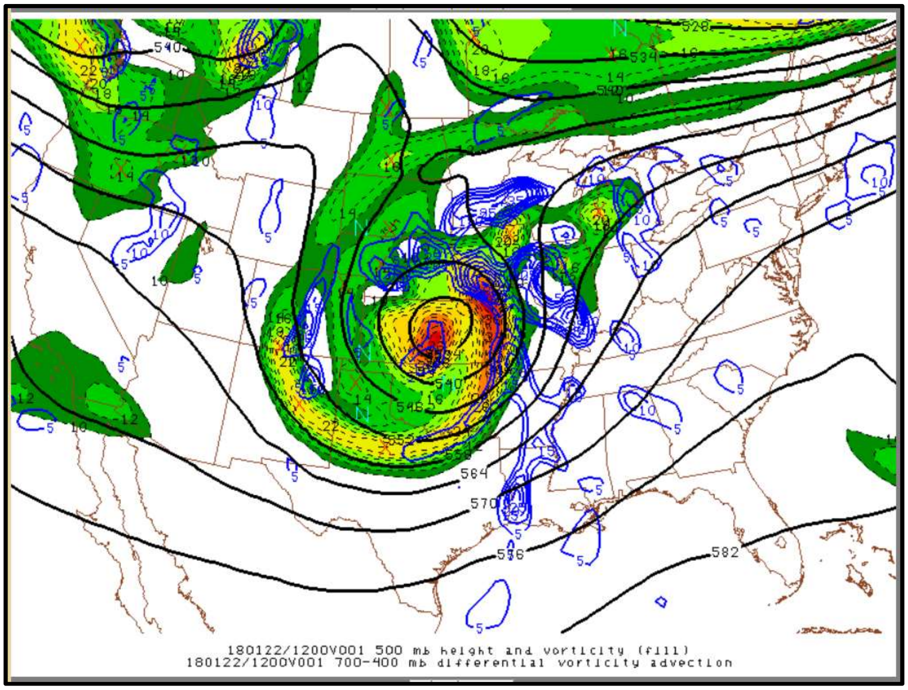


Figure 4.20: Vorticity and height at 500 hPa at 1200 UTC 22 January (SPC 2019)

high positive vorticity centered in the middle of the low pressure. There is another region to the east that spans over western Missouri and eastern Kansas. Rising motion is also caused when there is horizontal convergence at the surface, generating vertical stretching fostering greater rotation. The greater rotation leads to higher positive vorticity and divergence aloft. Without rising motion, the storm would dissipate. The centrally located area of positive vorticity has values reaching over $3.3 \times 10^{-6}\ s^{-1}$ which indicates a strong mid-latitude cyclone. In addition, a large concentration of rising motion is also due to warm air rising over colder air, increasing the risk for severe weather. As the impacts of the storm lessening over Nebraska around 0000 UTC 23 January, the highest values of vorticity are now located over Missouri and southeastern Iowa (Figure 4.21). The areas of rising motion have also shifted eastward at this time with the jet streak now located over the southeastern United States (Figure 4.22).

The critical thicknesses have shifted southward from the previous location at 1200 UTC 21 January and are now located in central Nebraska. The critical thicknesses are not quite aligned at 2000 UTC 21 January (Figure 4.23) which means that some of the thicknesses would indicate snow in some areas while other areas might receive other forms of precipitation. The placement of the critical thicknesses indicate that the lower levels of the atmosphere are warmer than the upper levels. At 2000 UTC 21 January, snow was occurring in western Nebraska, freezing rain was occurring in central Nebraska, and rain in eastern Nebraska. The NDOT-MDSS shows each of these precipitation types (Figure 4.24) falling at 2000 UTC 21 January in specific locations relating to the critical thickness lines. Freezing rain was not indicated on the atmospheric soundings at either NWS North Platte or NWS Omaha/Valley at either 0000 UTC or

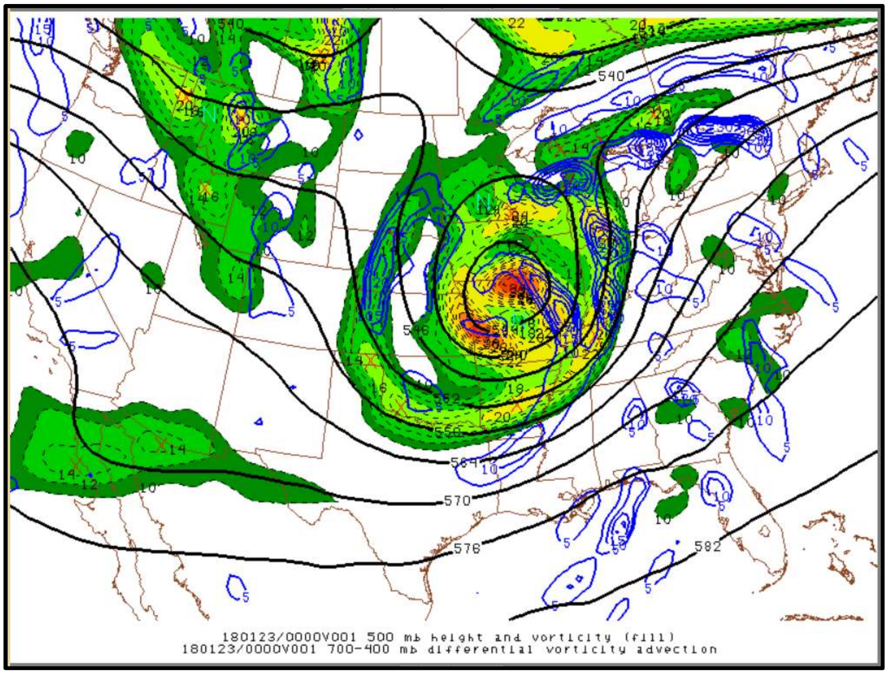


Figure 4.21: Vorticity and height at 500 hPa at 0000 UTC 23 January (SPC 2019)

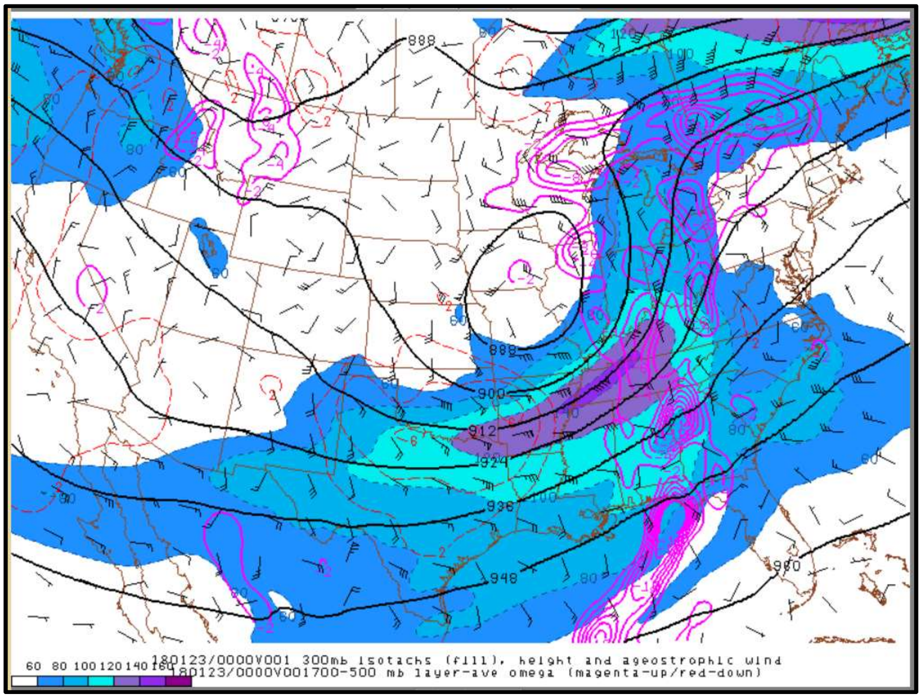


Figure 4.22: Average omega (850hPa) overlaid on the jet stream (300hPa) at 0000 UTC 23 January (SPC 2019)

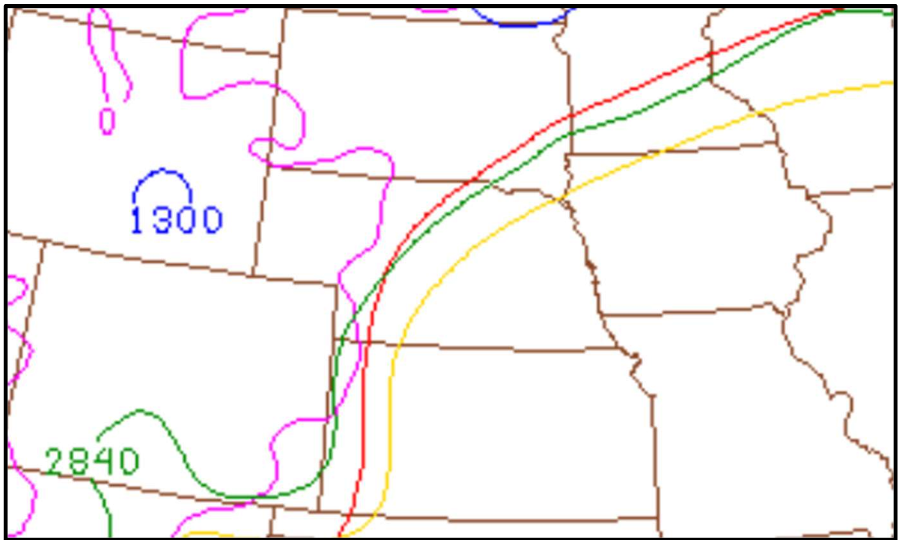


Figure 4.23: Critical thickness lines at 2000 UTC 21 January across 1000-500 hPa (red), 1000-700 hPa (green), 1000-850 hPa (blue), 850-700 hPa (yellow) and the surface 0° temperature (magenta) (SPC 2019).

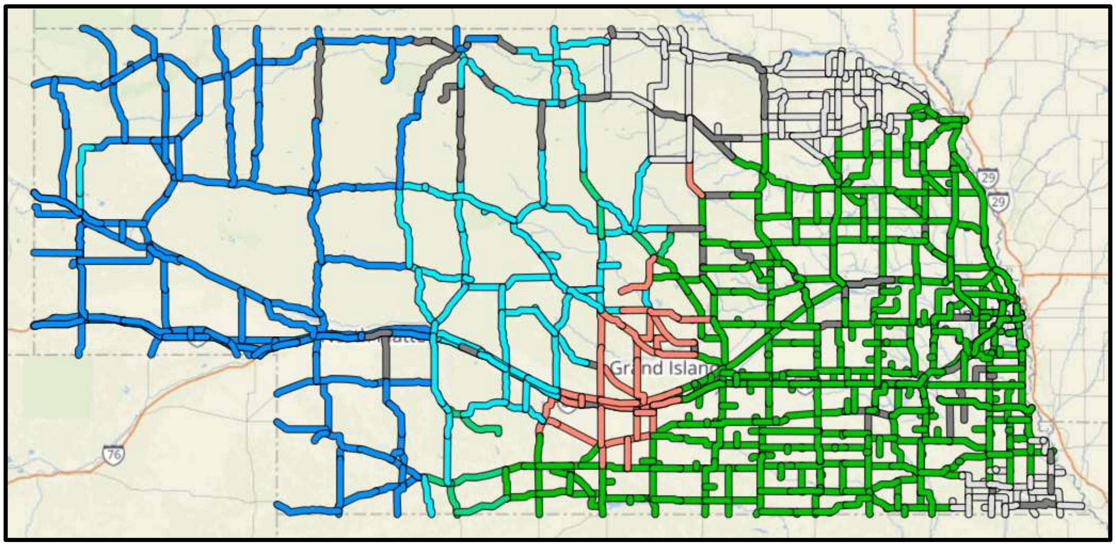


Figure 4.24: Analysis of conditions at 2000 UTC 21 January from the NDOT-MDSS (Colors correspond to legend in Figure 4.13) (WebMDSS™ 2018)

1200 UTC 22 January (Figures 4.2-4.5); however, the timing of the soundings differ slightly from when the freezing rain occurred so freezing rain was not present at the time in these locations.

At 1800 UTC 22 January (Figure 4.25), most of the critical thickness values have moved southward into the south-central part of the United States. Most of central and eastern Nebraska should be seeing snow at 1800 UTC 22 January as indicated by the NDOT-MDSS (Figure 4.26). The NDOT-MDSS shows the precipitation stopping in the western and central part of the state while the far southeastern parts of the state are still seeing rain at 1800 UTC 22 January. Above freezing surface temperatures and a portion of the 1000-850 hPa critical thickness line indicating the thickness of the layer is 1300 m is hovering over the area where rain was falling according to the NDOT-MDSS. The freezing levels (Figure 4.27) at 1800 UTC 22 January show that it is in approximately the same area that both the NDOT-MDSS map showing the analysis of the conditions and the critical thickness are. Each of these variables serve as a verification for the other as well as what NDOT-MDSS outputs.

At 0300 UTC 22 January (Figure 4.28), there is a range of .76-1.78 cm (0.3-0.7 in) of precipitable water in the lowest 400 hPa across Nebraska which can produce a good amount of snowfall, depending on the SLRs. The cold front spans from Missouri to the Louisiana-Texas border and has precipitable values of over 2.54 cm (1 in). The higher values indicate that there is a high chance for heavy rain along the front. Frontogenesis is occurring over the northeastern part of Nebraska at 1100 UTC 22 January at 700 hPa (Figure 4.29). The area of maximum frontogenesis is approximately where the heaviest snow is indicated by radar (Figure 4.30) and the NDOT-MDSS

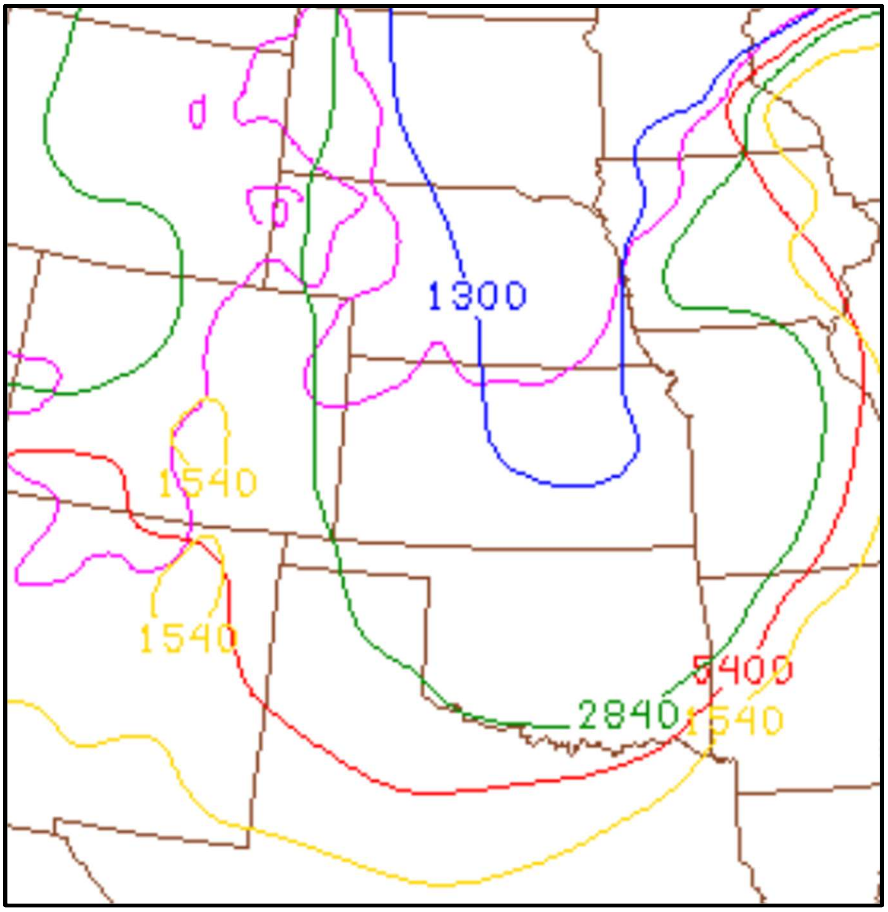


Figure 4.25: Critical thickness lines at 1800 UTC 22 January across 1000-500 hPa (red), 1000-700 hPa (green), 1000-850 hPa (blue), 850-700 hPa (yellow) and the surface 0° temperature (magenta) (SPC 2019)

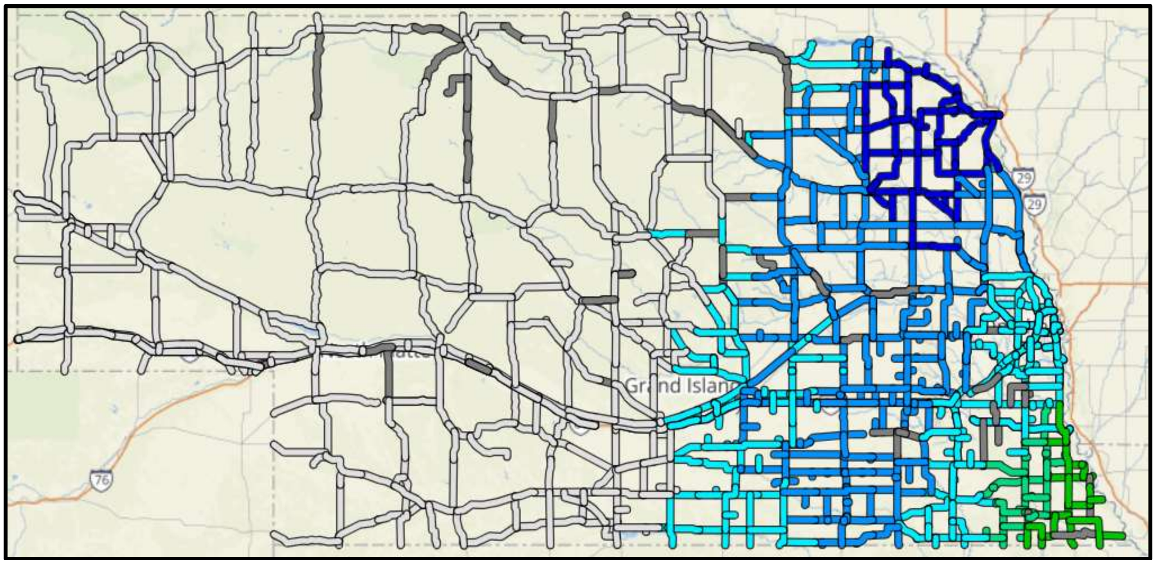


Figure 4.26: Analysis of conditions at 1800 UTC 22 January from the NDOT-MDSS (Colors correspond to legend in Figure 4.13) (WebMDSS™ 2018)

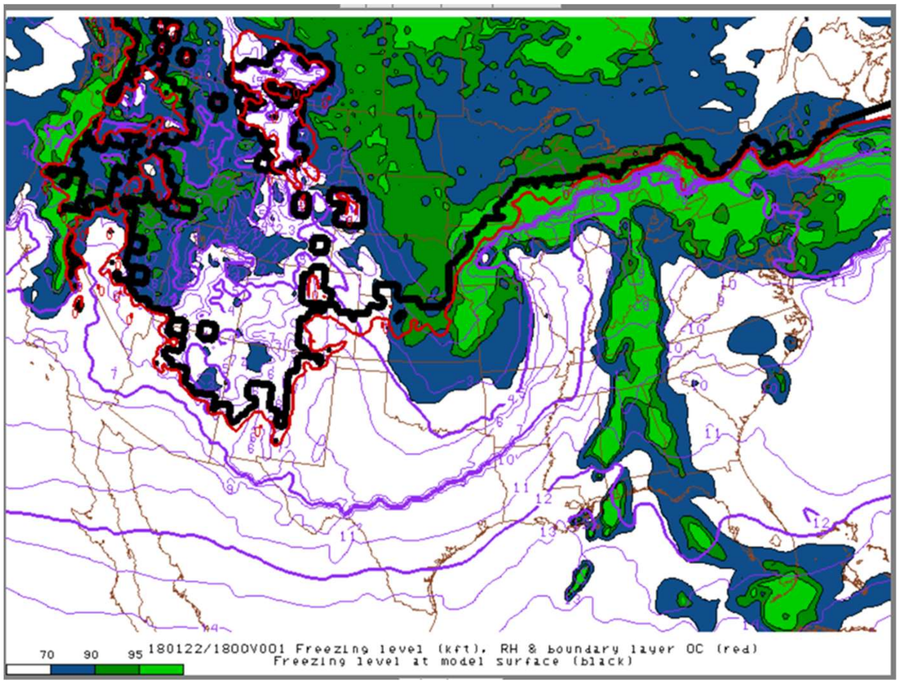


Figure 4.27: Freezing level at the surface (black) is at 1800 UTC 22 January. Also shown is the relative humidity and boundary layer 0°C line (red) (SPC 2019)

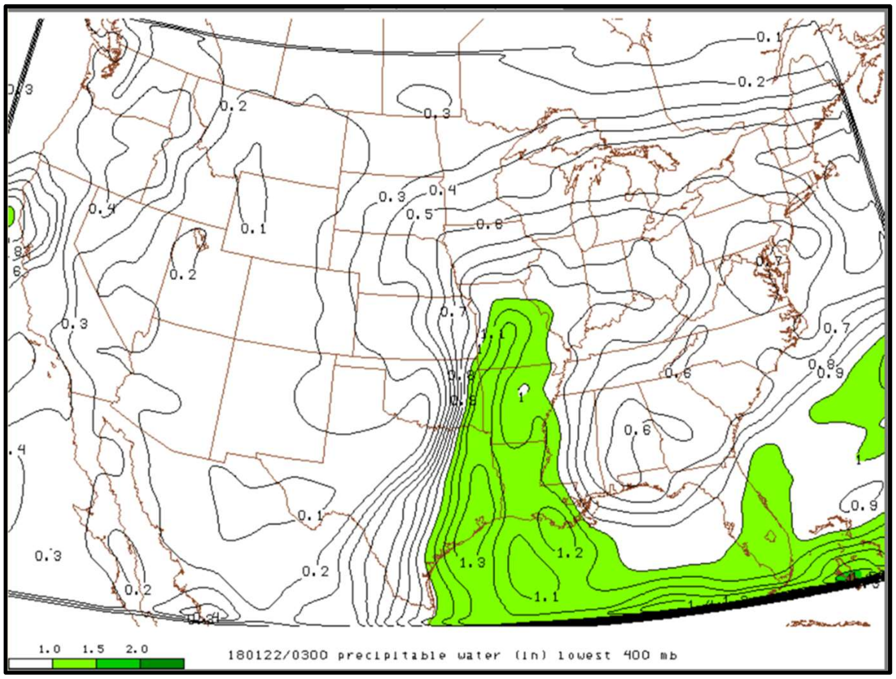


Figure 4.28: Precipitable water in the lowest 400 hPa at 0300 UTC 22 January (SPC 2019)

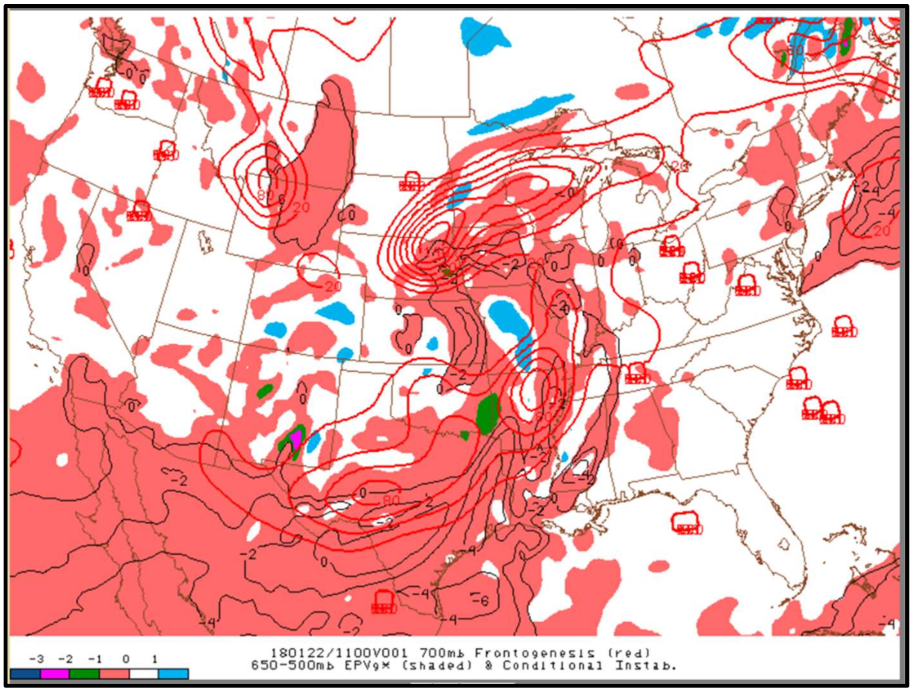


Figure 4.29: Frontogenesis (red) occurring at 700 hPa at 1100 UTC 22 January and areas of EPVg* and conditional instability (shaded) at 650-500 hPa. Positive values represent areas of frontogenesis. (SPC 2019)

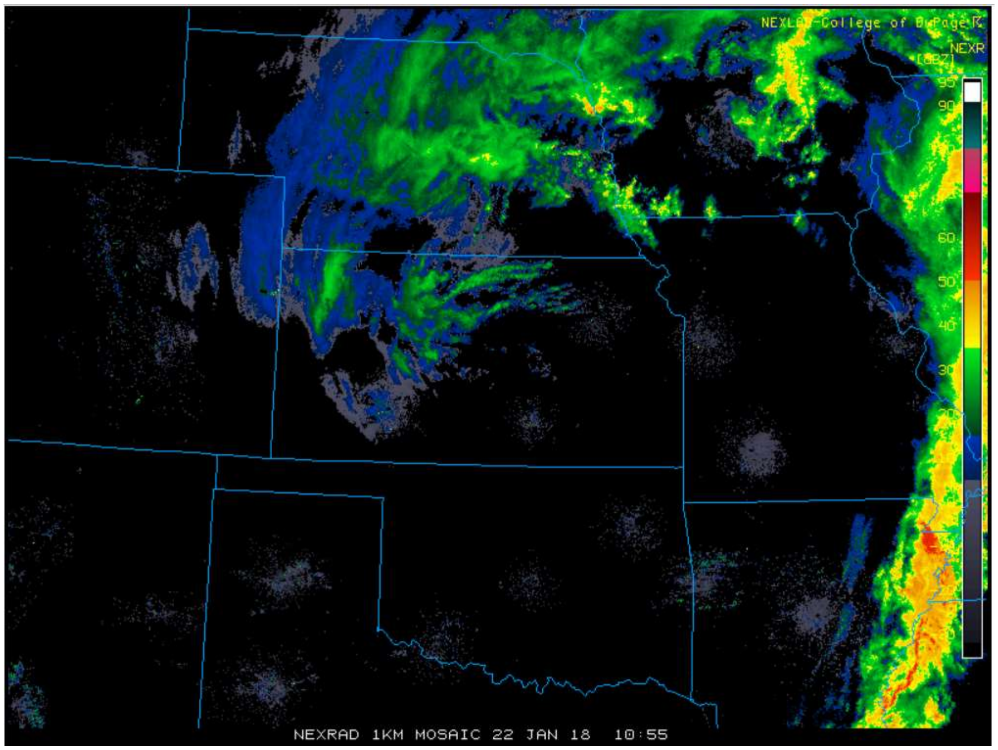


Figure 4.30: Radar observations at 0700 UTC 22 January (NCAR 2018)

analysis (Figure 4.31). The frontogenesis is accompanied by EPVg* and conditional instability which are both key ingredients in producing heavy snow bands (Evans and Jurewicz Sr. 2009). Negative values are ideal for EPVg* to play a role in creating an ideal environment capable of producing heavy snowfall as well as areas where frontogenesis is taking place. At the same time at 850 hPa (Figure 4.32), frontogenesis is most prominent along the cold front located in the Mississippi Valley. The large amount of frontogenesis taking place is co-located with large amounts of negative EPVg*.

4.2 January NDOT-MDSS results

When forecasting for a mid-latitude cyclone, knowing the location of the center of the low in each model run is important. Knowing the location will tell you where the precipitation will occur and what areas will be impacted. The progression of the storm forecast (Figure 4.33) shows how the predicted location of the center of the low pressure system shifted over time for 22 January 2018. The forecasted location of the center of the January low pressure system at 7 days out was over the Great Lakes. As the storm advances toward the Great Plains, the low pressure center was forecasted to slow down which shifts the track to the southwest for 22 January 2018. The decrease in the speed of the storm causes the precipitation chances to increase in most of the central United States (Figure 4.34). The tightest part of the pressure gradient moves over Nebraska, which led to high winds becoming more of a threat. At three days out, the predicted location of the center of the system was situated over far southwestern Iowa. Nebraska is now on the northwest side of the low which is the prime location to receive wintery precipitation. The highest chances of precipitation are now extending into northeastern Nebraska which

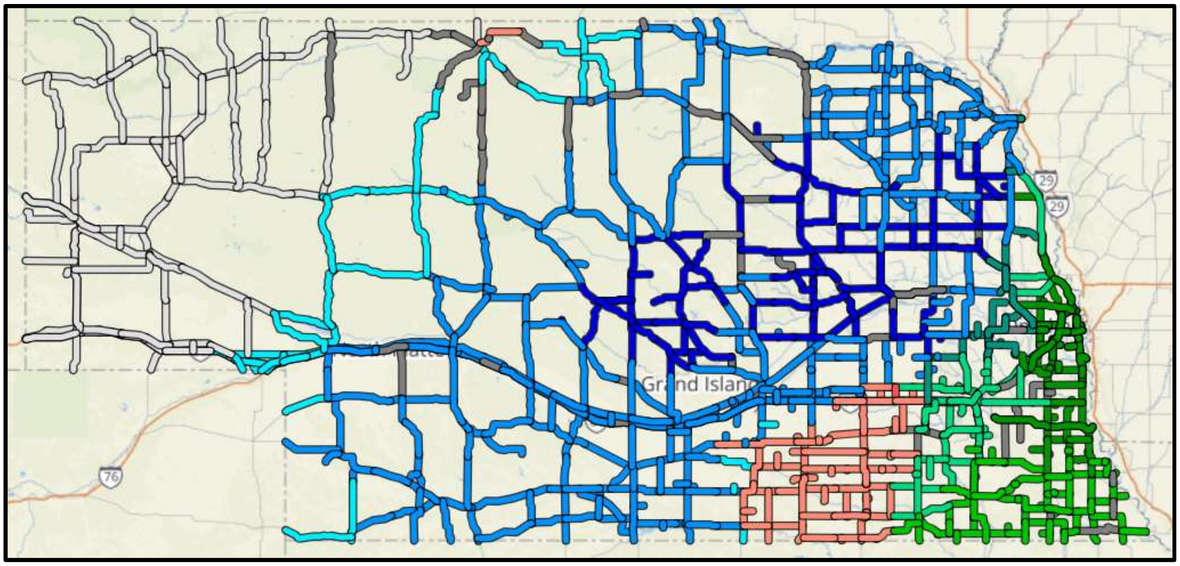


Figure 4.31: Analysis of conditions at 1800 UTC 22 January from NDOT-MDSS (Colors correspond to legend in Figure 4.13) (WebMDSS™ 2018)

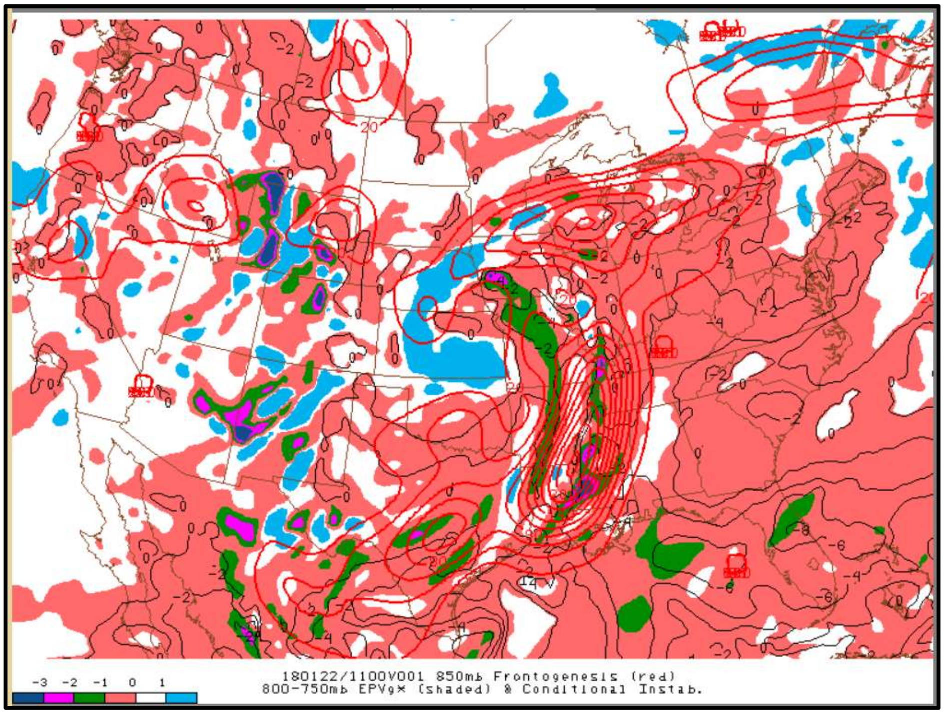


Figure 4.32: Frontogenesis (red) occurring at 850 hPa at 1100 UTC 22 January and areas of EPVg* and conditional instability (shaded) at 800-750 hPa.(SPC 2019)

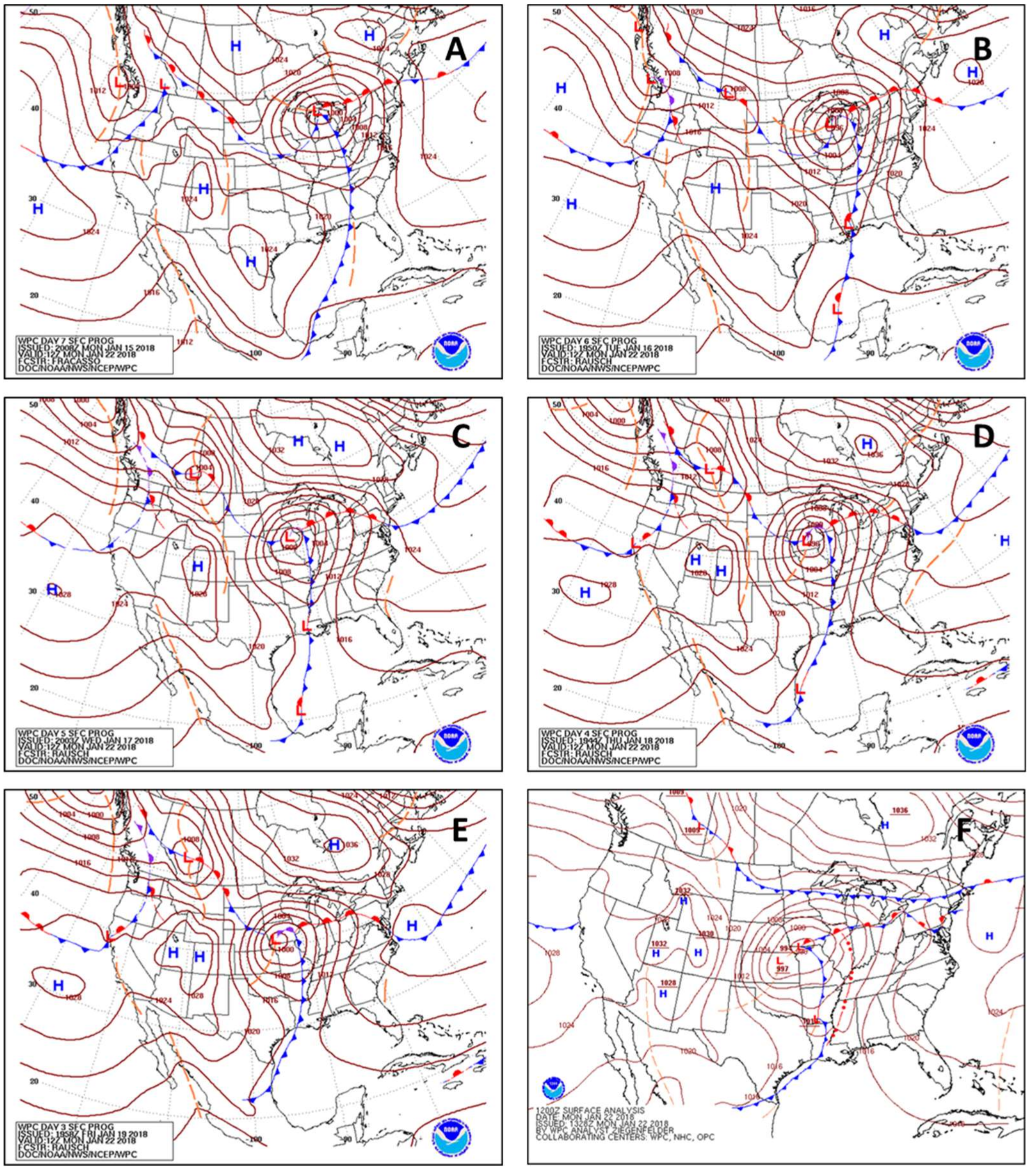


Figure 4.33: The progression of the forecast for the low pressure center of the winter storm that occurred on 22 January 2018. A) 15 January 2018, surface map forecast 7 days out. B) 16 January 2018, surface map forecast 6 days out. C) 17 January 2018, surface map forecast 5 day out. D) 18 January 2018, surface map forecast 4 days out. E) 19 January 2018, surface map forecast 3 days out. F) 22 January 2018, surface map of actual location of the center of the low during the winter storm (WPC 2019)

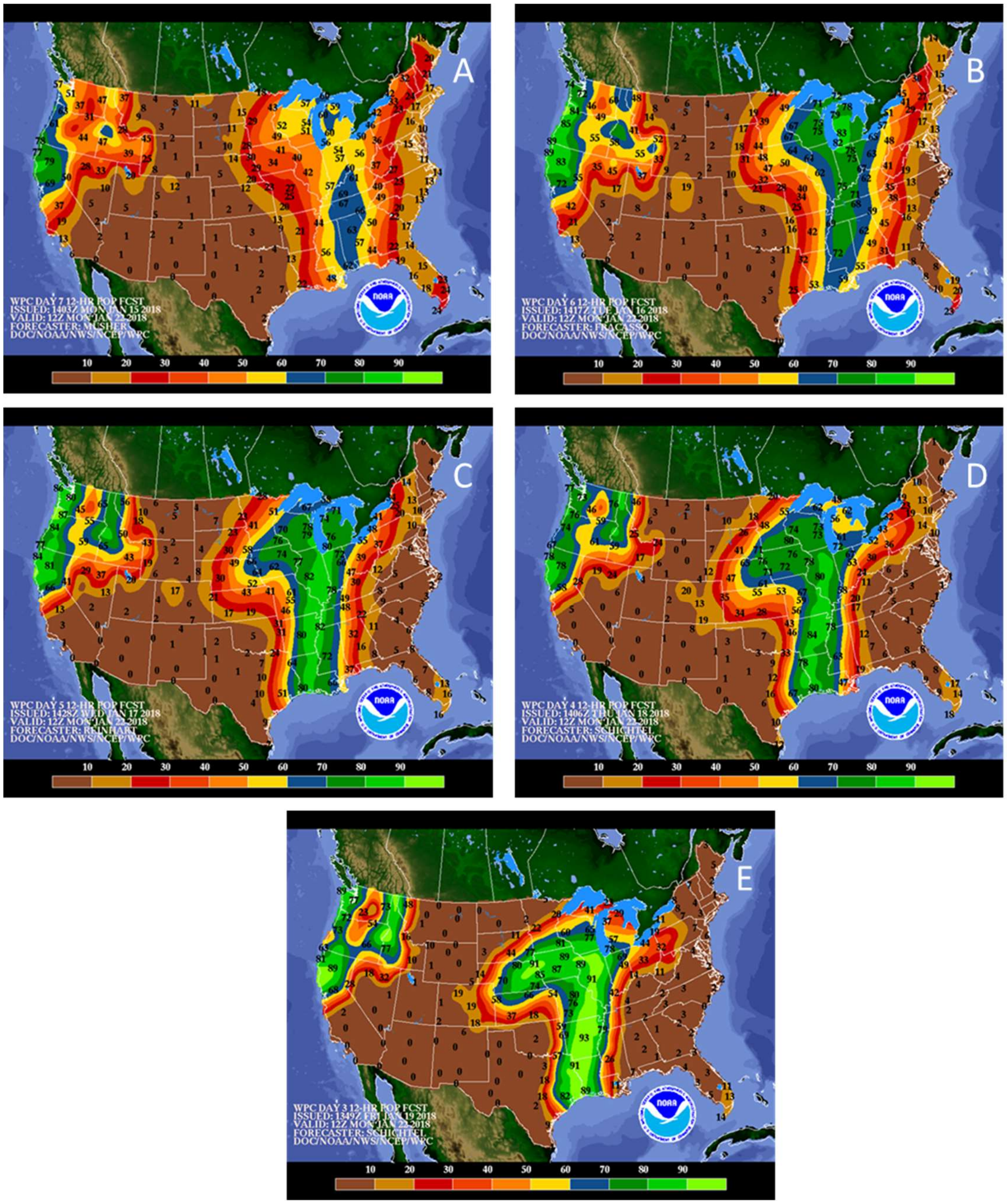


Figure 4.34: The progression of the forecast for the precipitation chances of the winter storm that occurred on 22 January 2018. A) 15 January 2018, precipitation probability forecast 7 days out. B) 16 January 2018, precipitation probability forecast 6 days out. C) 17 January 2018, precipitation probability forecast 5 day out. D) 18 January 2018, precipitation probability forecast 4 days out. E) 19 January 2018, precipitation probability forecast 3 days out (WPC 2019)

was leading forecasters to put out a Winter Storm Watch. The forecasts (Tables 4.1-4.4) show that even at seven days out, there was potential for some type of precipitation. The forecast gradually evolves into a major winter storm that will impact most of Nebraska. The threats include blizzard conditions, heavy snow and the threat of freezing rain. The first Winter Storm Watch was issued by all 4 offices at approximately 1000 UTC 19 January. Blizzard Warnings were issued by each office at roughly 1000 UTC 21 January and these warnings remained until the end of the storm at approximately 0400 UTC 23 January. The brunt of the storm was expected to occur from 21 January to 22 January. When the impacts of the storm were starting to be felt in Nebraska, the low pressure reached peak intensity over northern Missouri and southern Iowa with a mean sea level pressure (MSLP) of less than 996 hPa at 1000 UTC 22 January (Figure 4.35).

The forecasts in the NDOT-MDSS are highly dependent on the data that are input into the system so any changes in the forecasts will have a major impact on what is output by the NDOT-MDSS. The forecasted snow accumulations for each route (Figure 4.36) can be seen developing as new forecasts are issued by the NDOT-MDSS at three hourly increments. Route 1, 2, and 3 are located in eastern-northeastern Nebraska, Route 4 and 5 are located parallel to each other in southwestern Nebraska and Routes 6, 7, and 8 are located in central Nebraska (Figure 3.2). The missing forecasted snowfall data in most routes were due to the forecast period within the NDOT-MDSS not extending the full length of the storm at the beginning in various routes, so forecasted total snowfall accumulations were not obtained. Routes 1, 2, 3, and 8 all start out with predictions for snowfall accumulations of greater than 30 cm. The analysis of the snowfall accumulation totals decreased to almost half of what was originally forecasted

Table 4.1: NWS Sioux Falls forecast for the January Storm

Date Jan	Time UTC	Forecasted Snow Totals	Watches/Warnings	Comments
15	2122	N/A	No	A strong upper level wave looks like it may be headed to the area. A lot of uncertainty comes with it.
16	2123	N/A	No	There is potential for precipitation in the coming weekend. Many models are in agreement that over .25 QPF will be associated with the system. Location is still uncertain.
17	2100	N/A	No	Timing and location are still uncertain at this point. A few models agree that this storm will impact the Great Plains and bring heavy snow and high winds to the area.
18	2125	N/A	No	A few models have become consistent with timing while others are a bit slower. Forecasters are increasing percent of precipitation (PoP) and winds. Potential for blizzard conditions is now possible.
19	1008	5-9” with light glaze of ice	Winter Storm Watch	Freezing drizzle is now a threat to the area. Models have slowed the system down, lowering the PoPs. Low to mid-level frontogenesis will help saturate the storm and provide some lift. Watching the track will be key in this storm.
19	2132	4-10” with light glaze of ice	Winter Storm Watch	The path has shifted slightly south. The threat of freezing drizzle remains for Sunday. Winds are becoming more of a concern, especially during times of snowfall. Blowing snow is also a threat.
20	0953	5-10” with light glaze of ice	Winter Storm Watch	The location on the models is starting to align. The wave just entered California. The winds (25-40mph) have strengthened, leading forecasters to use the term “blizzard”
20	2136	Winter Storm Watch- 2-8” Winter Storm Warning- 5-14” with icing	Winter Storm Watch, Winter Storm Warning	Locations confidence has increased. The Lifted Index (LI) is -1 to -2 which will lead to extreme snow rates along with potential for thundersnow. Due to potential for dry-slotting in some areas, icing potential has increased.
21	0942	Winter Storm Warning-4-10” WWA-2-6” BW-5-15”	Winter Storm Warning, WWA, BW	Winds are a major concern because of how tight the pressure gradient is predicted to become. Intense snowfall rates will most likely occur along with thundersnow. This could change the snowfall totals due to the nature of thundersnows.
21	2123	Winter Storm Warning-3-6” WWA-1-3” BW-8-12”	Winter Storm Warning, WWA, BW	The heaviest snow has been shifted slightly south. Convection has become more likely farther to the south. Snow rates may exceed 1” per hour in these areas. Winds are expected to be up to 35-45 knots so blizzard conditions will be a major threat to the CWA.
22	0857	Winter Storm Warning-1-6” WWA-0-2” BW-9-14”	Winter Storm Warning, WWA, BW	Several lightning strikes have been reported. Snow rates could reach up to 2-3” per hour in some areas. Forecasters warned to be weather aware.

Table 4.2: NWS North Platte forecast for the January storm

Date Jan	Time UTC	Forecasted Snow Totals	Watches/Warnings	Comments
15	2113	N/A	No	Mention of “noise” in the mid and extended solution.
16	2135	Accumulating snow, no totals	No	Looks favorable for development of a Colorado Low. Good chance for accumulating snow in the entire forecast area
17	2113	N/A	No	Models are in agreement that there will be a system that impacts the area. Timing is still uncertain.
18	2025	N/A	No	Freezing drizzle may accompany this storm. Models are increasing in confidence in the features of the storm but not the location.
19	0945	3-7”	Winter Storm Watch	Lots of confidence in the larger scale aspects of the storm but the small scale and finer features have been relatively hard to predict
19	0905	5-9”	Winter Storm Watch	Fairly large winter storm with potential for heavy snowfall. Confidence is high. High winds have become a threat.
20	1020	5-11”	Winter Storm Warning	Patchy freezing drizzle to precede snowfall. Storm will be moving slowly, resulting in prolonged periods of heavy snow. Winds will approach 50kts during peak intensity.
20	2105	5-11” with locally higher amounts	Winter Storm Warning	Blizzard-like conditions are expected. Main concern for Sunday is high winds. Snowfall rates could also reach 1” per hour.
21	1042	BW-8-13” WSW-5-9”	Winter Storm Warning Blizzard Warning	System will go through rapid intensification which will lead to a significant winter storm (Classic Colorado Low)
21	2004	BW-8-12” WSW-4-7”	Winter Storm Warning Blizzard Warning	Snow will be entering the region this evening. Blizzard conditions are expected with winds gusting to 45mph. They system will exit the region Monday morning.
22	0933	12-14”	Winter Storm Warning Blizzard Warning	Snow will continue in some areas but will taper off soon. The decay of the deformation area will occur right as a new snow band develops. Strong winds will continue throughout the day.

Table 4.3: NWS Omaha forecast for the January storm

Date Jan	Time UTC	Forecasted Snow Totals	Watches/Warnings	Comments
15	2130	N/A	No	Active pattern Saturday-Sunday. Timing is consistent between models. Potential for a mesoscale band of precipitation
16	2008	N/A	No	A few models are showing precipitation for Saturday-Sunday. Snow possible for the northern CWA counties with rain/snow mix for the rest
17	2120	6-10”	No	Models are in agreement that there is potential for a winter storm. Moisture will be in place so the storm could produce large amounts of snow. A lot of uncertainty remains.
18	2057	6-12”	No	Northeast Nebraska seems to be the target of the storm and heavy snowfall. Blizzard conditions are possible. Storm tract is consistent in models. Chance for freezing rain and possible thunderstorms in CWA.
19	0933	4-7”, light icing possible	Winter storm watch	Even with a slight shift in the storm track, NE Nebraska is still projected to get the brunt of the storm. Southeast Nebraska could see convective showers.
19	2135	Winter Storm Watch-3-10”	Winter Storm Watch	Freezing drizzle may have big impact on travel Sunday morning. Heavy snow potential is highest in Western Nebraska and NE Nebraska. High winds are expected so drifting snow could be a threat
20	0940	5-8”, light glaze of ice	Winter Storm Watch	Models are in agreement with the path of the low pressure center. There are some discrepancies in the timing/amount/saturation of the atmosphere. Freezing drizzle is still expected Sunday morning
20	2050	Winter Storm Warning-8-15” Winter Storm Watch- 2-6”	Winter Storm Watch/Winter Storm Warning	Southeastern Nebraska should expect rain/snow mix due to the large temperature gradient present with this storm. Models are quite in agreement on when the storm will end although even after precipitation stops, blowing snow will persist.
21	0945	Winter Weather Advisory-1-4” Blizzard Warning-6-15”	Winter Weather Advisory, Blizzard Warning	The low is deepening near the Rockies and is expected to bring blizzard conditions to areas in Northeast Nebraska. Models agree on the timing and location of the storm. Winds are expected to blow 30-35mph with gusts up to 45mph during the peak of the snow.
21	2102	Winter Weather Advisory-1-5” Blizzard Warning-4-17”	Winter Weather Advisory, Blizzard Warning	Temperatures across the CWA will be important to watch because of the freezing drizzle and the potential for convection in the southeastern part of Nebraska. Not an extremely cold event but winds and heavy snow will persist.
22	2216	Winter Weather Advisory-0-2” Winter Storm Warning-3-5” Blizzard Warning-3-9”	Winter Weather Advisory, Blizzard Warning, Winter Storm Warning	Heavy snow and wind gusts up to 50mph along with lightning were reported in Western Nebraska. Timing of the change from rain to snow is crucial to the amounts that areas will receive

Table 4.4: NWS Hastings forecast for the January storm.

Date (Jan)	Time (UTC)	Forecasted Snow Totals	Watches/Warnings	Comments
15	2121	N/A	No	Chance for precipitation, mostly snow. Potential for strong winds due to the intensity of the surface low
16	2118	N/A	No	Location and timing are similar on all models. Precipitation should be mostly snow with a small potential for some rain
17	2125	N/A	No	Models are showing differences in timing and speed along with some potential for warmer temperatures
18	2134	N/A	No	Mention of winter storm potential. Higher winds speeds now expected so a blizzard is possible
19	1003	4-6”	Winter Storm Watch	Models are now mostly in agreement for timing and location. Accumulating snow likely across entire County Warning Area
19	2110	2-5”, 4-8”	Winter Storm Watch	Some icing is possible in areas. Warmer temperatures than thought before could lead to extremely heavy snow. The biggest question is where the heaviest snow will fall.
20	1057	Warned areas- 6-9” Watch areas- 2-5”	Winter storm warning, watch	Slight shift northwestward since last update. Freezing drizzle is a big threat. Continuing to monitor the track and potential for blizzard conditions
20	2102	Warned areas- 6-9”, 8-11” Watch areas- 3-5”	Winter Weather Advisory, Winter Storm Warning	The track has shifted so that the main snow band will occur in the northwestern part of the CWA. Potential for freezing rain is high at the beginning of the storm. High wind gusts are still expected.
21	1019	Warned areas- 7-11” Watch areas- 3-5”	Winter Weather Advisory, Dense fog advisory, Blizzard Warning	Track has shifted yet again, moving more to the southeast which puts most of the CWA right in the heaviest snowfall. Blizzard warnings were put out because of this major shift along with the strong winds and snow that will persist for many hours.
21	2050	BW- 4-7”, 10-14” WWA- 2-4”	Blizzard Warning, Winter Weather Advisory	The storm has slowed down which may cause snowfall amounts to rise. The heavy snowfall has shifted more to the south. The snow is expected to be heavier and denser than seen previously in the season.
22	0717	BW- 5-8” WWA- 1-3”	Winter Weather Advisory, Blizzard Warning	Snow amounts lowered due to lull in snowfall. Areas are still expected to see snow but not as much as was originally predicted

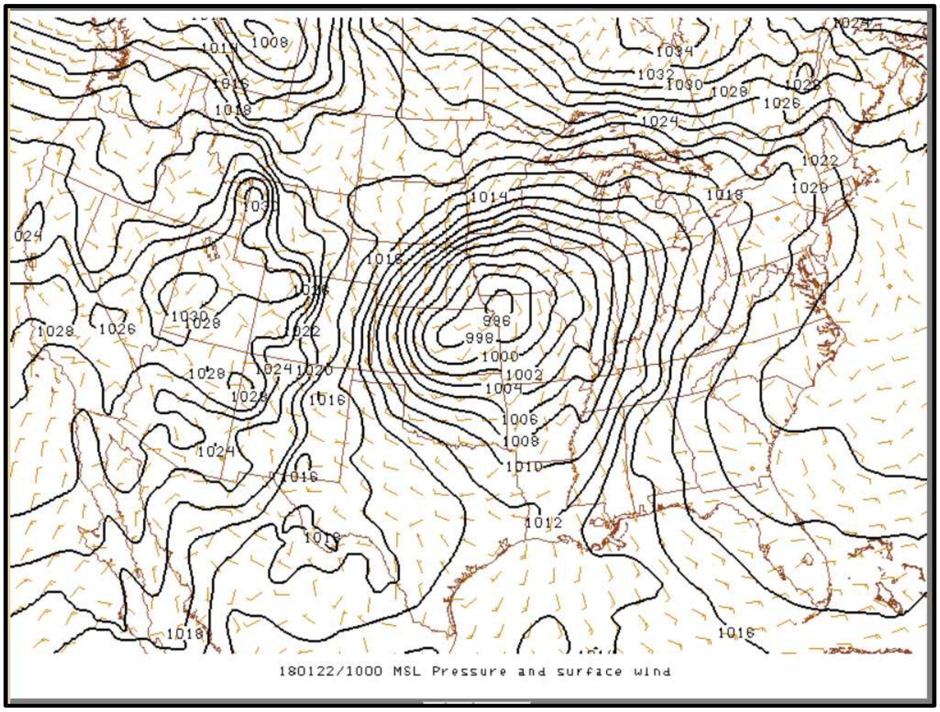


Figure 4.35: MSLP at 1000 UTC 22 January (SPC 2019)

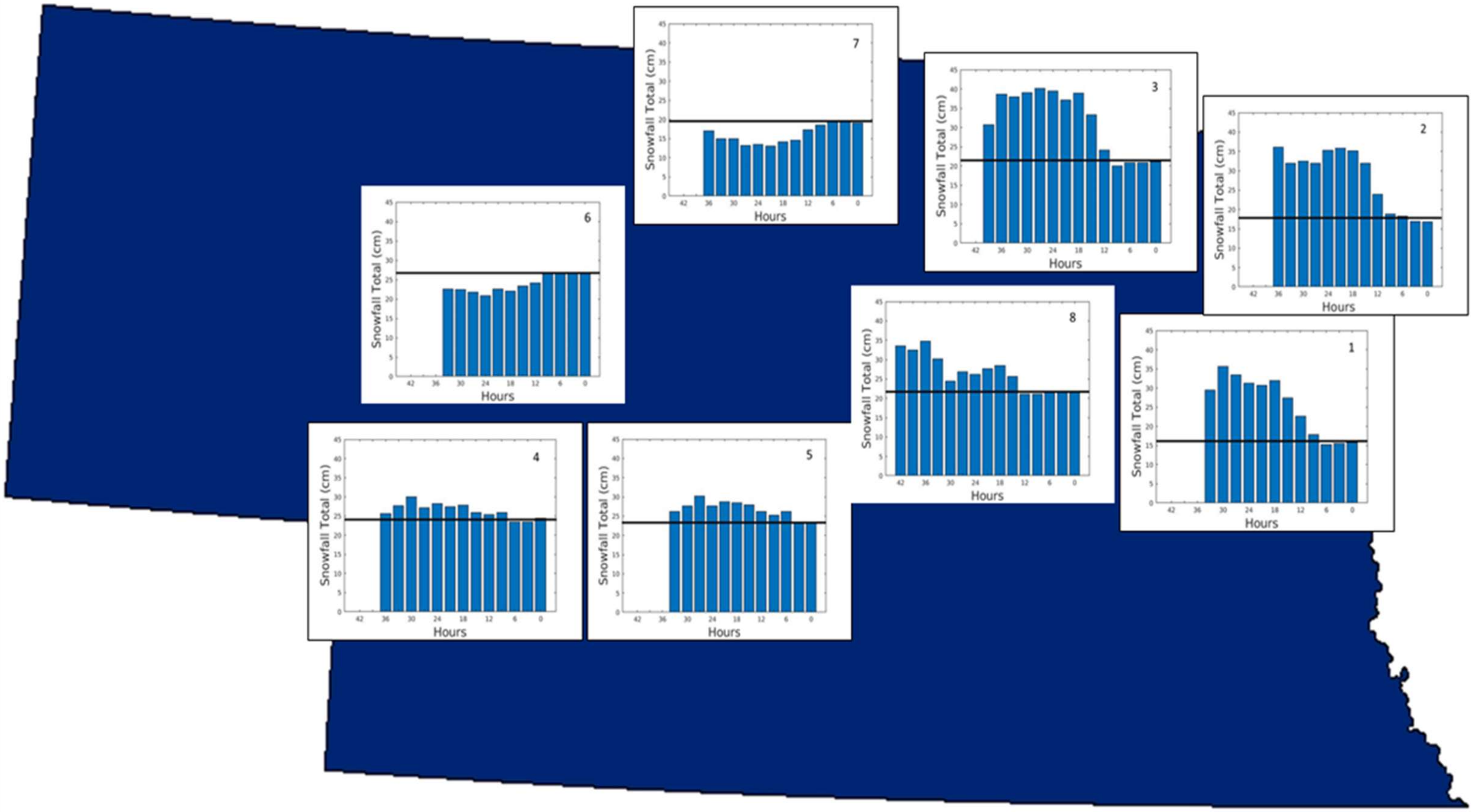
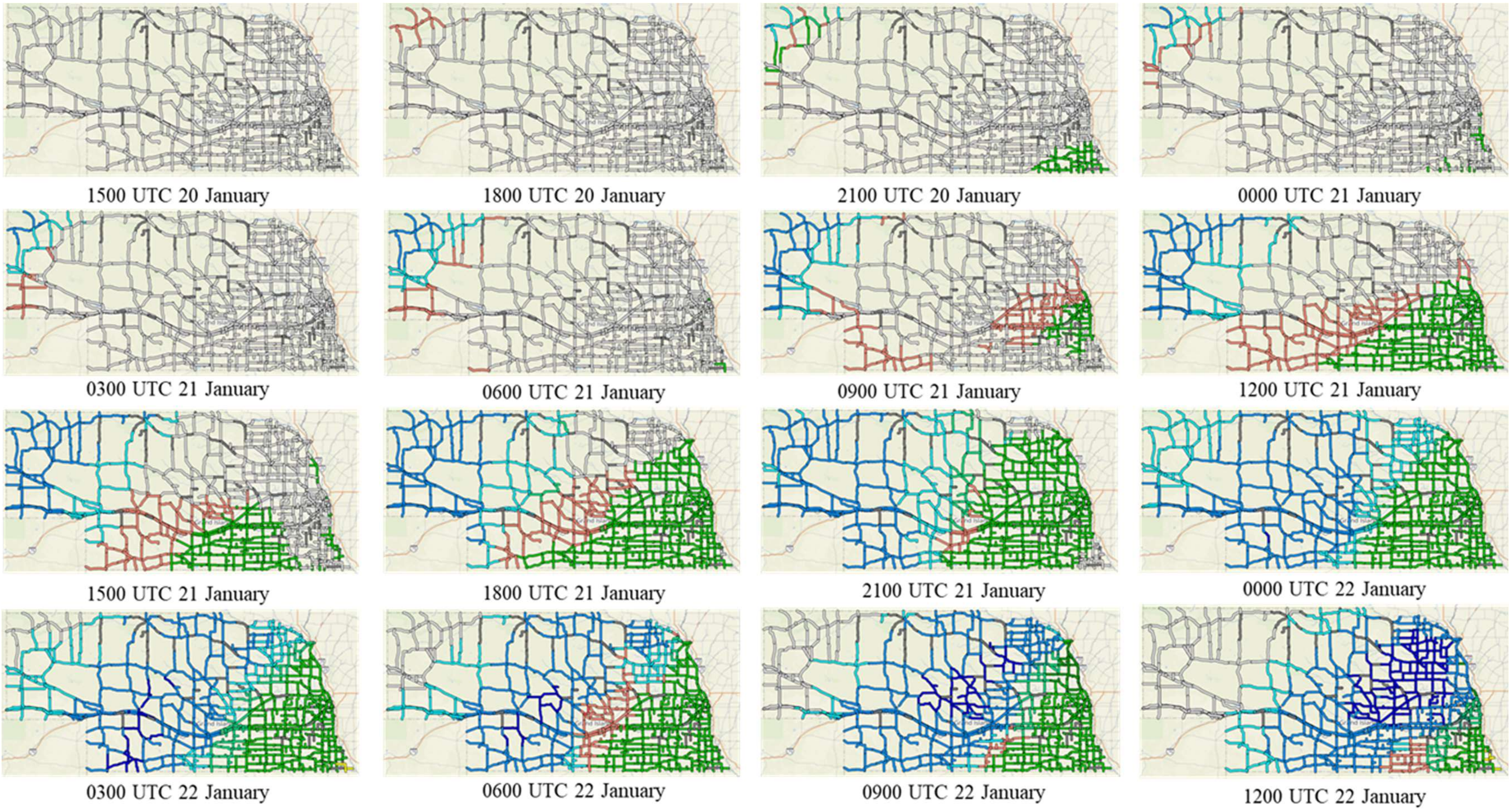


Figure 4.36: Forecasted total snow accumulations from the NDOT MDSS (blue) as the storm progresses for each route in their respective location throughout Nebraska during the January storm and the analysis of the total snow accumulations from NDOT MDSS (black).

for these routes. Major decreases in the forecasted snowfall accumulations took place between 18 and 9 hours before from the end of the precipitation for the routes that had the initial forecast totaling over 30 cm. Routes 1, 2, and 3 in eastern-northeastern Nebraska saw decreases of 14-18 cm from 18 to 9 hours out while Route 8, which is located a little farther to the west saw a decrease of approximately 7 cm during the same time period. Routes 4 and 5, located in southwestern Nebraska, remained relatively consistent with the forecasted total snowfall accumulations.

Routes 6 and 7 show comparable snowfall accumulation patterns, although, the totals do vary. The routes in central Nebraska, routes 6, 7 and 8 are in similar locations; however, due to the slightly more eastern location of Route 8, the forecast resembles routes 1, 2, and 3. The eastern routes are the most inaccurate with the forecasts while the central and southwestern routes are much more consistent and accurate. Routes 4 and 5 both have a total deviation of their forecasted snow accumulation of roughly 7 cm over the entire time period. The variation of forecasting ability based on the geographic location of the routes could have been caused by the major shifts in the track and timing of the low pressure system (Figure 4.33). The system seems to slow down throughout the 7 days prior to the onset of the storm. The center of the low pressure also shifted from central Iowa to the border of Iowa and Missouri on the day of the event. Although the shift may seem minor, it had an impact on the location of the heaviest snow. The routes in northeastern Nebraska were northwest of the low center, where greater snow accumulations associated with Colorado lows can occur. If any minor shifts in the storm track occurred, the routes would no longer be in a prime location for heavy snowfall. As much as the system had shifted in the forecast period before the event, a minor shift before impacting northeastern Nebraska is very plausible. An increase in the speed of the storm could lead to a large decrease in total snow accumulation for the routes. The storm system would not be over the area for quite as long, leading to lower snowfall totals. Another potential cause of the decrease in forecasted total snowfall accumulations for Routes 1, 2, 3, and 8 is because the transition from rain to snow took longer than was originally predicted by the NDOT-MDSS. Rain started in these routes at approximately 1500 UTC 21 January. When the rain started, the forecasted start time of snowfall was 0000 UTC 22 January. The analysis of the start time of the snowfall was 1000 UTC 22 January, which means that the rain lingered ten hours longer than was expected in eastern Nebraska decreasing snowfall totals.

The progression of the January storm from 1500 UTC 20 January to 0300 UTC 22 January within the NDOT-MDSS (Figure 4.37) highlights the changing weather conditions across Nebraska. Precipitation, mostly rain (eastern) and freezing rain (western) is taking place across Nebraska starting at 0900 UTC 21 January. Freezing drizzle was discussed in the AFDs prepared by all 4 NWS offices that contain an identified study route as a potential hazard (Tables 4.1-4.4). The NDOT-MDSS seemed to do a satisfactory job of picking up on freezing drizzle. The freezing drizzle changes over to snow at approximately 2100 UTC 21 January in central Nebraska (Figure 4.37). There is still rain present in the eastern and southeastern parts of the state. Three hours later, heavy snow is present from 0000 UTC to 1800 UTC 22 January in central and northeastern Nebraska. The areas of heavy snowfall amounts shown within the NDOT-MDSS are consistent with the snowfall totals provided by the KLBF NWS (Figure 4.1). The southeastern part of Nebraska receives mostly rain with some snow mixed in at the



1500 UTC 20 January

1800 UTC 20 January

2100 UTC 20 January

0000 UTC 21 January

0300 UTC 21 January

0600 UTC 21 January

0900 UTC 21 January

1200 UTC 21 January

1500 UTC 21 January

1800 UTC 21 January

2100 UTC 21 January

0000 UTC 22 January

0300 UTC 22 January

0600 UTC 22 January

0900 UTC 22 January

1200 UTC 22 January

Figure 4.37: Progression of the January Storm through time using the current conditions of each segment (WebMDSS™ 2018)

1500 UTC 22 January

1800 UTC 22 January

2100 UTC 22 January

0000 UTC 23 January

0300 UTC 23 January

MDSS Weather Alerts

Error / Not Available	No Precipitation	Drizzle
Light Rain	Moderate Rain	Heavy Rain
Thunderstorms	Blowing Snow	Light Snow
Moderate Snow	Heavy Snow	Light Rain/Snow Mix
Moderate Rain/Snow Mix	Heavy Rain/Snow Mix	Light Sleet
Moderate Sleet	Heavy Sleet	Freezing Drizzle
Light Freezing Rain	Moderate Freezing Rain	Heavy Freezing Rain

Figure 4.37 (con't) Progression of the January Storm through time using the current conditions of each segment (WebMDSS™ 2018)

very end of the storm (Figure 4.37). The lack of snowfall in southeastern Nebraska shown by the NDOT-MDSS is also consistent with the totals from the NWS. During the January storm, the main maintenance action that was done was patrolling.

All routes had differences of 5 hours between the forecasted start times and the analysis of the start times within the NDOT-MDSS (Table 4.5). The minor differences between the forecasted and the analysis of the start times in the NDOT-MDSS shows that the forecast was relatively accurate. The accuracy of a start time is based off of the time difference that occurred between the forecasted and analysis of the start times in the NDOT-MDSS. Routes 1 and 3 had forecasted start times greater than 7 hours when compared to the analysis of the start times within the NDOT-MDSS. The NDOT-MDSS start time analyses were comparable with the radar observed start times. A change in the timing of the storm could be a cause of the erroneous forecasted start times produced by the NDOT-MDSS for the eastern routes; however, Route 2 is in the vicinity of Route 1 and 3, although it did not see a timing issue. The differences in start times between the NDOT-MDSS and the radar could be due to the inability of the NDOT-MDSS to forecast the heavy snow, which is what can be detected more easily by the radar. Route 6 was the most accurately predicted, with no differences in any of the start times.

Differences in forecasted end times within the NDOT-MDSS analysis and radar observations were also found for the studied routes (Table 4.6). The variations between the forecasted and analysis of the end times within the NDOT-MDSS (Table 4.6) are larger than the start times (Table 4.5). There was never an instance where the forecasted end times within the NDOT-MDSS occurred during the same hour as the analysis of the end times within the NDOT-MDSS. The forecasted end times were always earlier than

Table 4.5: Differences in start times for January Storm (Hrs)

	NDOT-MDSS Forecasted vs. NDOT-MDSS Analysis	NDOT-MDSS Forecasted vs. Radar Observed	NDOT-MDSS Analysis vs. Radar Observed
Route 1	-4.0	+6.5	+10.5
Route 2	+1.0	+3.5	+2.5
Route 3	-4.0	+2.5	+6.5
Route 4	0.0	+1.0	-1.0
Route 5	+1.0	0.0	-1.0
Route 6	0.0	0.0	0.0
Route 7	-5.0	+4.0	+1.0
Route 8	+4.0	0.0	-4.0

Table 4.6: Difference in end times for January Storm (Hrs)

	NDOT-MDSS Forecasted vs. NDOT-MDSS Analysis	NDOT-MDSS Forecasted vs. Radar Observed	NDOT-MDSS Analysis vs. Radar Observed
Route 1	-4.0	+2.0	+6.0
Route 2	-1.0	+4.0	+5.0
Route 3	-3.0	+4.0	+7.0
Route 4	-5.0	-2.0	+3.0
Route 5	-5.0	-2.0	+3.0
Route 6	-2.0	-0.5	+2.5
Route 7	-6.0	-1.0	+7.0
Route 8	-5.0	+0.5	+5.5

+= NDOT-MDSS started/ended later

-=NDOT-MDSS started/ended earlier

the analysis of the end times within the NDOT-MDSS (Table 4.6). The discrepancy in the forecasted end times could have been caused by the storm slowing down over Nebraska, causing the storm duration to be extended. In many cases, light flurries occurred after the heavy snow ended, which would cause the storm to be extended longer in time than was forecasted. Light flurries at the end of the storm may also be the cause of differences in the analysis of end times within the NDOT-MDSS when compared with the radar observed end times. The analysis end times within the NDOT-MDSS always ended later than what were observed by the radar. Flurries may not have been picked up by the radar depending on the height of the radar beam and distance away from the radar. When the forecasted end time within the NDOT-MDSS was compared to the radar observed end time, there was less variation than when the forecasted end time within the NDOT-MDSS was compared to the analysis of the end time within the NDOT-MDSS. These minor inaccuracies were probably caused by the NDOT-MDSS predicting when the heavy snow would end rather than the flurries. The radar's ability to pick up on the heavy snow may have caused the forecasted start times within the NDOT-MDSS and the radar observed end times to align relatively well since flurries were not forecasted well by the NDOT-MDSS and may not be visible in the radar images.

The overall accuracy for predicting total snowfall accumulation varied from route to route. Some of the miscalculations were potentially based on track and timing changes at the various locations of the routes. Routes farther to the west were more accurately predicted than the routes to the east. The location of the route did not appear to have any major influence on the start and end time differences. It could potentially be said that the routes farther to the east were again the least accurate of all locations because of the large amount of variation, although, other routes in different locations also experienced moderate differences in their start and end times. Because of the way the NDOT-MDSS saves events, the forecasts for the western routes also had a shorter lead time before the storm impacted them, making forecasts in the western part of the state slightly more accurate due to the shorter lead time. Start times, for the most part, were more accurate than end times in every category that was analyzed. Another limitation was the location of the route with respect to the radar because snowfall would have not been picked up in some cases due to the precipitation occurring below the beam of the radar.

Having accurate wind speeds for each route is vital for maintenance crews because wind speeds will help determine whether to apply chemicals or whether to let the snow blow off the roadways. Adding chemicals during high wind events will melt the snow on the roadways and chemicals will have to be continually applied throughout the storm to avoid icy conditions. The most common action is to let the wind blow the snow off the roadway instead of applying anything. Wind speeds and gusts from all 8 routes in the NDOT-MDSS were compared to ASOS stations data in the route's general area. Routes 1, 2, and 3 are located in the same general area, so the reports from the ASOS station located at Wayne Municipal Airport (KLCG) were used for comparison (Figure 3.2). During the January storm, the Route 3 NDOT-MDSS sustained winds best followed the data from the KLCG ASOS station because they are very closely located (Figure 4.38a). Route 1, located to the southwest of the KLCG ASOS station, had lower sustained winds than what the ASOS station reported during most hours. They both followed the same general pattern except for between 1200-1300 UTC 22 January. The NDOT-MDSS sustained winds decreased in Route 1 to 7.2 m s^{-1} (14 kts) while the

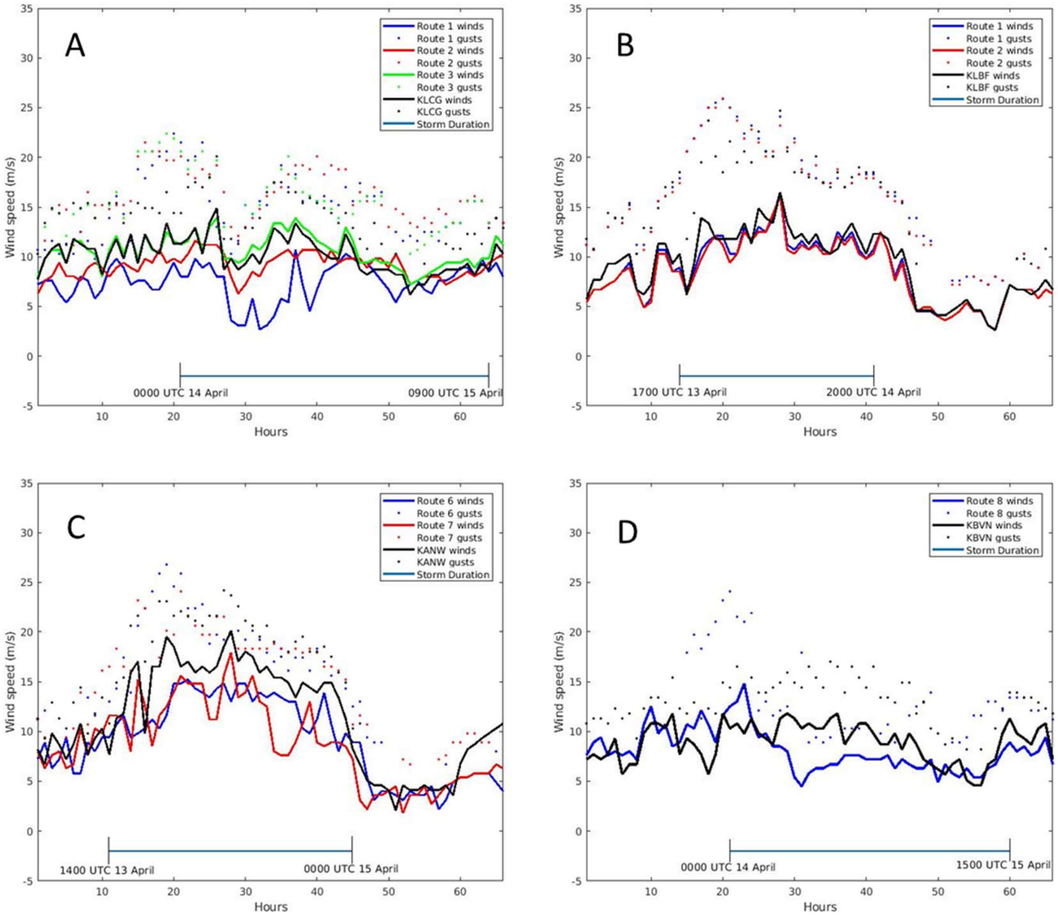


Figure 4.38: Sustained wind speeds and wind gusts during the January storm. A) Route 1 (blue), Route 2 (red), Route 3 (green), and KLCG ASOS station (black). B) Route 4 (blue), Route 5 (red), KLBF ASOS station (black). C) Route 6 (blue), Route (7), and KBVN ASOS station (black). D) Route 8 (blue) and KANW ASOS station (black). The storm duration was plotted (light blue) to show when the storm was taking place per each route.

KLCG ASOS was reporting sustained winds of 12.4-12.7 m s^{-1} (24-25 kts). Route 2 had much lower winds than both the KLCG ASOS and Routes 1 and 3 between 1400-1800 UTC. The cause for the difference of approximately 7.7 m s^{-1} (15 kts) is unknown. The wind gusts from the NDOT-MDSS and the KLCG ASOS followed a similar pattern to the sustained winds. Route 2 generally had lower wind gusts and Route 3 had gusts very similar to what the KLCG ASOS was reporting. Route 1 and 3 were reporting much higher wind gusts than the KLCG ASOS while Route 2 was reporting much lower wind gusts 25-30 hours after the storm started. There was only one notable difference in the Route 2 winds at 64 hours from the start of the saved storms that seemed abnormal. All of the other wind gusts appeared to be similar to what they were when the storm was not taking place.

Routes 4 and 5 were grouped with the KLBF ASOS station (Figure 3.2). The routes were in agreement within the NDOT-MDSS, which is expected due to their close proximity and same orientation (Figure 4.38b). The route values within the NDOT-MDSS were in agreement with the KLBF ASOS values given for winds. The KLBF ASOS values were slightly higher in most hours than both routes. Between 1400-1500 UTC 22 January, no data were reported from the KLBF ASOS. There were no major inconsistences in the wind gusts reported for Routes 4 and 5 and what the KLBF ASOS reported. Towards the end of the storm, gusts did not meet the criteria to be reported by either source.

Routes 6 and 7 had a centrally located ASOS station at Ainsworth Regional Airport (KANW) (Figure 3.2). The two routes were not right beside the KANW ASOS, although the routes were within a reasonable distance. Route 6, located to the southwest of the KANW ASOS was more in agreement with the KANW ASOS data reports than Route 7 (Figure 4.38c). Route 7, located to the northwest of the KANW ASOS had lower sustained winds with a large decrease occurring from 0600-1000 UTC 22 January. The overall pattern was not as aligned as the other routes and their ASOS stations; however, this may be caused by the greater distance between the NDOT-MDSS routes and the KANW ASOS. The gusts from Route 7 were consistently lower than the gusts reported from Route 6 and the KANW ASOS. Route 6 was reporting higher wind gusts than the KANW ASOS at the start of the storm; however, as the storm progressed, the gusts started to become more similar in value. Towards the end of the storm, the wind gusts were not high enough to be reported by either the NDOT-MDSS or the KANW ASOS. Route 8 was not close enough to any of the ASOS stations that the other routes were grouped with so it was individually grouped with the Albion Municipal Airport (KBVN) (Figure 3.2). The NDOT-MDSS values for wind speed are not quite in agreement with the values from the KBVN ASOS (Figure 4.38d). At 1100 UTC 22 January, the NDOT-MDSS reported sustained winds at 4.1 m s^{-1} (8 kts) while the KBVN ASOS has the sustained winds at 10.8 m s^{-1} (21 kts). The NDOT-MDSS and KBVN ASOS wind speeds throughout the storm follow the same overall pattern; however, there are inconsistencies when looking more in detail the sustained winds being reported by both the KBVN ASOS and the NDOT-MDSS. The wind gusts reported by the NDOT-MDSS in Route 8 are relatively similar to what was being reported by the KBVN ASOS. There were no major inconsistencies between the two, although there were no wind gusts that met the criteria to be considered high enough during certain periods in the storm.

The ASOS stations that were used to find the accuracy of the NDOT-MDSS wind data were also the ones used for the analysis of the temperature data in the NDOT-MDSS. During the January storm, Routes 1, 2, and 3 as well as the KLCG ASOS station have temperatures that were in agreement up until 60 hours from the start of the storm (Figure 4.39a). Route 1 sees a temperature decrease while the KLCG ASOS station sees a temperature increase. Routes 2 and 3 are decreasing at a relatively steady rate at this time. After the sharp increase in temperatures at the KLCG ASOS station, there is a large decrease where it drops down 5-7 °C lower than all of the routes. Route 3 increases to approximately what the other routes are seeing within the NDOT-MDSS. Routes 4 and 5 were perfectly in agreement within the NDOT-MDSS during the January storm (Figure 4.39b). The KLBF ASOS station followed the same pattern as the routes up until 40 hours from the start of the storm. At approximately 70 hours from the start of the storm, both Route 4 and Route 5 had a large decrease in temperature; however, the KLBF station stayed warmer. The KLBF ASOS station is in exactly the same location as both routes so this result shows some inaccuracy.

The temperatures from Routes 6 and 7 followed the same pattern as the KANW ASOS station, although all three temperatures were a few degrees off from one another (Figure 4.39c). This slight difference occurred throughout most of the saved storm. Temperatures in Route 6 were consistently lower than the other two temperatures, especially at the end of the saved storm where Route 6's temperatures plummet close to 10 °C below what is being reported at the KANW ASOS station and the analysis of the temperatures by the NDOT-MDSS at Route 7. The temperatures from the KANW ASOS station and Route 7 were in good agreement throughout the saved storm. The pattern of

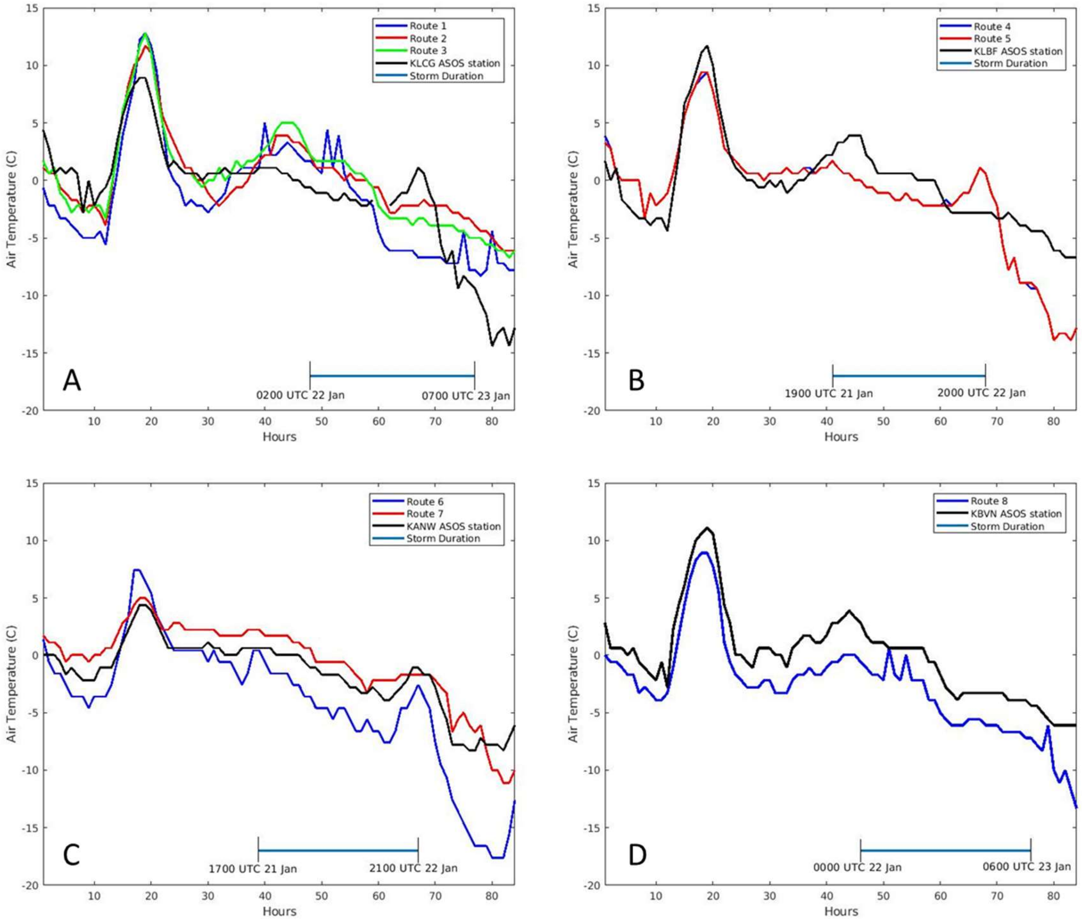


Figure 4.39: Air temperatures during the January storm. A) Route 1 (blue), Route 2 (red), Route 3 (green), and KLCG ASOS station (black). B) Route 4 (blue), Route 5 (red), KLBF ASOS station (black). C) Route 6 (blue), Route (7), and KBVN ASOS station (black). D) Route 8 (blue) and KANW ASOS station (black). The storm duration was plotted (light blue) to show when the storm was taking place per each route.

the air temperatures reported by the KBVN ASOS station was very similar to the analysis of the air temperatures by the NDOT-MDSS for Route 8 (Figure 4.39d). The temperatures in the NDOT-MDSS were slightly lower than the air temperatures at the KBVN ASOS station. There are two peaks that occur in the analysis of the air temperature between 50 and 60 hours from the start of the saved storm that were not seen at the ASOS station. Another peak in the analysis of the air temperatures by the NDOT-MDSS occurred around 80 hours from the start of the saved storm. This was followed by a decrease in the air temperature that was also not seen by the KBVN ASOS station. Throughout the storm duration in Routes 1, 2, and 3, there were no large deviations from the normal temperature; however, the KLCG ASOS station observed a major increase in temperature at 66 hours from the start of the saved storm then it decreases very rapidly until the end of the storm. The issues between Routes 4 and 5 and the KLBF ASOS station began approximately when the storm began. After the storm began at 1900 UTC 21 January, the route and the ASOS temperatures were not in agreement through the end of the saved storm.

Routes 1, 2, and 3 are grouped with the Scriber RWIS station (Figure 3.2). The Emerson RWIS station did not have data available for the April storm so the Scribner RWIS was chosen in its place due to the similar location and pavement temperature values. The pavement temperatures in Routes 1, 2, and 3 in the January storm were very in agreement with the Scribner RWIS station although the RWIS station had slightly lower pavement temperatures (Figure 4.40a). The pavement temperatures from the Emerson RWIS station were very similar to the pavement temperatures at the Scribner RWIS station. The only area of divergence of the road temperatures occurs from 60 to 84

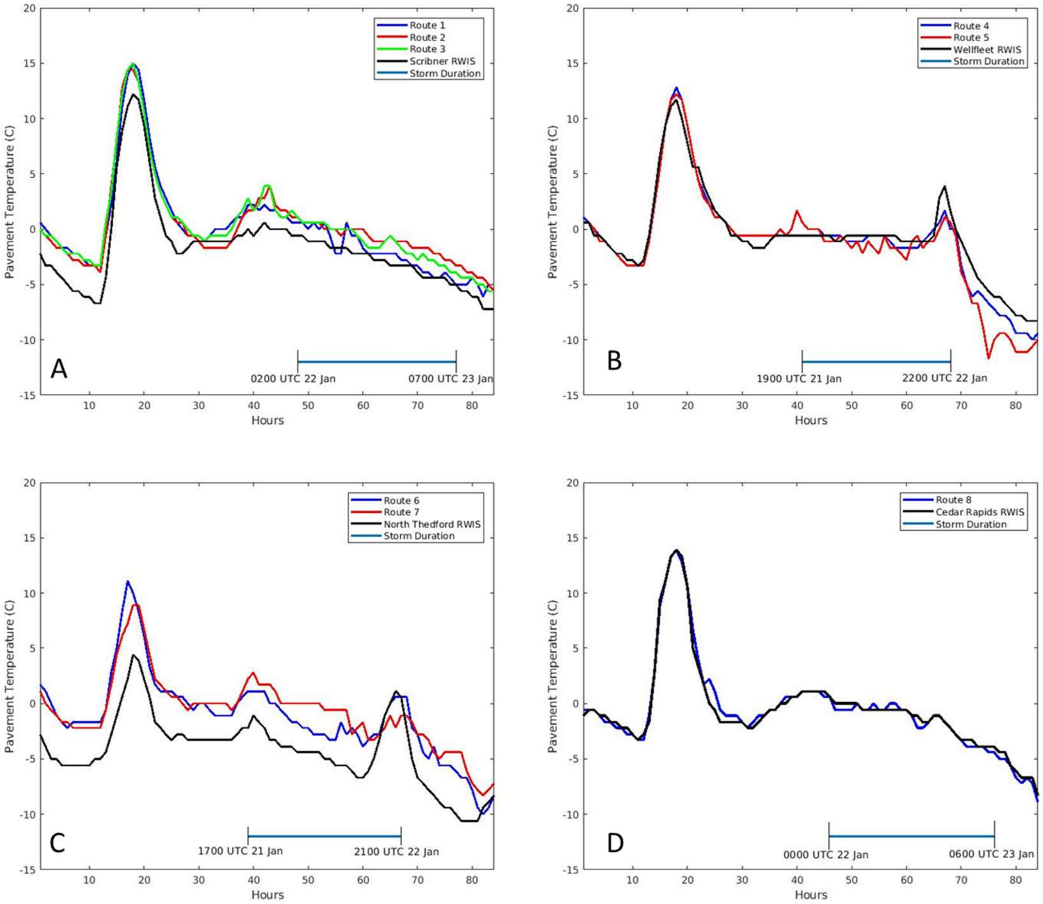


Figure 4.40: Pavement temperatures during the January storm. A) Route 1 (blue), Route 2 (red), Route 3 (green), and Scribner RWIS station (black). B) Route 4 (blue), Route 5 (red), and Wellfleet RWIS station (black). C) Route 6 (blue), Route (7), and North Thedford RWIS station (black). D) Route 8 (blue) and Cedar Rapids station (black). The storm duration was plotted (light blue) to show when the storm was taking place per each route.

hours from the start of the storm, although the difference was not very large. The Wellfleet RWIS station was grouped with Routes 4 and 5 in the NDOT-MDSS (Figure 3.2). The pavement temperatures in Routes 4 and 5 were in agreement in the January storm up until approximately 70 hours from the start of the storm (Figure 4.40b). The pavement temperatures obtained from the Wellfleet RWIS station were in agreement with both routes until up to 70 hours from the start of the storm as well. Route 6 and 7 were grouped with the centrally located North Thedford RWIS station (Figure 3.2). The North Thedford RWIS station pavement temperatures are lower than the pavement temperature both Routes 6 and 7 although they did follow the same overall pattern (Figure 4.40c). The inconsistency of the RWIS station could be due to its farther distance to the study routes. Route 8 was grouped with the Cedar Rapids RWIS station due its very close proximity (Figure 3.2). Route 8's pavement temperatures agreed extremely well with the Cedar Rapids RWIS station (Figure 4.40d). There are almost no differences in the values. The January pavement temperatures from all routes and ASOS stations had no major deviations from the normal patter observed when the storm was occurring to when it was not.

It is very important for an RWIS and a similarly located ASOS station to have the same or relatively similar temperatures. Different temperatures could mean that all variables are inconsistent which could lead to different weather conditions than what is being reported. The Scribner RWIS station was compared to the KLCG ASOS station. Both stations followed the same pattern until about 60 hours from the start of the January storm (Figure 4.41a). The ASOS temperature then spiked and proceeded to drop down to

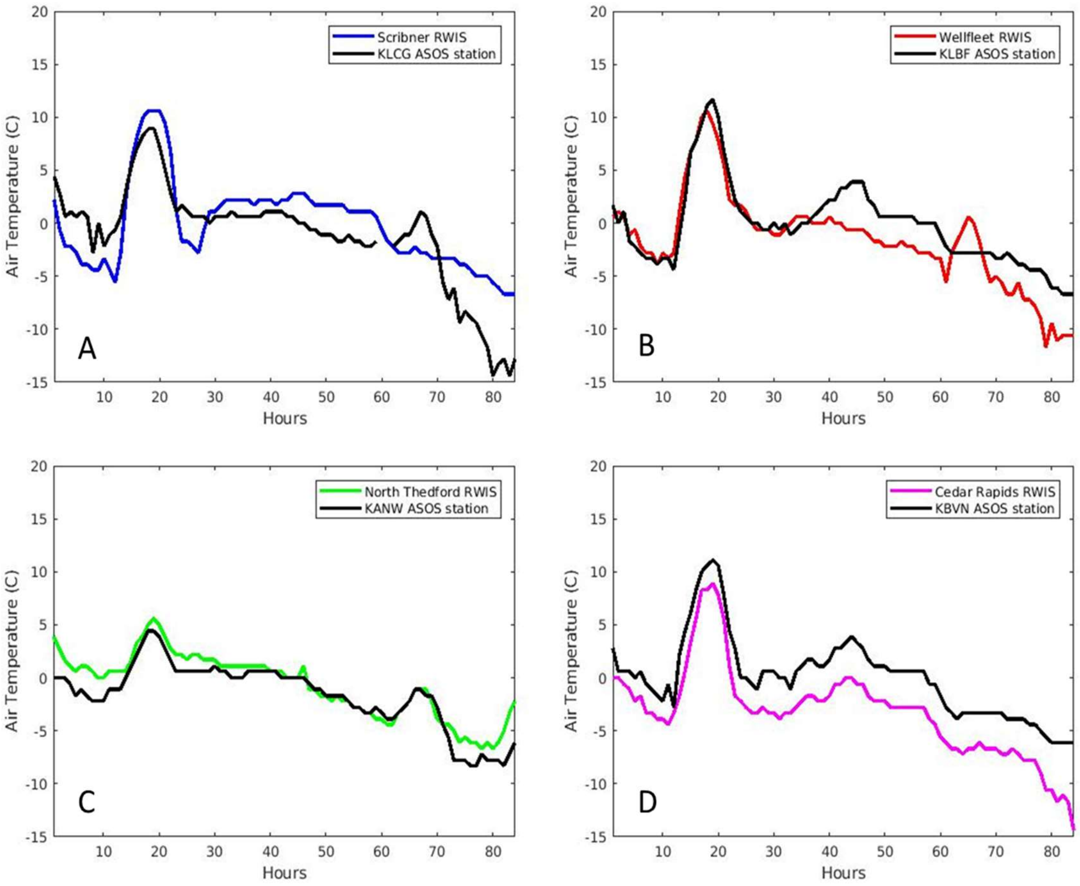


Figure 4.41: Air temperatures during the January Storm. A) Scribner RWIS station (blue) and KLCG ASOS station (black). B) Wellfleet RWIS station (red) and KLBF ASOS station (black). C) North Thedford RWIS station (green) and KBVN ASOS station (black). D) Cedar Rapids RWIS station (magenta) and KANW ASOS station (black).

4-9 °C below the temperature observed at the Scribner RWIS station. The Scribner RWIS is located approximately 70 km south of the KLCG ASOS station (Figure 3.2) so that may be what caused the difference in the two stations. The Wellfleet RWIS station was compared to the KLBF ASOS station. The station temperatures are in agreement up until 40 hours from the start of the storm (Figure 4.41b). The KLBF ASOS station reports slightly warmer temperatures until the Wellfleet RWIS temperatures spike at approximately 65 hours from the start of the storm. After this spike, the KLBF ASOS station goes back to being slightly warmer than what was being reported at the Wellfleet RWIS station. The differences are relatively small between these two stations. The KANW ASOS station reported more warming at approximately 20 hours from the start of the storm in comparison to the North Thedford RWIS (Figure 4.41c). Throughout the rest of the storm, there was not much of a difference in temperature; however, the KANW ASOS station generally reported slightly warmer temperatures than what was being reported at the North Thedford RWIS station. The Cedar Rapids RWIS station was compared to the KBVN ASOS station. The temperatures followed relatively the same pattern aside from a few spikes in temperature from both stations (Figure 4.41d). The first peak that differs between the station starts at 11 hours from the start of the storm. The Cedar Rapids RWIS station is reporting temperatures that are 3-5 °C greater than the temperatures being reported at the KBVN ASOS station. The temperatures decrease rapidly and end up 2-3 °C cooler for the next 15-20 hours. The second spike in temperature starts at approximately 60 hours from the start of the storm where temperatures at the KBVN ASOS station are 2-5 °C warmer than the Cedar Rapids RWIS temperatures.

4.3 April Synoptic Results

Moist air was advected northward into the Great Plains as a low pressure system moved in from the west on 13 April 2018. The presence of the moisture and the cold air produced rapid rising motion which brought strong winds and heavy snow to the Plain States. Severe thunderstorms were also observed in parts of the Midwest and Mississippi Valley. The storm system first brought snow and high winds to the western part of Nebraska on 13 April 2018 and moved eastward throughout the day. Heavy snow fell in central Nebraska during 14 April with snow totals ranging from 20.32-45.72 cm (8 to 18 in) by 15 April (Figure 4.42). Many road closures were reported across Nebraska during the event, including Interstate 80. Closures were caused by the heavy snow along with snow drifts that reached over a meter in height in many places. Temperatures dropped below freezing which most likely affected which deicing chemicals had to be applied to the road surface due to the different temperature thresholds of each of these chemicals. High profile vehicles also had difficulty traveling because of high winds that accompanied the event (U.S. Department of Commerce 2018b).

The 0000 UTC 14 April 2018 atmospheric sounding for North Platte (Figure 4.43), indicates that the temperature does not exceed 0 °C (32 °F) in the atmospheric column. The DGZ is located between approximately 650hPa and 500hPa and is nearly saturated, allowing for ice crystal growth to occur in this layer. Below the DGZ layer the atmosphere is saturated, aiding crystal growth to the surface. North Platte was receiving precipitation as indicated by radar (Figure 4.44) at 0025 UTC; however, the KLBF ASOS was reporting no precipitation. The radar is approximately 25 minutes

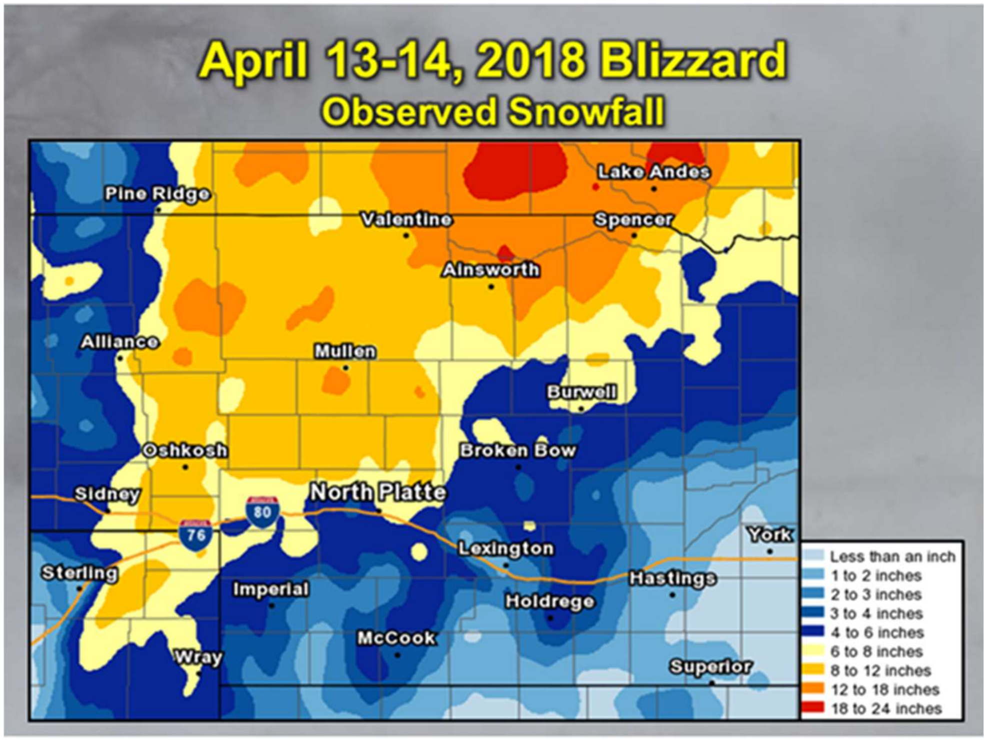


Figure 4.42: Snowfall totals throughout the state of Nebraska from the NWS for the April storm (U.S. Department of Commerce 2018b)

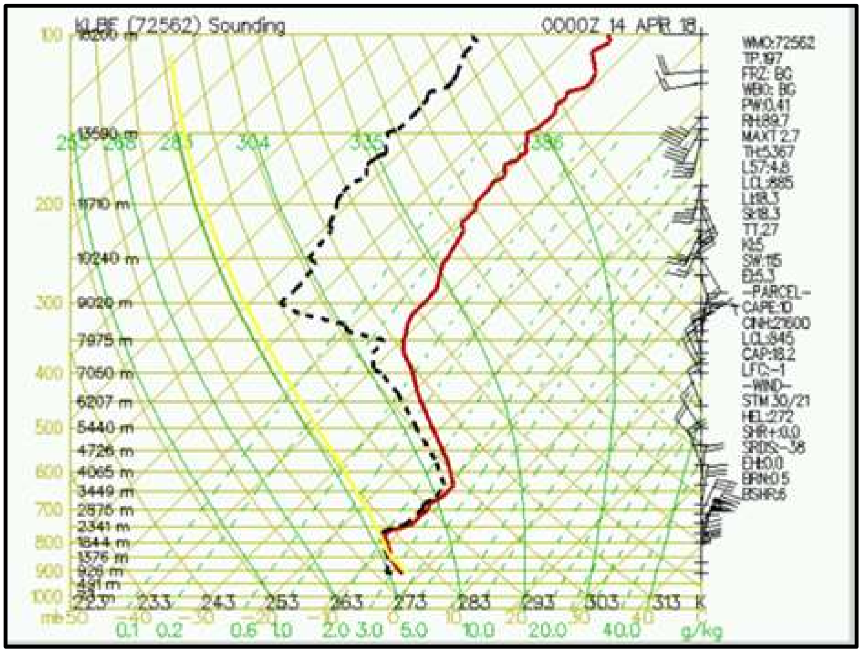


Figure 4.43: The profile of the atmosphere for North Platte, NE at 0000 UTC 14 April 2018 (Plymouth State 2018)

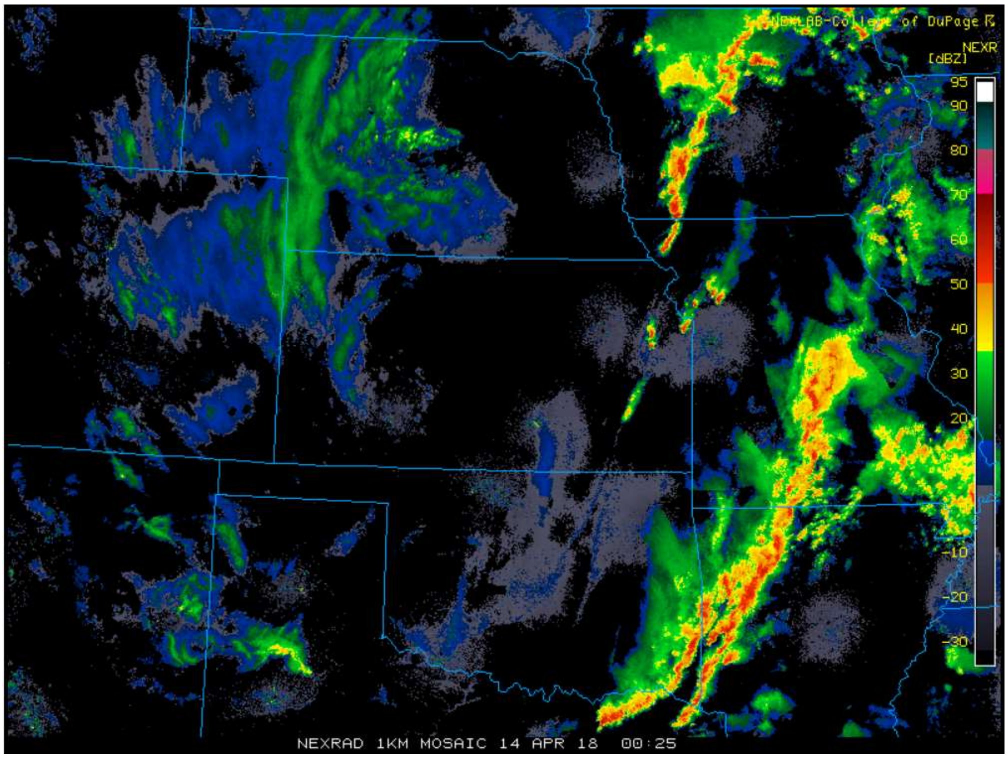


Figure 4.44: Radar image 0025 UTC 14 April 2018 (NCAR 2018)

past the hour so there could have been a break in precipitation at the KLBF ASOS station prior to when the radar image was taken at 0025 UTC. At 0000 UTC April 14, the Omaha/Valley sounding (Figure 4.45) is showing there is no snow occurring at this time due to the lack of saturation in the DGZ. The amount of precipitable water in the atmosphere is 1.78 cm (0.70 in). The temperature at the surface reaches approximately 15 °C (59 °F) which means that if any precipitation was falling, it would be rain. The atmospheric sounding shows that there is dry air, which coincides with the radar showing no precipitation over eastern Nebraska at 0025 UTC 14 April (Figure 4.44). Twelve hours later at 1200 UTC 14 April, the North Platte sounding (Figure 4.46) shows that the atmosphere is still very close to saturation and all the temperatures are under 0 °C (32 °F). When compared to the radar composite (Figure 4.47), there are areas of light precipitation still taking place even though the system is moving out of the area. The Omaha/Valley sounding (Figure 4.48) shows that the DGZ is nearly saturated at the lowest levels, although there is a layer of dry air in place from approximately 650-550 hPa. The dry layer may be the cause of the lack of precipitation occurring near Omaha as shown by radar (Figure 4.47). The main areas of heavy snowfall are still situated over central Nebraska. A 500 hPa shortwave trough becomes visible at approximately 0000 UTC 12 April 2018 off the coast of California (Figure 4.49). The trough is positively tilted so it is continuing to build at this time. The progression of the shortwave places the trough inland over the western states by 0000 UTC April 13 (Figure 4.50). The shortwave intensified during the next 24 hours as it further moved eastward. A closed low has yet to form by 1200 UTC 13 April 2018 (Figure 4.51) and the intensity of the system has remained constant. The system strengthens and becomes closed by

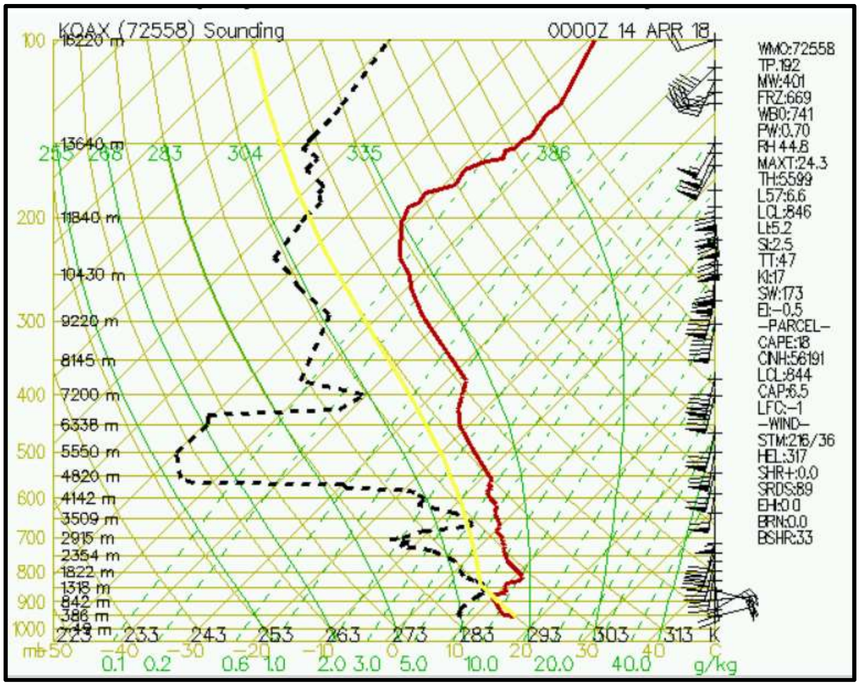


Figure 4.45: The profile of the atmosphere for Omaha, NE at 0000 UTC 14 April 2018 (Plymouth State 2018)

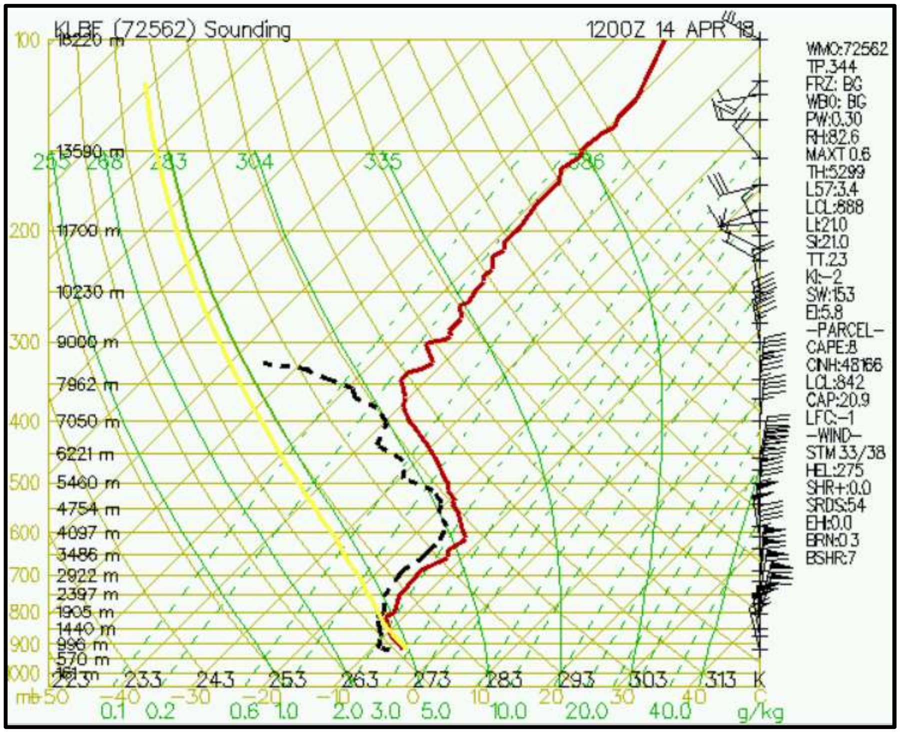


Figure 4.46: The profile of the atmosphere for North Platte, NE at 1200 UTC 14 April 2018 (Plymouth State 2018)

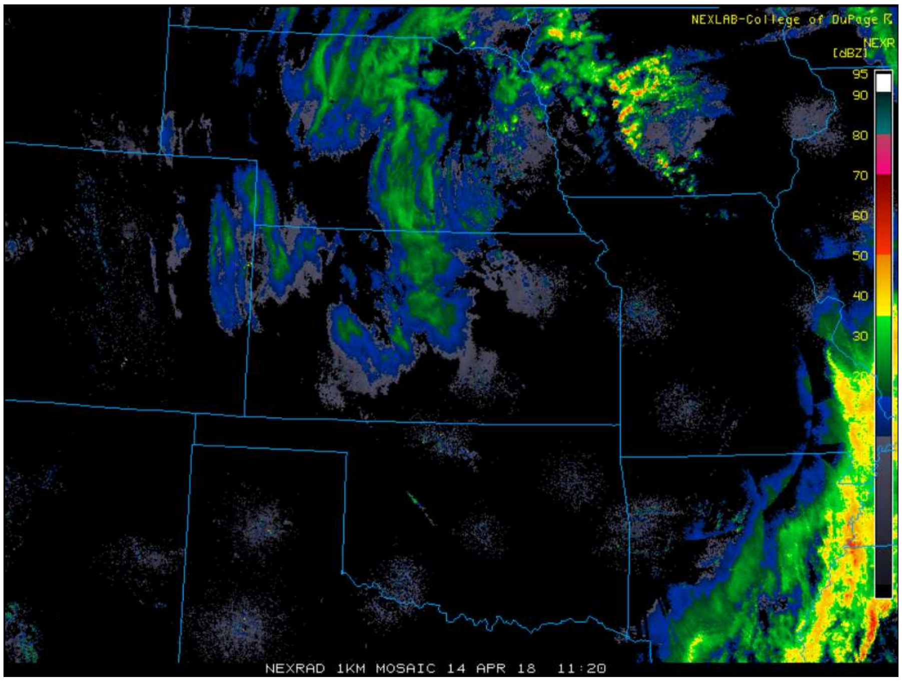


Figure 4.47: Radar image at 1120 UTC 14 April (NCAR 2018)

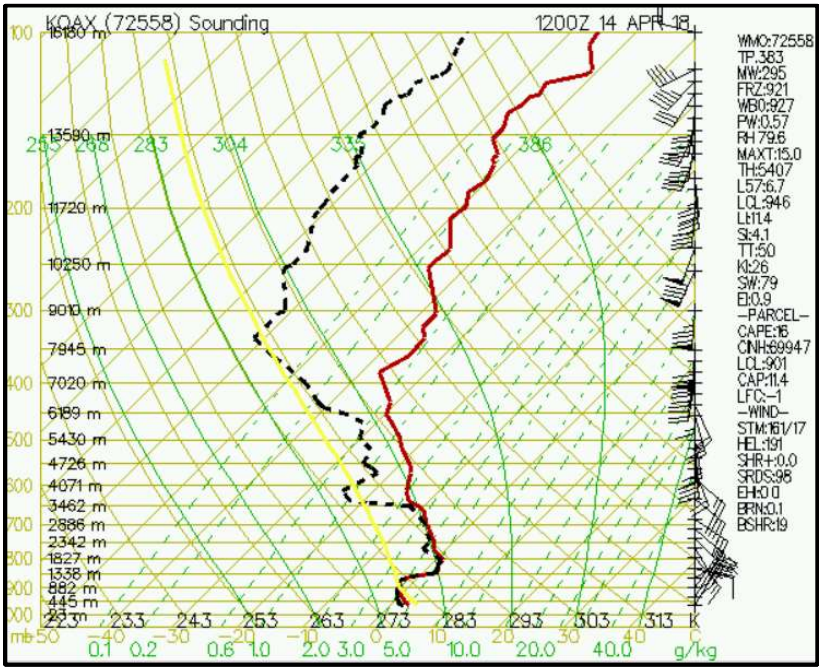


Figure 4.48: The profile of the atmosphere for Omaha, NE at 1200 UTC 14 April 2018 (Plymouth State 2018)

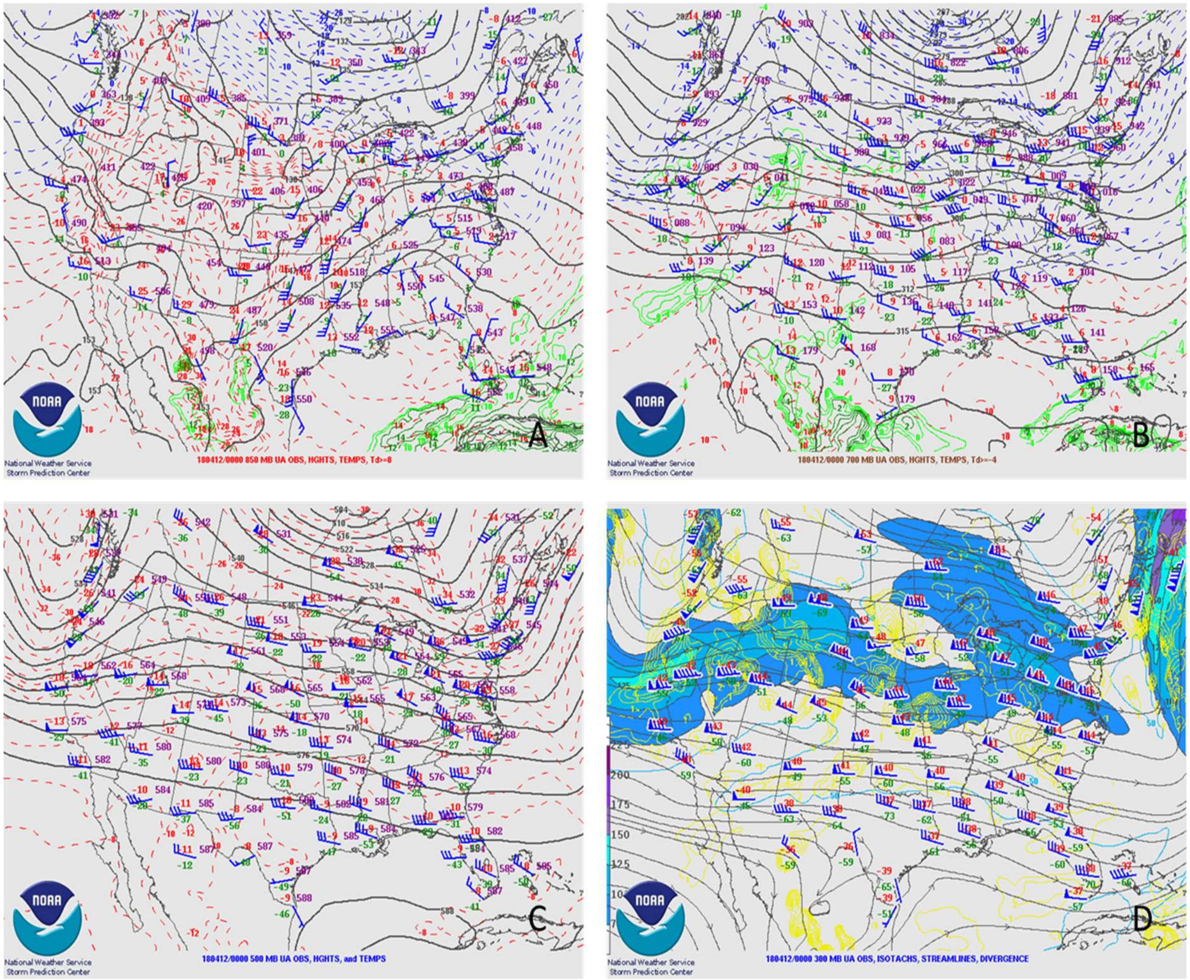


Figure 4.49: Different levels in the atmosphere at 0000 UTC 12 April 2018. a) 850 hPa b) 700 hPa c) 500 hPa d) 300 hPa (SPC 2019).

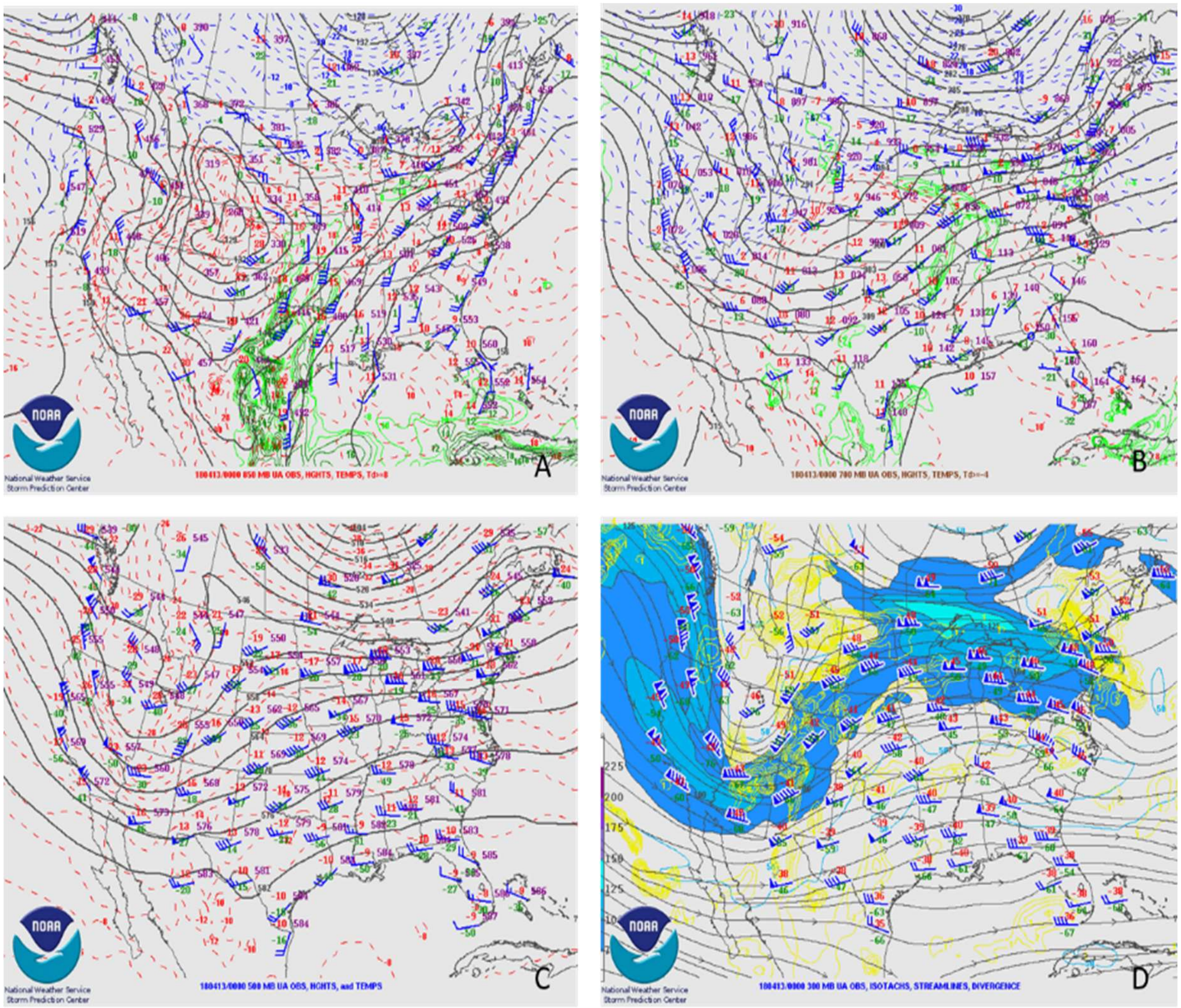


Figure 4.50: Different levels in the atmosphere at 0000 UTC 13 April 2018. a) 850 hPa b) 700 hPa c) 500 hPa d) 300 hPa (SPC 2019)

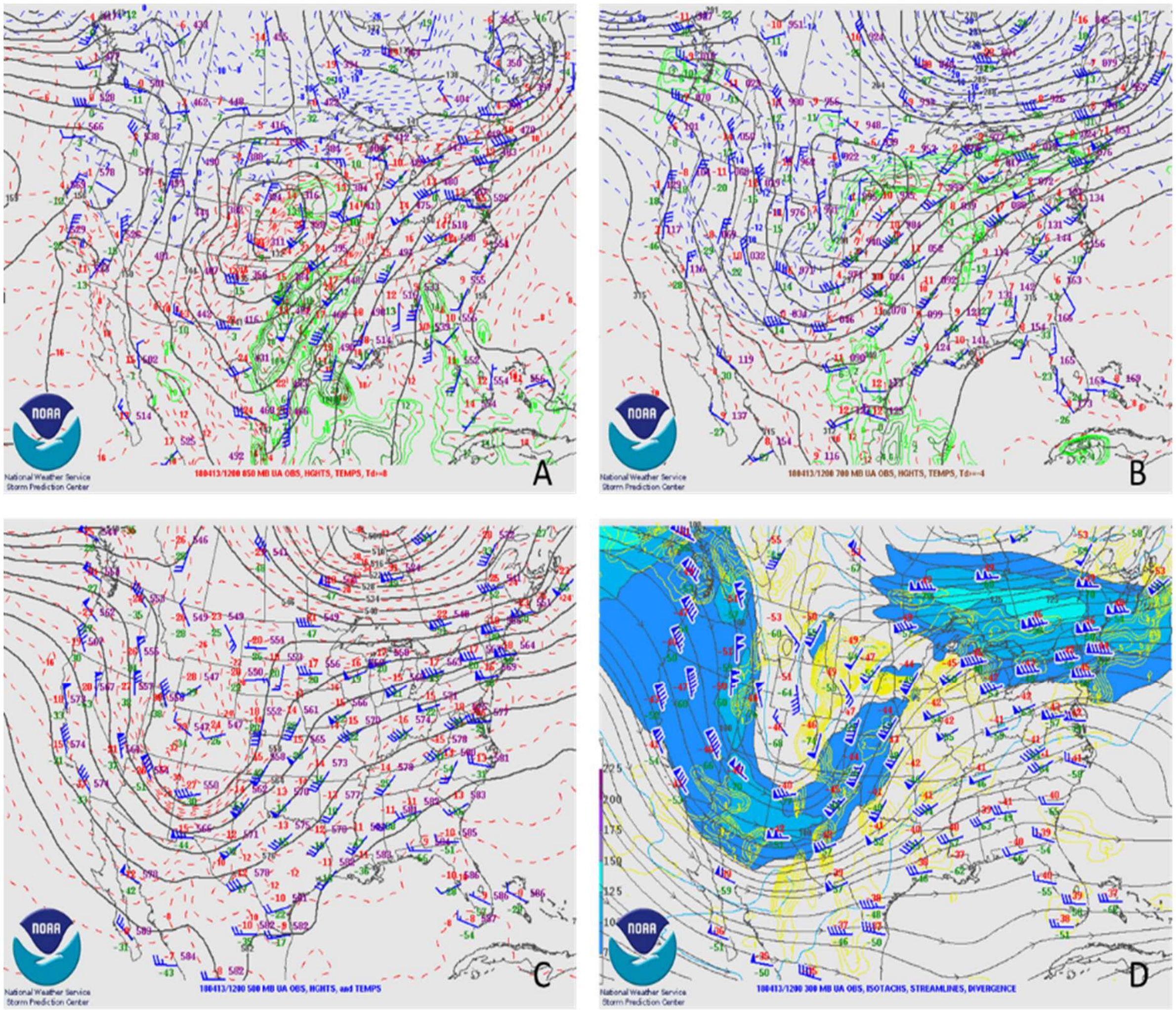


Figure 4.51: Different levels in the atmosphere at 1200 UTC 13 April 2018. a) 850 hPa b) 700 hPa c) 500 hPa d) 300 hPa (SPC 2019)

0000 UTC 14 April 2018 (Figure 4.52). The strengthening occurs after the shortwave passes over the mountains which indicates that lee-side cyclogenesis occurred prior to 0000 UTC 14 April. At this time, the effects of the storm were starting to be felt in Nebraska. By 1200 UTC 14 April (Figure 4.53), the storm is at peak intensity over the state. CAA can be seen at 850 hPa (Figure 4.53a) to the left of the trough axis over Nebraska and Kansas.

At 1900 UTC 13 April at 700 hPa (Figure 4.54), frontogenesis is occurring over most of northwestern Nebraska. The analysis of the conditions in northwestern Nebraska, according to the NDOT-MDSS, is a combination of heavy and moderate snow (Figure 4.55). A large area of frontogenesis is joined with negative values of EPVg* along with some conditional instability. These conditions are ideal for producing snowfall. At 0000 UTC 14 April, the center of the low pressure system is located in northwestern Kansas (Figure 4.56) with areas of vorticity concentrated on the left side of the trough. This is co-located with a jet streak at 300 hPa (Figure 4.57). The critical thicknesses are spread out across the central Plains (Figure 4.58) with all layers except 1000-500 hPa coming into central Nebraska. At 0700 UTC 14 April at 500 hPa (Figure 4.59), an area of positive vorticity can be seen covering parts of Nebraska, Kansas, Oklahoma and Texas. The highest amount of positive vorticity can be seen in eastern Nebraska and north central Kansas. This is roughly where the surface low pressure is centered. Vorticity exceeds $3 \times 10^{-6}\ s^{-1}$. Both the jet streak and the area of positive vorticity indicates that the region has a lot of divergence aloft, which is a favorable synoptic set-up for a winter storm. In addition to vorticity, vertical motion, found at 850 hPa, can show the amount of upper-level divergence that is occurring.

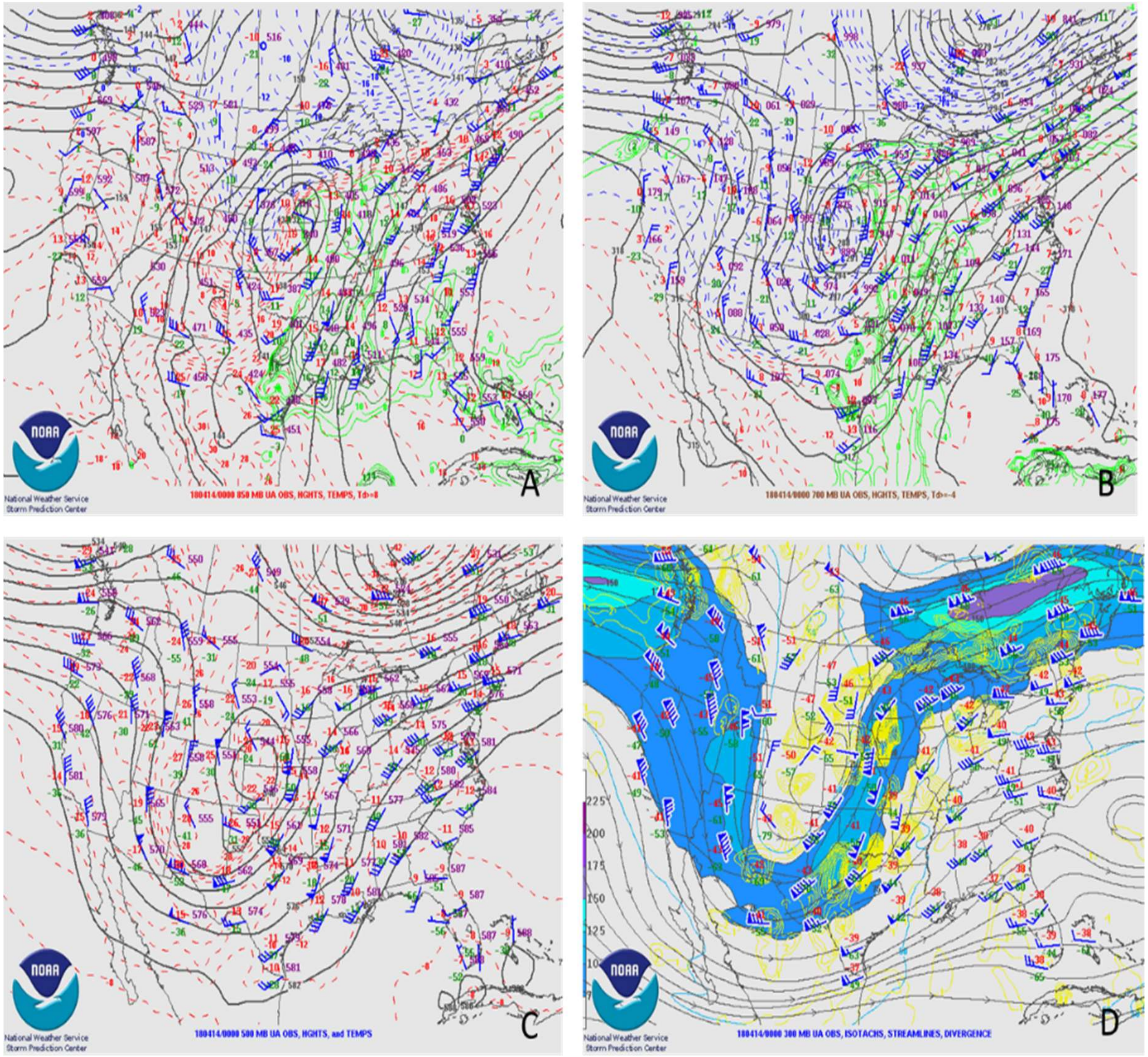


Figure 4.52: Different levels in the atmosphere at 0000 UTC 14 April 2018. a) 850 hPa b) 700 hPa c) 500 hPa d) 300 hPa (SPC 2019)

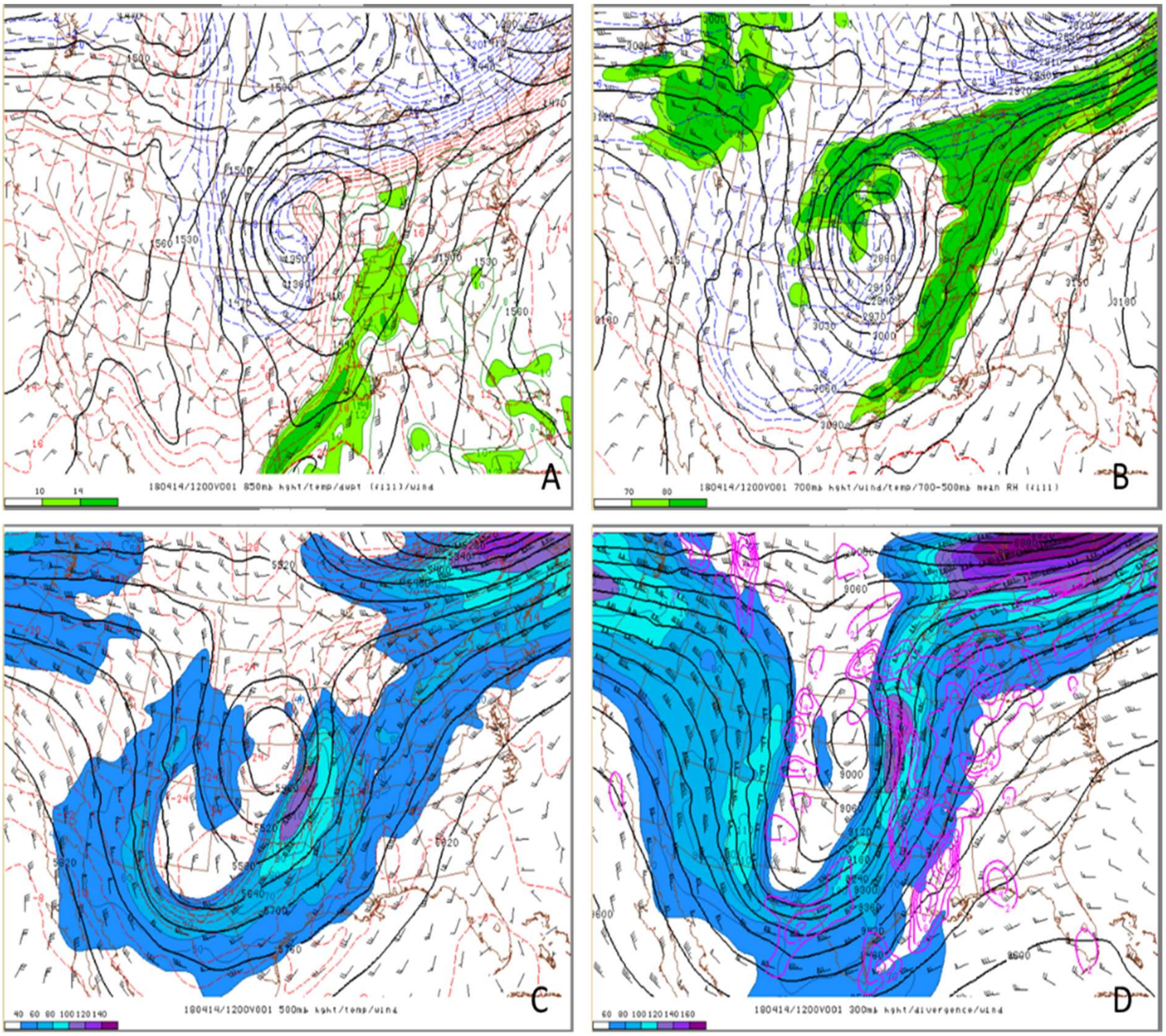


Figure 4.53: Different levels in the atmosphere at 1200 UTC 14 April 2018. a) 850 hPa b) 700 hPa c) 500 hPa d) 300 hPa (SPC 2019)

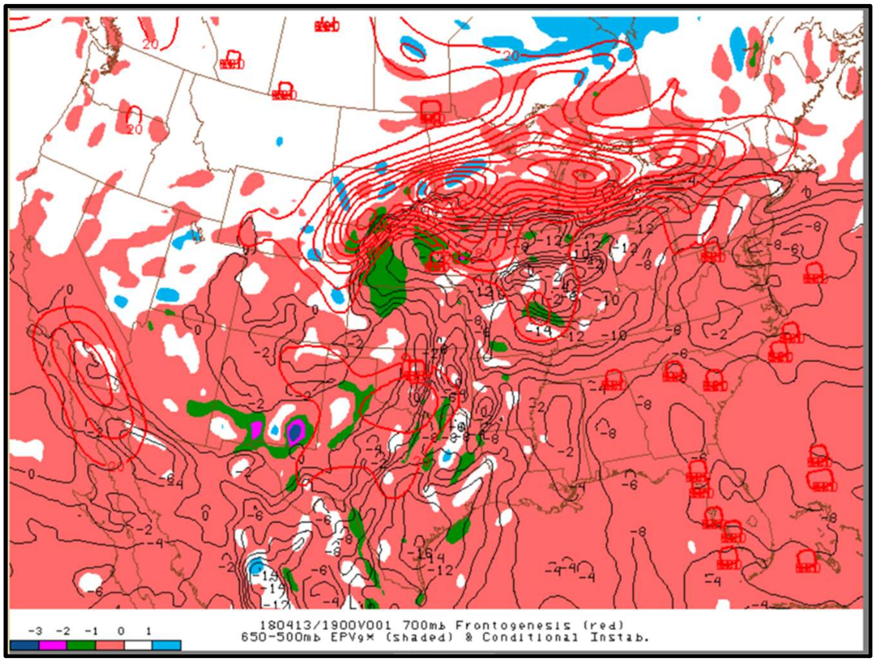


Figure 4.54: Frontogenesis (red) is occurring at 850 hPa at 1900 UTC 13 April and areas of EPVg* and conditional instability at 800-750 hPa. (SPC 2019)

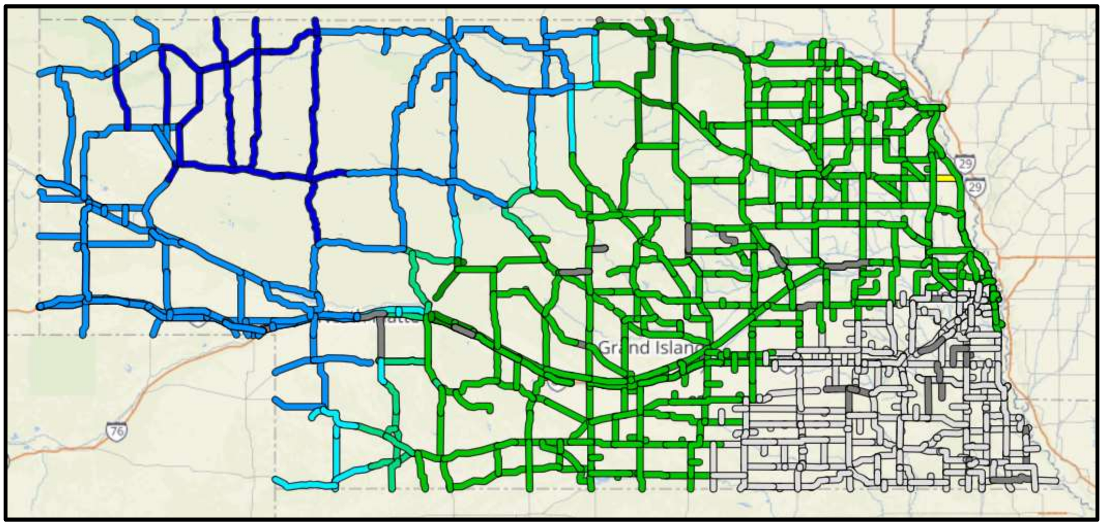


Figure 4.55: Analysis of conditions at 1900 UTC 13 April from the NDOT-MDSS (Colors correspond to legend in January Synoptic) (WebMDSS™ 2018)

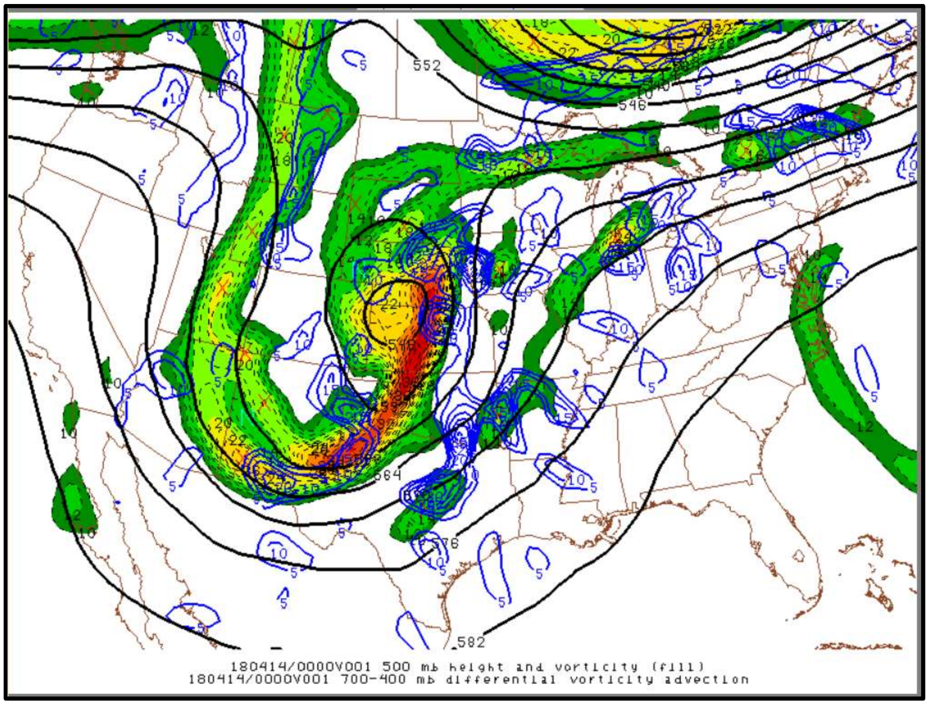


Figure 4.56: Vorticity and height at 500 hPa at 0000 UTC 14 April (SPC 2019)

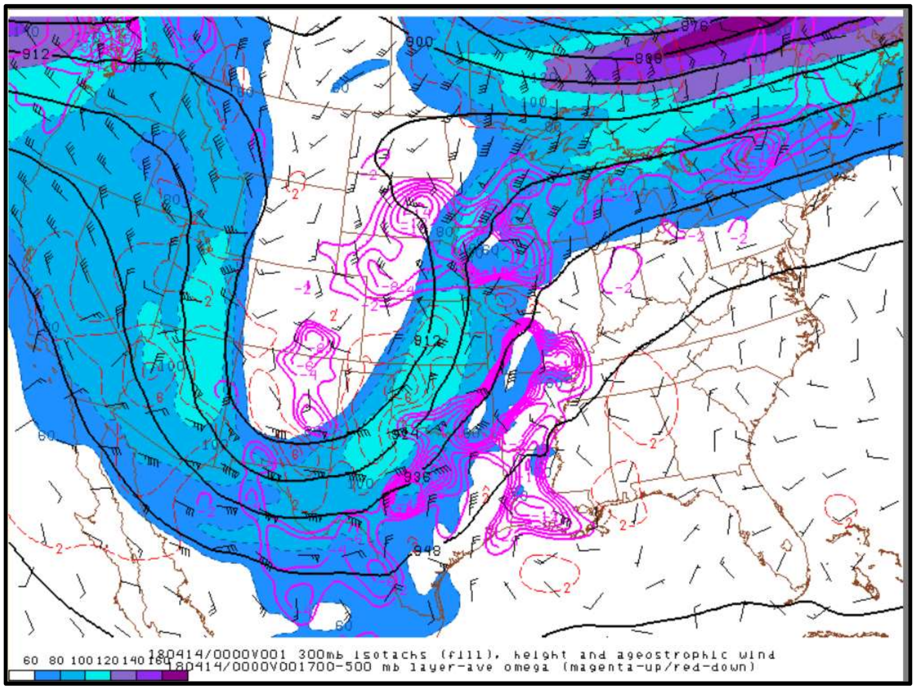


Figure 4.57: Average omega (850hPa) overlaid on the jet stream (300hPa) at 0000 UTC 14 April (SPC 2019)

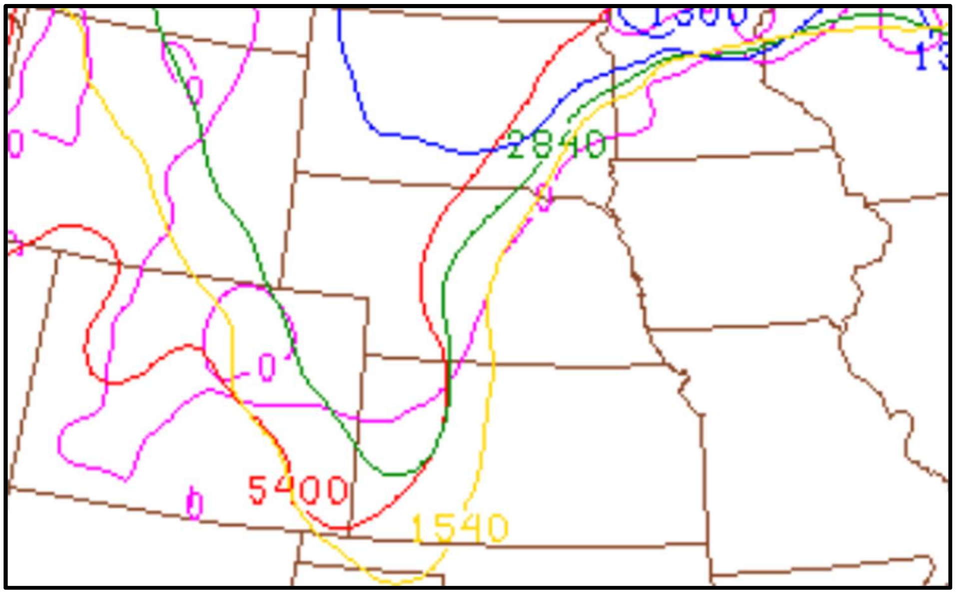


Figure 4.58: Critical thickness lines at 0000 UTC 14 April across 1000-500 hPa (red), 1000-700 hPa (green), 1000-850 hPa (blue), 850-700 hPa (yellow) and the surface 0° temperature (magenta) (SPC 2019)

The critical thickness lines for the layers of 1000-500 hPa, 1000-700 hPa and 850-700 hPa at 0600 UTC 14 April (Figure 4.60), which is where the rain-snow line falls approximately, are all located over east-central Nebraska. The location of the critical thickness lines imply any precipitation falling in the eastern part of the state should be rain, while the western part of the state should be snow, especially since all the critical thickness lines are close together. The rain-snow division shown by the NDOT-MDSS at 0600 UTC 14 April (Figure 4.61) is roughly in the same location, with the appropriate precipitation type occurring in the right areas of the state. The average vertical motion at 0700 UTC 14 April (Figure 4.62) is overlaid on top of the jet stream (300 hPa). The area of enhanced vertical motion over north central and eastern Nebraska aligns with areas of higher vorticity and the jet streak which means that there is sufficient divergence occurring for vertical motion to be possible. At the 300 hPa level at 1200 UTC 14 April (Figure 4.53d), the trough extends across the western part of the United States with a jet streak situated over the central states. The placement of the jet streak allows for divergence aloft over Nebraska as the storm moves through. Divergence aloft also suggests that there is convergence at the surface which favors lift. Divergence aloft is a necessary ingredient for strong Colorado low type storms, which the April event was.

By 0900 UTC 14 April (Figure 4.63), there was a large area of high levels of frontogenesis centered directly over northeastern Nebraska. The frontogenesis is also accompanied by optimal amounts of EPVg*. At approximately the same time the frontogenesis was occurring over northeastern Nebraska, the NDOT-MDSS was showing heavy snowfall in the area (Figure 4.64). At 0900 UTC, eastern Nebraska has the highest precipitable water content in the lowest 400 hPa of the atmosphere with 1.5 cm (0.2 in)

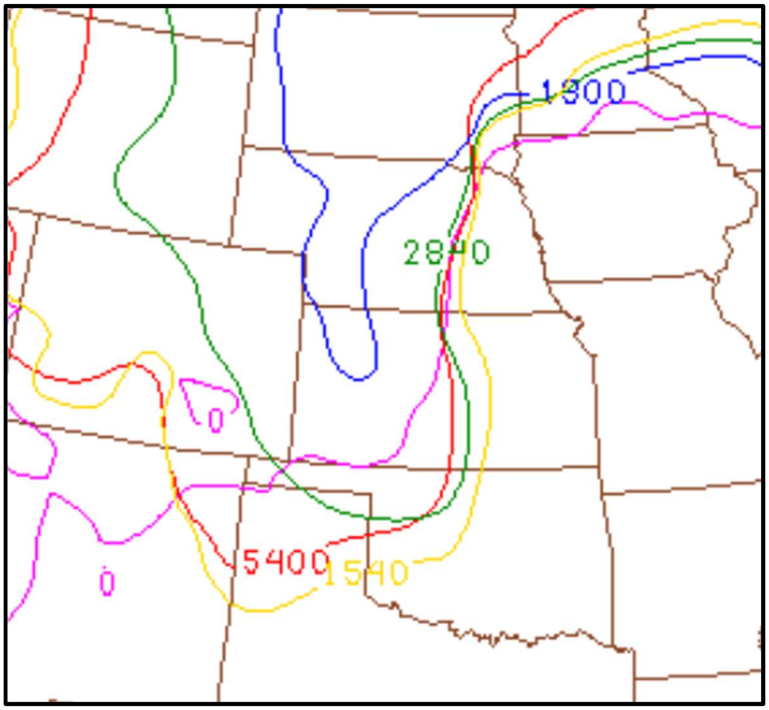


Figure 4.60: Critical thickness lines at 0600 UTC 14 April across 1000-500 hPa (red), 1000-700 hPa (green), 1000-850 hPa (blue), 850-700 hPa (yellow) and the surface 0° temperature (magenta) (SPC 2019)

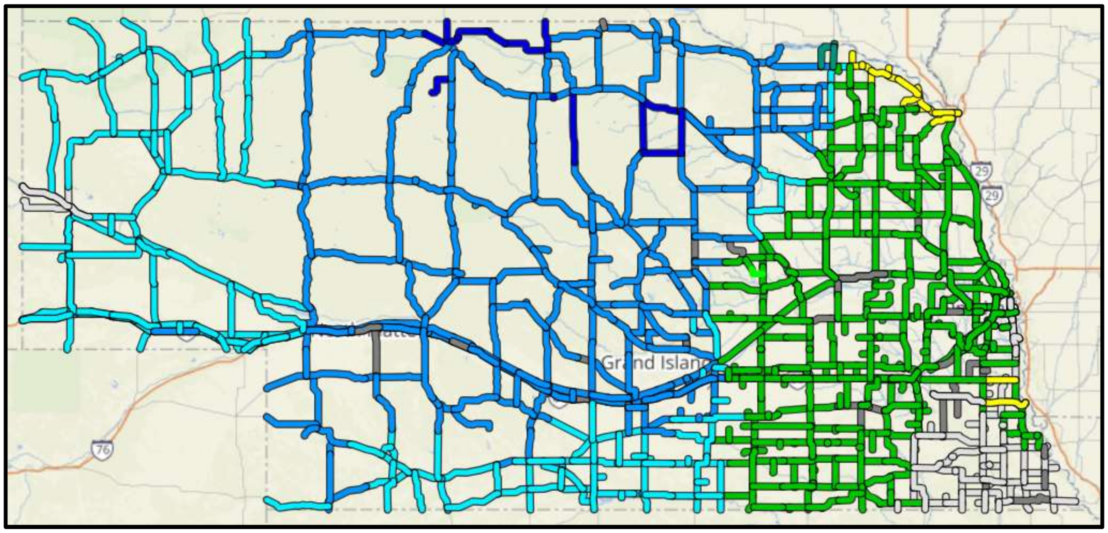


Figure 4.61: Analysis of conditions at 0600 UTC 14 April from the NDOT-MDSS (Colors correspond to legend in January Synoptic) (WebMDSS™ 2018)

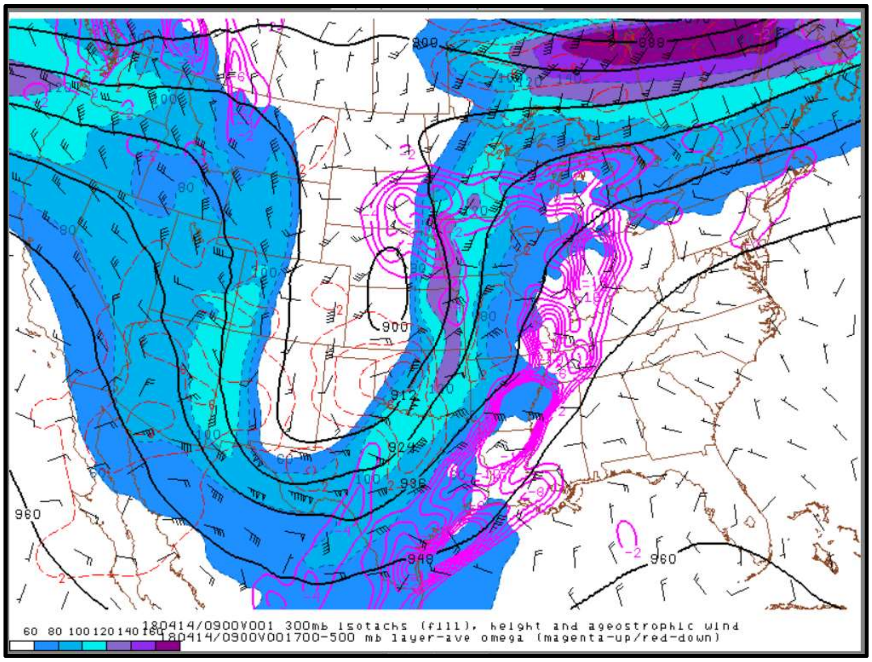


Figure 4.62: Average omega (850hPa) overlaid on the jet stream (300hPa) at 0700 UTC 14 April (SPC 2019)

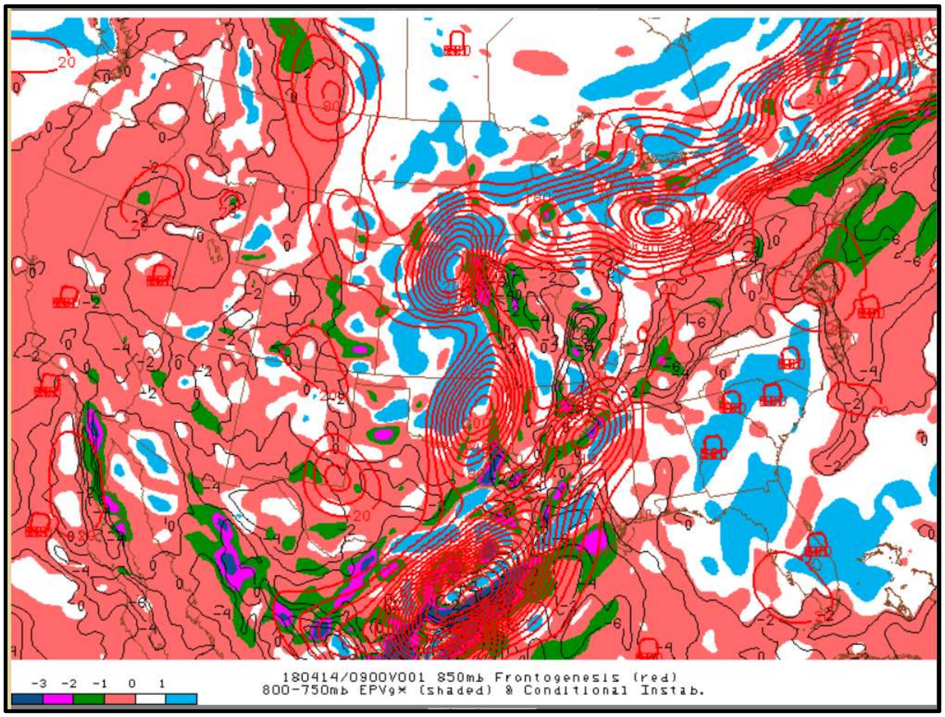


Figure 4.63: Frontogenesis (red) is occurring at 850 hPa at 0900 UTC 14 April and areas of EPVg* and conditional instability at 800-750 hPa. (SPC 2019)

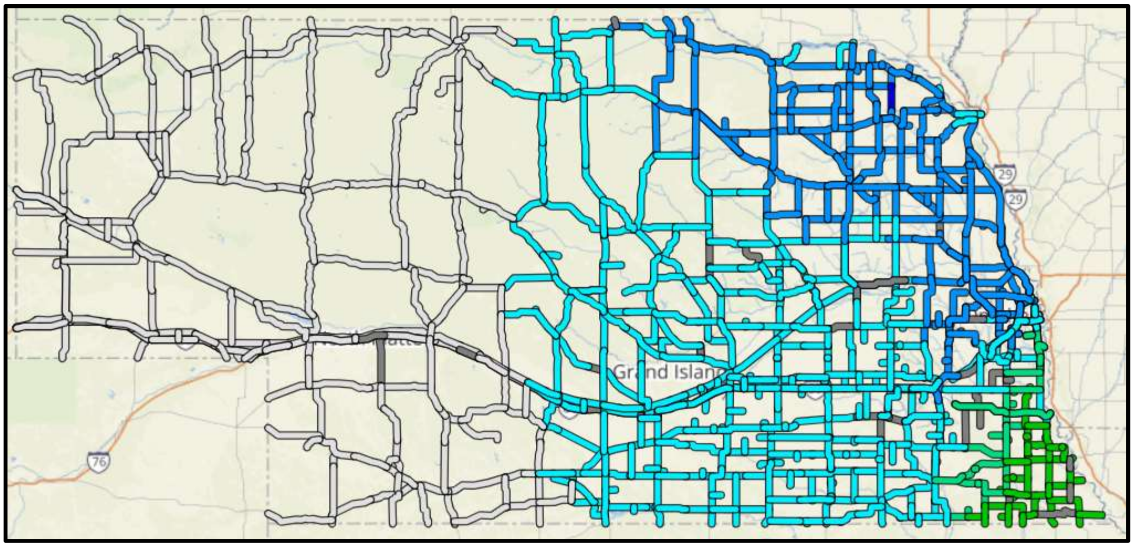


Figure 64: Analysis of conditions at 0900 UTC 14 April from the NDOT-MDSS (Colors correspond to legend in January synoptic) (WebMDSS™ 2018)

(Figure 4.65). Eastern Nebraska is receiving mostly rain. Central Nebraska has precipitable water values of 0.76-1.3 cm and is receiving snowfall. The highest precipitable water values are found along the cold front that runs through the Mississippi Valley (Figure 4.66). The shape of the storm seen in visible satellite imagery is a comma shape which means that mid-latitude cyclone has begun to occlude.

The critical thickness line at 1800 UTC 14 April (Figure 4.67) can be seen all the way down into the Texas panhandle. The placement of the critical thickness lines indicates that the precipitation type for the majority of Nebraska is expected to be snow except for potentially the southeastern corner of Nebraska. The image that the NDOT-MDSS provides for 1800 UTC 14 April (Figure 4.68) verifies that there is snow taking place in most parts of the state besides southeastern Nebraska. The rain that is falling in southeastern Nebraska could be due to the critical thickness line of 1300 m that represents the 1000-850 hPa layer that is hovering over the southeastern part of Nebraska. The critical thickness line not quite reaching southeastern Nebraska indicates that the layer between 1000-850 hPa is above freezing. This would allow for melting of the ice crystals, leading to rain in the area. These lines do not align quite as well as the critical thickness lines from 0600 UTC, so using the critical thickness of the layers might not be quite as accurate in predicting where the rain-snow line will fall. The freezing line at 1800 UTC 14 April (Figure 4.69) shows the vicinity where the rain-snow line should be. The line is in approximately the same area where the critical thickness lines fall (Figure 4.67). The NDOT-MDSS map exhibiting the analysis at the surface at 1800 UTC (Figure 4.68) shows that the far southeastern part of Nebraska is still experiencing rain while the rest of the state is experiencing snow. The vorticity is now maximized over

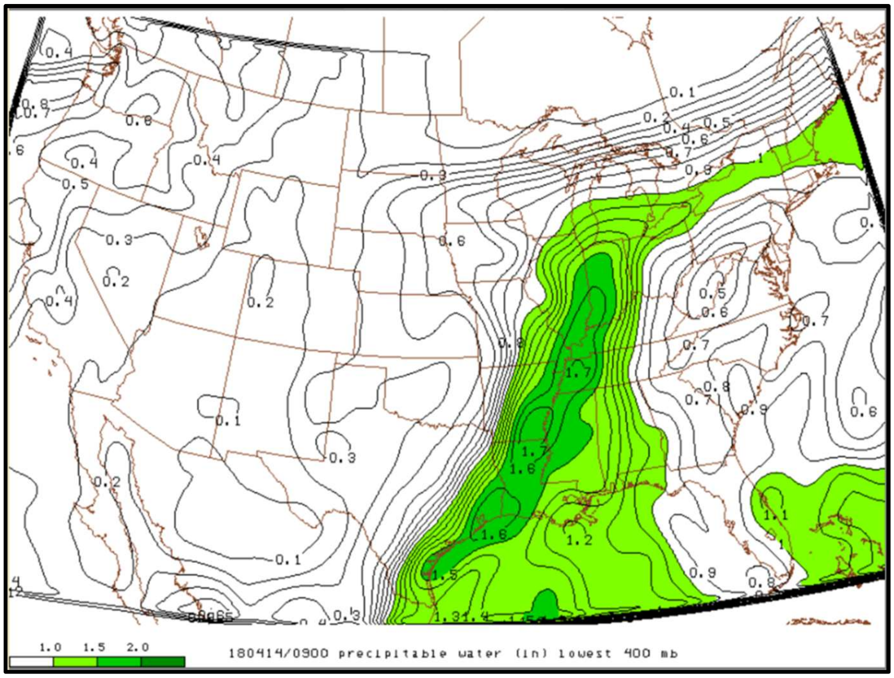


Figure 4.65: Precipitable water content in the lowest 400 hPa at 0900 UTC 14 April (SPC 2019)

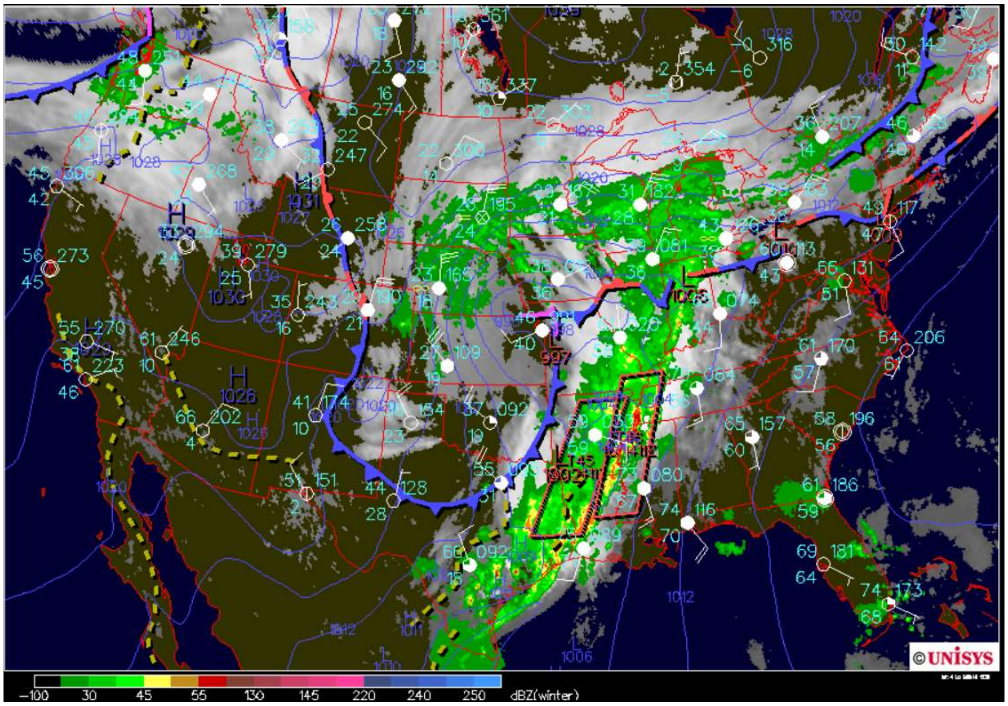


Figure 4.66: Satellite surface map of the United States at 0930 UTC 14 April (Unisys 2018)

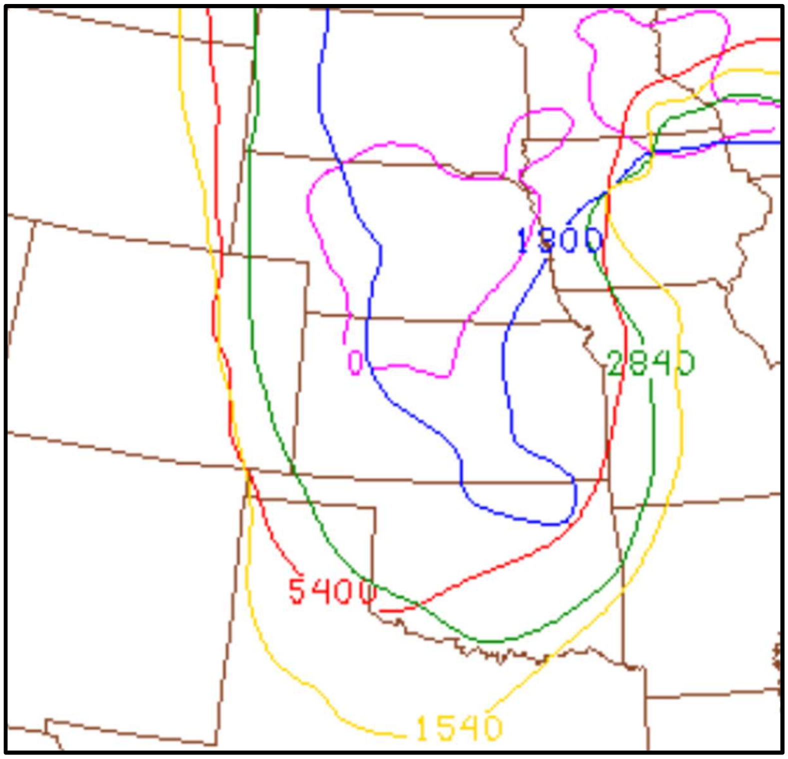


Figure 4.67: Critical thickness lines at 1800 UTC 14 April across 1000-500 hPa (red), 1000-700 hPa (green), 1000-850 hPa (blue), 850-700 hPa (yellow) and the surface 0° temperature (magenta) (SPC 2019)

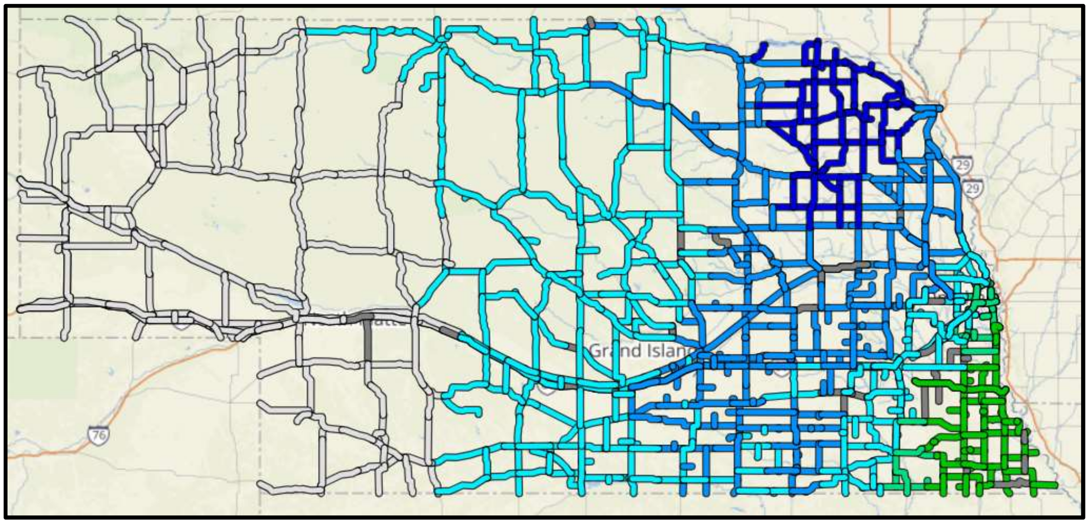


Figure 4.68: Analysis of conditions at 1800 UTC 14 April from the NDOT-MDSS (Colors follow legend in January Synoptic) (WebMDSS™ 2018)

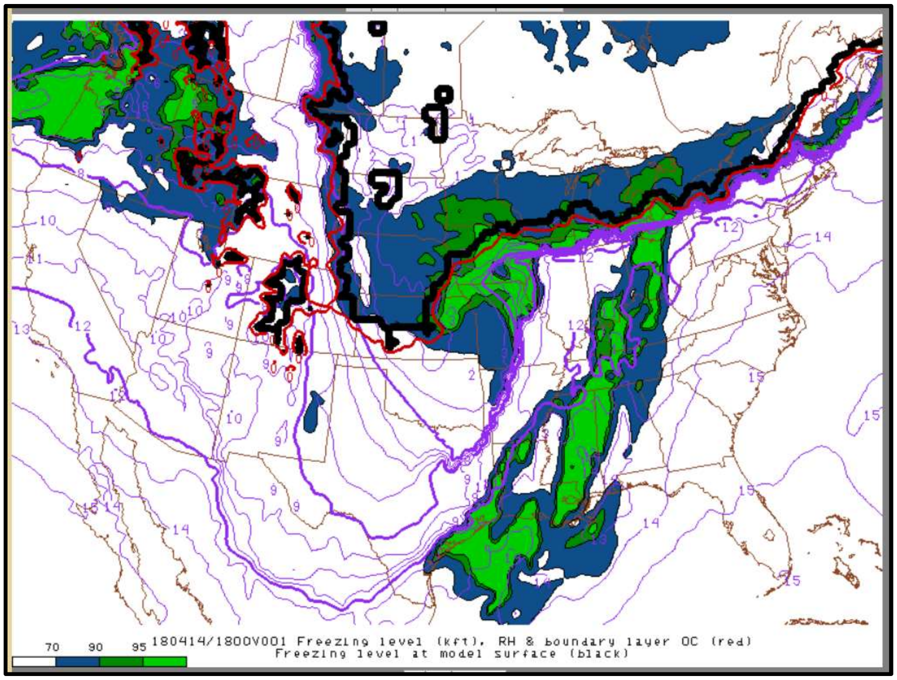


Figure 4.69: Freezing level at the surface (black) at 1800 UTC 14 April. It also shows the relative humidity and boundary layer 0°C line (red) (SPC 2019)

Kansas and is very concentrated from Missouri down to Texas (Figure 4.70). The jet streak, located at 300 hPa, is co-located with areas of vorticity as well as areas of rising motion (Figure 4.71).

4.4 April NDOT-MDSS Results

The predicted location of the low pressure center for 14 April 2018 (Figure 4.72) was modified during the preceding week before major impacts were seen. The forecasted location at 7 days out was over northwestern Iowa with a strong pressure gradient already in place. Over the next few days, the forecasted location of the low's center only experienced minor shifts to a slightly more southern location in Iowa. The pressure gradient remained strong through these shifts. The observed center at 1330 UTC 14 April 2018 was over northeastern Kansas (Figure 4.72f). The pressure gradient had weakened somewhat as well. The precipitation probabilities (Figure 4.73) 7 days out were correct in the location of the precipitation with only minor variations. As the confidence increases, the probabilities increase and the comma shape of the mid-latitude cyclone is very prominent. Northeastern Nebraska has the highest probability to receive precipitation from the storm.

The forecasts from the NWS offices (Tables 4.6-4.10) predicted that there would be a winter storm that would impact the area 7 days out. The confidence of the offices that a storm will be impacting the area so far out corresponds well with how the location of the center of the low having only minor shifts over time in the model outputs. Winter storm watches were issued relatively early due to the confidence in the forecasts. The NWS offices were also extremely confident that high winds would be a major threat to

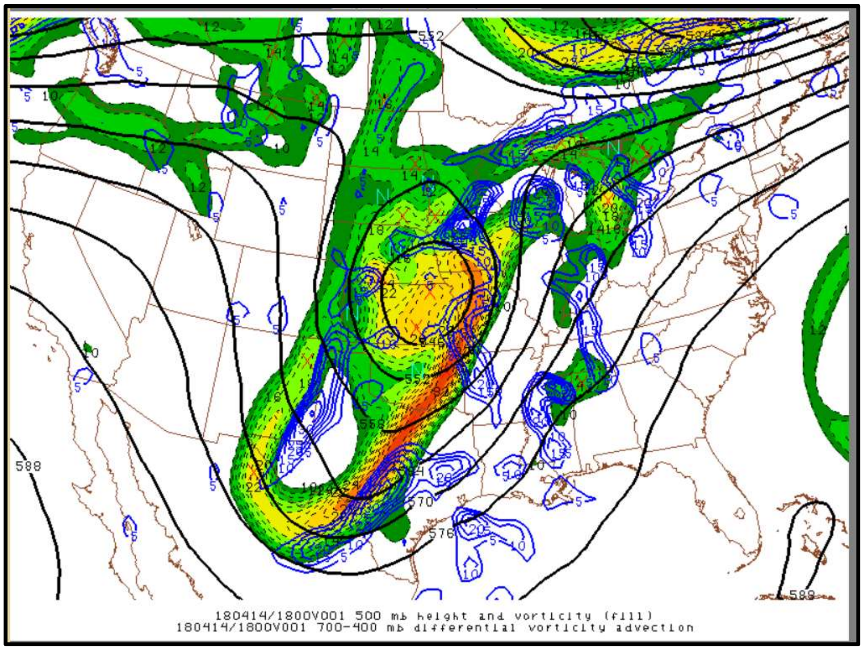


Figure 4.70: Vorticity and height at 500 hPa at 1800 UTC 14 April (SPC 2019)

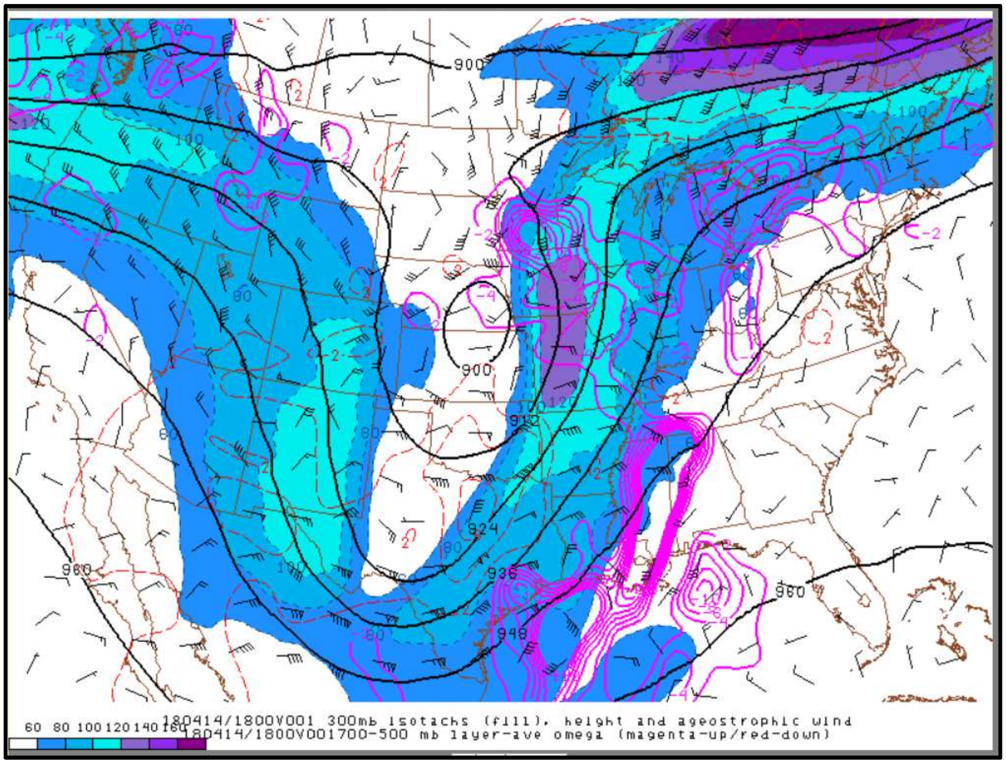


Figure 4.71: Average omega (850 hPa) overlaid on the jet stream (300 hPa) at 1800 UTC 14 April (SPC 2019)

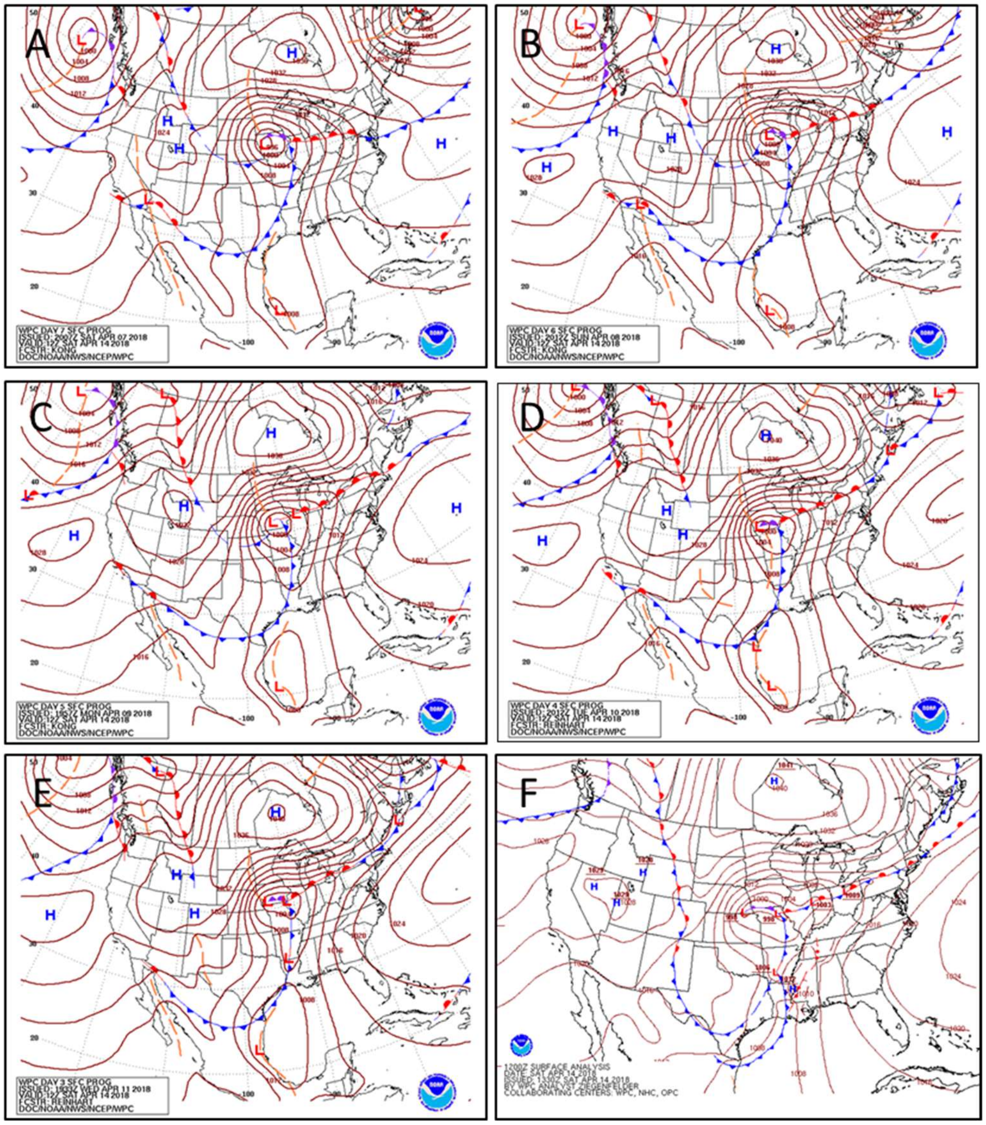


Figure 4.72: The progression of the forecast for the winter storm that occurred on 14 April 2018. A) 7 April 2018, surface map forecast 7 days out. B) 8 April 2018, surface map forecast 6 days out. C) 9 April 2018, surface map forecast 5 day out. D) 10 April 2018, surface map forecast 4 days out. E) 11 April 2018, surface map forecast 3 days out. E) 14 April 2018, surface map of actual location of the center of the low during the winter storm (WPC 2019).

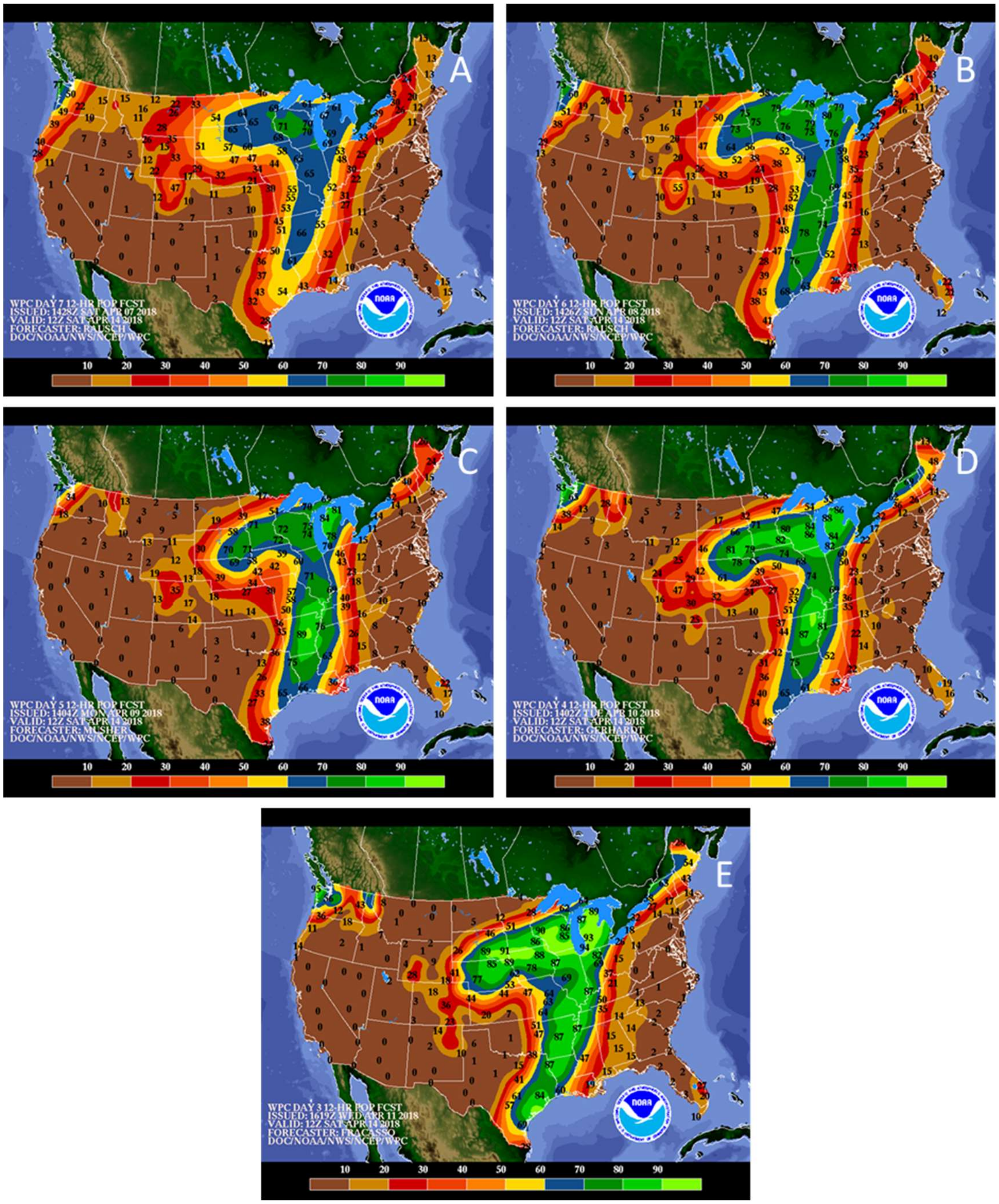


Figure 4.73: The progression of the forecast for the winter storm that occurred on 14 April 2018. A) 7 April 2018, precipitation probability forecast 7 days out. B) 8 April 2018, precipitation probability forecast 6 days out. C) 9 April 2018, precipitation probability forecast 5 day out. D) 10 April 2018, precipitation probability forecast 4 days out. E) 11 April 2018, precipitation probability forecast 3 days out (WPC 2019).

Table 4.7: NWS Sioux Falls forecast for the April storm

Date April	Time UTC	Forecasted Snow Totals	Watches/Warnings	Comments
8	1607	N/A	No	There is a strong system coming into the Central Plains. The timing is uncertain. Temperatures are trending below normal leading up to the storm.
9	1558	N/A	No	Models are showing a deep trough coming through the region fri/sat. There is also some potential for convection in the area with it. Potential for blizzard conditions with this storm.
10	1650	N/A	No	The timing of the storm is starting to line up with the faster GFS solution being eliminated. All models are showing heavy precipitation and strong winds. Some convection may occur as well.
11	1605	N/A	No	Potential for convection on Thursday before the storm arrives on Fri/Sat. Snowfall rates of over an inch/hour along with strong winds will most likely come with this storm. The location of the heaviest bands are uncertain. There is a threat of freezing rain but that depends on the surface temperatures.
12	343	3-15” with a light glaze of ice	Winter Storm Watch	Predicted wind speeds have increased. Models are agreeing on the overall forecast. As the storm matures full, rates of over 2in/hr could be seen. This will combine with strong winds to decrease visibility.
12	1558	BW-4-16” Winter Storm Watch-3-5” with light glaze of ice	BW, Winter Storm Watch	Winds will start to increase as the pressure gradient strengthens. Thunderstorms are expected to occur in northwest Iowa with CAPE values upward of 2000J/kg. Possible ice accumulations will be a threat. Main issue is the blizzard conditions through most of the CWA.
13	453	BW-5-16” Winter Storm Watch-3-5’ with light glaze of ice	BW, Winter Storm Watch	Conditions will be deteriorating throughout the day, starting with the threat of thunderstorms which then will transition into blizzard conditions. There is a high confidence in heavy snow occurring in the CWA. Models are less confident in the snow amounts and the location of the heavy bands. Snowfall rates of 1-2” are expected. Snow totals have increased and moved eastward.
13	1526	BW-4-16”	BW	Thunderstorm development is expected in the evening in Iowa. Sleet may become a threat if the models are correct about a warm layer aloft. Intense snowfall rates will occur with this storm. The strong pressure gradient will bring strong winds and blizzard conditions.
14	402	BW-2-15”	BW	Lots of moisture being transported into the region today. Blizzard conditions are expected throughout the CWA today. There is still a threat of sleet, mainly in the east. Major impacts will be reduced visibility and lots of snow accumulation
14	1535	BW-Additional snow accumulations of 1-7”	BW	Blizzard is ongoing in the area. The system is leaving the area slower than expected so snow totals have been raised. Pressure gradient is still strong so high winds are still a threat.

Table 4.8: NWS Omaha forecast for the April storm

Date April	Time UTC	Forecasted Snow Totals	Watches/Warnings	Comments
8	259	N/A	No	There is potential for thunderstorms on Thursday. A threat of a strong cyclone is in place for the coming weekend.
9	257	N/A	No	Models are in good agreement that there will be a system affecting the area over the weekend. They are less confident in the smaller details of the storm.
10	351	N/A	No	Thunderstorms are expected to precede the winter storm. High winds are now a threat. Rain will change to moderate to heavy snow in some areas.
11	358	3-12”	Winter Storm Watch	As the storm moves closer, the intensity of the threat of high winds and heavy snow increases. Prior to the storm, thunderstorms may be bringing different types of threats such as hail and tornadoes. Due to the high pressure forming to the north, the pressure gradient will be pretty strong.
12	416	3-12”	Winter Storm Watch	Freezing rain is no longer a threat for the approaching storm. Thunderstorms are still predicted to take place over the CWA prior to the storm. Depending on the time of the transition from rain to snow, the totals could be lowered. Mention of blizzard conditions.
12	339	BW-4-10” Winter Storm Watch-1-3”	Winter Storm Watch, Blizzard Warning	The large pressure gradient will be accompanied by fire conditions and potential for severe storms on Friday. Blizzard conditions will be seen across much of Nebraska. Northeast Nebraska could see very heavy snow, however, the rest of the CWA could experience possible blizzard conditions.
13	333	BW-3-14” Winter Storm Watch-2-4” with	Blizzard Warning, Winter Storm Watch	Threat of Severe weather will be here throughout the day. Once the event transitions to a winter storm, the heaviest accumulations will be in northeast Nebraska. There is still not much confidence about the forecast for southeast Nebraska.
13	1559	WS Warning-2-4” BW-3-14” WWA-0-2”	Winter Storm Warning, BW, WWA	Severe storms are still lingering in the Snowfall amounts did trend up slightly. Visibility is expected to decrease rapidly with the combination of high winds and heavy/blowing snow.
14	330	WS Warning-2-5” BW-4-10” of add. acc. WWA-2-4”	Winter Storm Warning, BW, WWA	Temperatures have cooled down more than expected. There is a slight chance of freezing rain but will not be a major impact. Could see winds gusting up to 50kts.
14	1426	WWA-1-3’ BW-1-3” of additional snow	BW, WWA	Accumulations have decreased a bit due to sleet that has been mixed in with the snow this morning. Winds are still gusting up to 45mph, making taking measurements difficult. All precipitation is expected to end on Sunday morning.

Table 4.9: NWS Hastings forecast for the April storm

Date April	Time UTC	Forecasted Snow Totals	Watches/Warnings	Comments
8	2033	N/A	No	Models are in agreement that a closed low will enter the region in the coming weekend. High winds may bring fire weather impacts and the system may bring snow.
9	2058	N/A	No	The system could bring thunderstorms to the area Thursday night. There will be cold air accompanying this system along with the chance of snow. The track is still uncertain.
10	2120	N/A	No	The system is expected to bring in relatively cold air with highs only reaching the mid-20s. Thunderstorms are still a threat on Thursday evening. Snow will take over the CWA on Saturday morning but heavy snow will be to the north. Strong winds will also occur with this storm.
11	1958	3-5" with a light glaze of ice	Winter Storm Watch	There is mention of blizzard conditions associated with the low. There are only a few inches of snow forecasted, however, with winds gusting up to 50mph, visibility will decrease greatly.
12	0941	3-6"	Winter Storm Watch	Winter storm to impact the CWA Friday through Saturday. Strong winds and snowfall are the main threats. Winds could gust up to 50mph. The storm track has shifted slightly south so snow totals farther south have increased.
12	2152	Winter Storm Warning- 2-5" BW-4-10"	Winter Storm Warning, BW	Cyclogenesis is occurring over Colorado at this time. The track hasn't shifted much and high winds and heavy snow is expected on Friday evening through Saturday. Thunderstorms are becoming less likely in the area.
13	1039	WWA-1-3" BW-2-8"	WWA, BW	There is a relatively tight snowfall gradient so any minor shift to the track could change snowfall totals. Winds will be gusting over 50mph. the storm should dissipate in the afternoon on Saturday.
13	2051	BW-3-7" WWA-1-3"	BW, WWA	The storm is on the sale track and the snow totals have remained the same. Winds will increase tonight with gusts reaching 60mph in some areas. Plenty of moisture in the atmosphere so models are in agreement about the snowfall amounts.
14	1040	BW-1-3", 6-9" WWA-1-3" with light ice accumulations	BW, WWA	The most certain aspect of this storm has been the winds. Snowfall totals have been difficult to predict. Because of some entrainment of dry mid-level air, there is now more of a chance of a wintry mix in some locations. Snow will dissipate in the evening hours.
14	2120	BW-additional snowfall of 2" WWA-additional snowfall of 1"	BW, WWA	At this time, the intensity of the snowfall is decreasing as the storm tracks east. There is still potential for blowing snow since the winds are still present. Cold temperatures will follow this storm.

Table 4.10: NWS North Platte forecast for the April storm

Date April	Time UTC	Forecasted Snow Totals	Watches/Warnings	Comments
8	2040	N/A	No	For the weekend, the models are agreeing that there is a disturbance coming through the area. High winds will be associated with this disturbance. Rain will change over to snow at some point on Friday.
9	2125	2-5”	No	Mention of light accumulating snow. High winds are expected to affect the region. This event will take place on Friday to Saturday afternoon.
10	2115	3-6”	Winter Storm Watch	A winter storm is going to be moving into the region on Thursday until late Saturday afternoon. There is moderate confidence for when the storm will impact the area along with the snow totals. There is much higher confidence with the high winds that are predicted.
11	2116	3-10”	Winter Storm Watch	Potential for blizzard conditions due to high winds. Gusts could reach up to 55mph. Confidence with snow amounts is increasing but melt on impact could decrease them. The lee-side cyclone will develop over the Rockies on Thursday night.
12	0853	5-14”	Winter Storm Watch	The winter storm is now a major threat to most of the CWA with blizzard conditions almost certain. There are only minor inconsistencies between models with the location, timing and strength. Even with these inconsistencies, the forecast for a crippling winter storm is strong.
12	2122	7-17”	BW	There will be a strong frontogenesis band set up over parts of the CWA. This will cause high snow rates. The heavy snow rates will be accompanied by very high wind gusts. The storm will start to dissipate on Saturday morning
13	0836	6-15”	BW	There will be some mid-level instability present which may produce thunderstorms. The winds will start increasing as the day goes on and the precipitation will change over to snow. Pressure will start to rise throughout the day as the storm starts to weaken. Whiteouts are expected.
13	2002	6-15”	BW	Precipitation has started to transition to snow. Road closures are already occurring. Wind gusts are expected to pick up along with snow rates. Snow is predicted to dissipate on Saturday afternoon.
14	0841	Additional accumulations: 0-5”	BW	Heavy snow is being seen across the CWA due to a band that has set up over the area. Cloud and snow cover will keep the temperatures relatively low throughout the day. High winds will remain in the area until nighttime.
14	2017	Additional accumulations: 0-2”	BW	The low has mostly moved out of the CWA. Some precipitation is still lingering. High winds are still a threat to the area and may cause areas of blowing snow.

the area, due to the tight pressure gradient that models were predicting. Blizzard warnings were issued at 1600 UTC 12 April from both Sioux Falls and Omaha as a result of the combination of snow and high winds. North Platte and Hastings issued blizzard warning for parts of their CWA at 2200 UTC 12 April. The main impacts from the storm were expected to occur on 13 April to 14 April over the state of Nebraska. When the storm came through the area, the lowest pressure that was reached by the system was 988 hPa at 0500 13 April (Figure 4.74) over west-central Kansas.

The forecast for the April storm did not change too much over the 7 prior to the event and this can be seen in the NDOT-MDSS forecasted total snow accumulations. The evolution of the forecasted total snow accumulations for each route within the NDOT-MDSS (Figure 4.75) shows slight variations as the storm moves toward Nebraska. Routes 1, 2, 3, and 8, all had similar forecasts with Route 3 predicted to receive the highest total snowfall accumulation of approximately 25 cm. Route 6 and 7, also had very similar forecasts which is expected due to their similar geographic locations. The central part of Nebraska had the highest snowfall accumulation analysis and were well represented by the NDOT-MDSS forecasts.

Routes 4 and 5, which run parallel to one another, had a much higher forecasted total snowfall accumulation than what actually occurred. Big decreases in forecasted total snowfall accumulation took place 18-12 hours prior to the end of the storm in each route. Route 4 saw a decrease of approximately 11 cm while Route 5 saw a decrease of 8.6 cm. Route 4 saw only 6.6 cm while Route 5 saw 10.7 cm. Since these routes are located parallel to each other, it is expected that they have the same or extremely similar forecasts. It was originally hypothesized that since the NDOT-MDSS, compaction, melt,

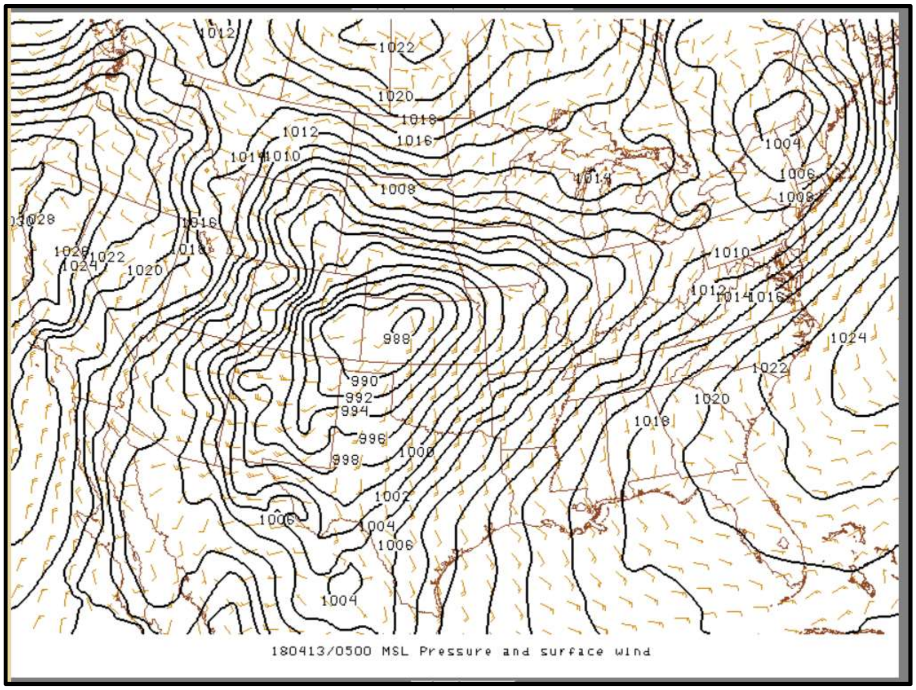


Figure 4.74: Mean sea level (MSL) pressure at 0500 UTC 13 April (SPC 2019)

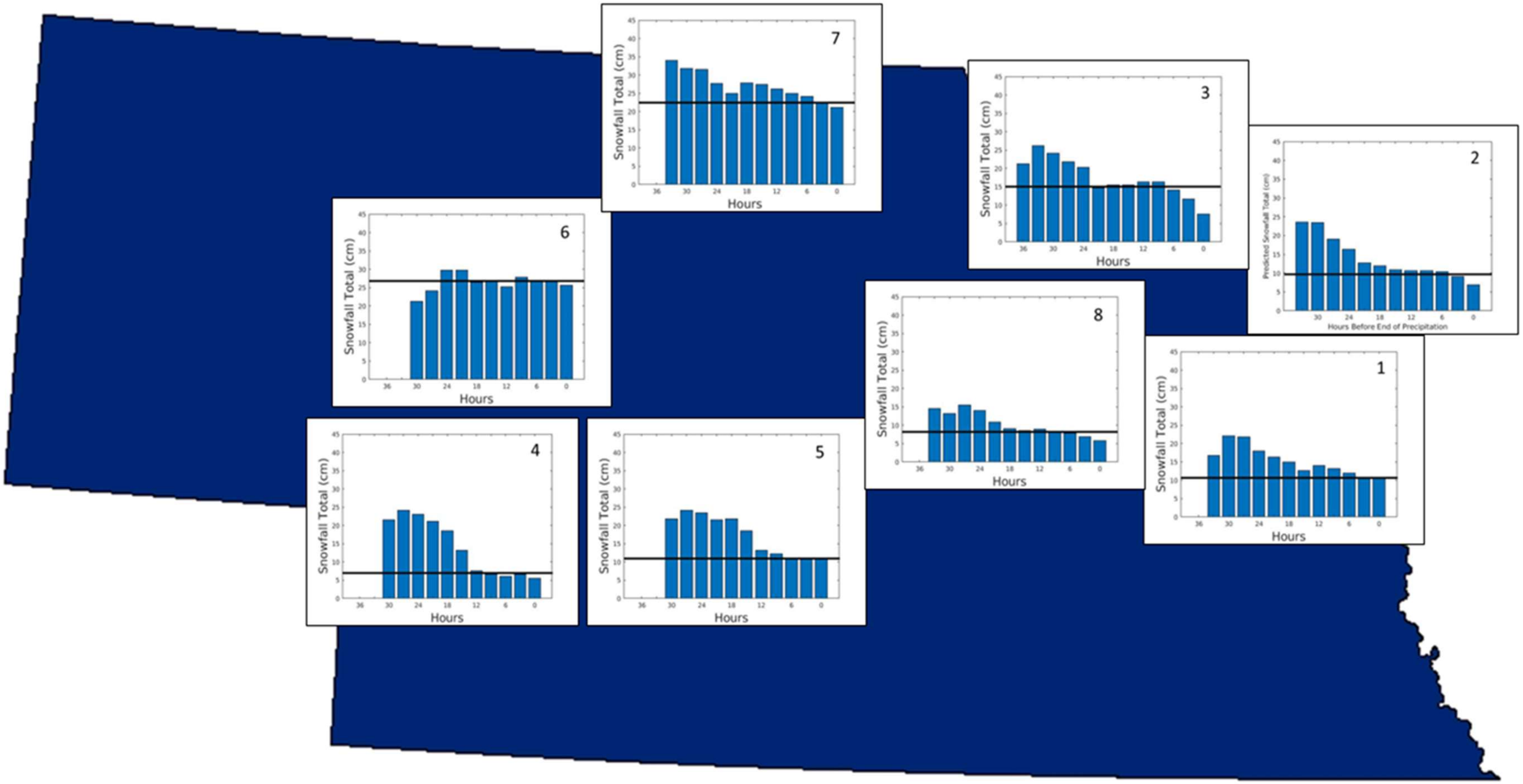
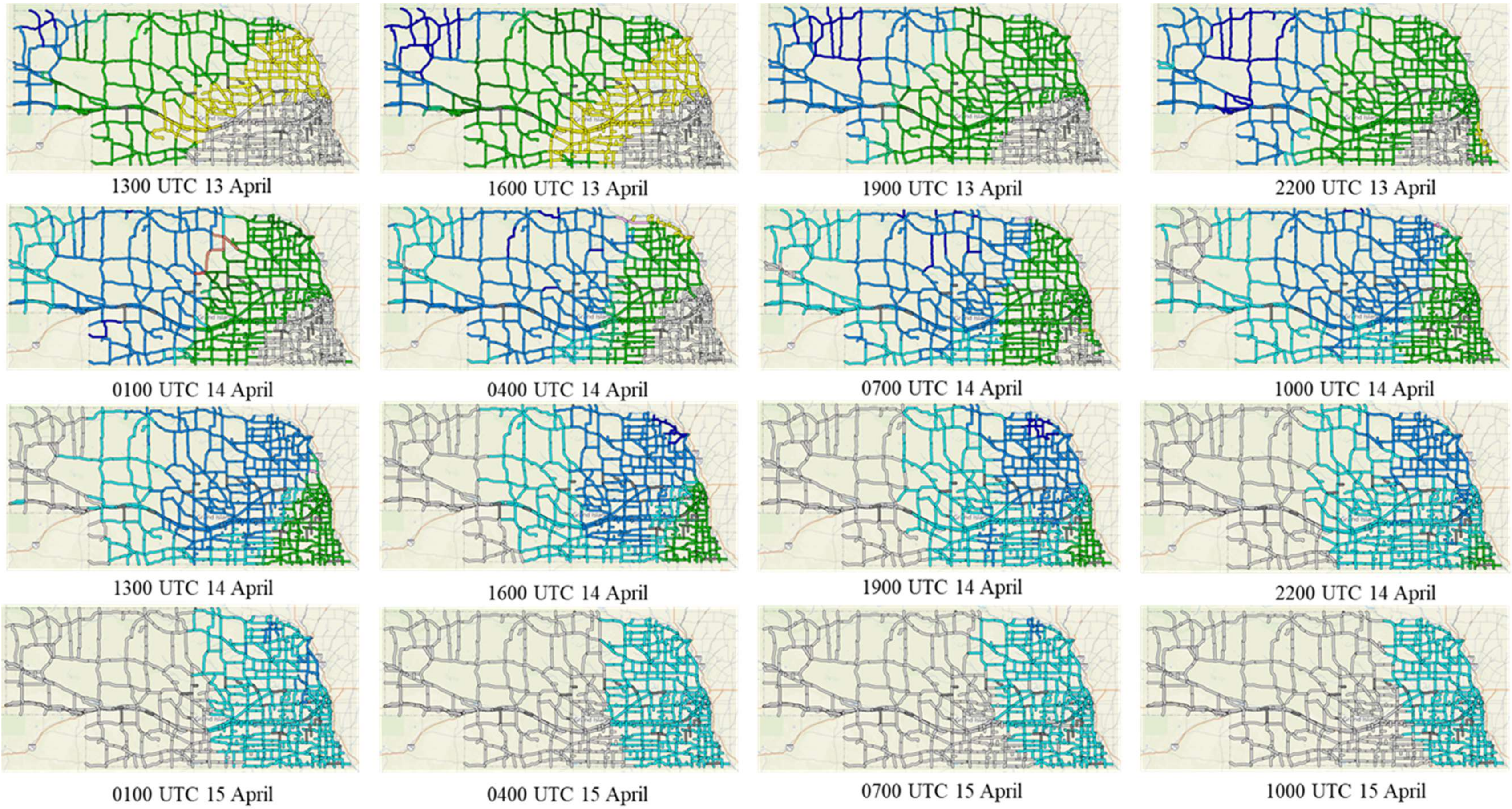


Figure 4.75: Forecasted total snowfall accumulation from the NDOT MDSS (blue) as the storm progresses for each route in their respective location throughout Nebraska during the April storm and the analysis of the total snowfall accumulation by the NDOT MDSS (black)

and treatment are taken into account, that Interstate 80 (Route 5) would see less total snow accumulation than US-30 (Route 4) due to the higher LOS leading to more treatment; however, Interstate 80 actually saw the higher total snowfall amount of the two routes. With a difference of 4 cm, there may have been an error with the model within the NDOT-MDSS. The snowfall gradient was looked at to determine if there was an acute snow gradient in the area; however, there was no snow gradient that could have produced that much of a difference between the two routes. Route 4 saw only 3 hours of snowfall rates exceeding 0.75 cm hr^{-1} while Route 5 saw 6 hours exceeding that snowfall rate. The other routes had a relatively consistent forecast for total snowfall accumulation. All routes, with the exception of Route 6, did see a decrease in the forecasted total snowfall accumulation, although most decreases were minor. The reason for the decrease in Routes 4 and 5 does not appear to be a timing issue or an issue with the transition from rain to snow. The rain ended and transitioned to snow within an hour of when the NDOT-MDSS forecasted it to. The snow rate decreased earlier than was expected. The heavier snow rates of over 0.75 cm hr^{-1} were forecasted to end at 1300 UTC 14 April; however, they ended at approximately 0700 UTC 14 April according the NDOT-MDSS. This would have led to decreasing snowfall totals in both of these routes.

The snow starts in the far western part of the state within the NDOT-MDSS at 1300 UTC 13 April while rain and thunderstorms occur elsewhere except the southeastern portion of the state (Figure 4.76). As the storm progresses, the thunderstorms start to dissipate around 1900 UTC 13 April and the rain changes over to snow. Heavy snow lingers in the northeastern region of Nebraska until approximately 1600 UTC 15 April when all precipitation has ended across Nebraska. North central



1300 UTC 13 April
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Figure 4.76: Progression of the April Storm through time using the current conditions of each segment (WebMDSS™ 2018)

1300 UTC 15 April

1600 UTC 15 April

Figure 4.76 (con't) Progression of the April Storm through time using the current conditions of each segment (WebMDSS™ 2018)

Nebraska had the highest snowfall totals for this event (Figure 4.76). The analysis of conditions provided by the NDOT-MDSS have a good handle on the locations of precipitation and where the heaviest snow was occurring during the storm. With this storm, there was rain ahead of the snow so the road maintenance crews had to take that into account where they were pre-treating the roads. The treatment recommendations for the routes consisted of mostly patrolling areas and plowing them if necessary.

The accuracy of the start time of an event is crucial to road maintenance crews for chemical application on the roadways. During the April storm, the NDOT-MDSS forecasted start times were within 5 hours of the NDOT-MDSS analysis of the start times in Routes 2, 3, 4, 5 and 8 (Table 4.11). Routes 6 and 7 had 5-6 hours difference in their forecasted and their analysis of the start times within the NDOT-MDSS. The biggest difference was Route 1 with a 9 hour difference between the forecasted and the analysis of the start times within the NDOT-MDSS. When looking into a reason for why Route 1 had such a large difference in comparison to the other routes, it was noted that the rain transitioned over to snow earlier than was predicted. The early transition led to a much earlier start times analyzed within the NDOT-MDSS than was forecasted. There does not appear to be a link to the geographic location with respect to the difference in start within the NDOT-MDSS. The NDOT-MDSS forecasted start time agreed well with the radar observed start times. The largest difference that occurred was in Route 8 with a 5 hour difference. Routes 1 and 2's The NDOT-MDSS forecasted start time agreed perfectly with the radar observed start time. This result shows that the NDOT-MDSS did an acceptable job of predicting the onset of heavier snow for the April event with only moderate errors in Routes 6 and 7. The NDOT-MDSS analysis of the start times also

Table 4.11: Difference in precipitation start times for April Storm (Hrs)

	NDOT-MDSS Forecasted vs. NDOT-MDSS Analysis	NDOT-MDSS Forecasted vs. Radar Observed	NDOT-MDSS Analysis vs. Radar Observed
Route 1	+9.0	0.0	-9.0
Route 2	+3.0	0.0	-3.0
Route 3	+2.0	-2.5	-4.5
Route 4	+3.0	+2.0	-1.0
Route 5	+3.0	+2.0	-1.0
Route 6	+6.0	+3.0	-3.0
Route 7	+5.0	+4.5	-0.5
Route 8	+4.0	-5.0	-9.0

agreed relatively well with the radar observed start times with the radar observed start times with the exception of Routes 1 and 8. Routes 1 and 8 both saw differences of 9 hours. The NDOT-MDSS analysis of the storm starting much earlier than was observed by radar. All other routes had differences of less than 5 hours. Any differences in start times did not appear to have much relation to the geographic location of the route. Routes 4 and 5 had the same analysis and forecasted start times within the NDOT-MDSS which is expected because they are so close together.

The difference in end times was found between the same variables as the start times (Table 4.12). The accuracy of the forecasted end times within the NDOT-MDSS was comparable to the accuracy of the forecasted the NDOT-MDSS start times. Routes 1, 2, and 3, located in eastern Nebraska, all had major issues with the NDOT-MDSS forecasted versus the NDOT-MDSS analysis of the end times. The differences were all over 5 hours. Routes 4, 5, 6, 7 and 8 all had differences of 4 hours and under, which shows that there was a lot more accuracy with the forecast of end times with these routes. The reasoning behind the major differences observed in Routes 1, 2, and 3 were caused by the storm speeding up when it got to eastern Nebraska. The NDOT-MDSS forecasted that the end time would be much later than was actually reported by NDOT-MDSS, which is why an increase in speed of the system is expected to have occurred. An increase can also be seen when looking at the NDOT-MDSS forecasted versus radar observed end times. There is also a major difference in these variables in Routes 1, 2, 3 and 8, which is also located more to the east than all other routes. The large differences between the NDOT-MDSS forecasted end times and radar observed end times shows that the NDOT-MDSS did not forecast the increase in speed of the system very well. The

Table 4.12: Difference in precipitation end times for April Storm (Hrs)

	NDOT-MDSS Forecasted vs. NDOT-MDSS Analysis	NDOT-MDSS Forecasted vs. Radar Observed	NDOT-MDSS Analysis vs. Radar Observed
Route 1	+9.0	+10.5	+1.5
Route 2	+5.0	+14.0	+9.0
Route 3	+9.0	+17.0	+8.0
Route 4	+2.0	0.0	-2.0
Route 5	+2.0	0.0	-2.0
Route 6	+3.0	0.0	-3.0
Route 7	+3.0	+3.5	+0.5
Route 8	+1.0	+11.0	+10.0

differences for these routes ranged from 10.5 to 17 hours. This is a major inaccuracy. Routes 4, 5, 6 and 7 did not have any major differences between the NDOT-MDSS forecasted end times and radar observed end times, with Routes 4, 5, and 6 having no difference. The increase in speed of the system did not seem to affect the routes located to the west. While Routes 2, 3 and 8 all saw a large difference within the NDOT-MDSS analysis and radar observed end times, Route 1 only had a 1.5 hour difference. With all 4 routes being located in the eastern part of the state, the differences should be relatively similar, yet Route 1 is very different. Light snow occurred in Routes 1, 2, 3, and 8. The snow ended earlier in Route 1. The NDOT-MDSS analysis of the end time aligned well for Routes 1, 4, 5, 6 and 7. The western and central routes were more accurately predicted than the eastern routes, which was most likely caused by the increase in the speed of the system as it approached eastern Nebraska. The difference in the speed could have also had an impact on the forecasted total snow accumulations in the eastern routes as well.

During the April storm, Route 3, the route closest to the KLCG ASOS was once again the most agreeable with the data from the KLCG ASOS (Figure 4.77a). The route that had the least agreement with the data from the KLCG ASOS was Route 1 which is located to the southwest of the airport. Route 1 saw winds that were much lower than what was being reported by the KLCG ASOS. Route 2 followed the same overall pattern as Route 3 and the KLCG ASOS; however, the winds were lower during most hours. The KLCG ASOS reported wind gusts were surprisingly lower during most hours than all three routes. There was no pattern to which route had the highest wind gusts during the event. Hours 30 to 54 from the start of the storm, Route 2 generally had the highest wind gusts while Route 3 did a marginally better job of being in agreement with the KLCG

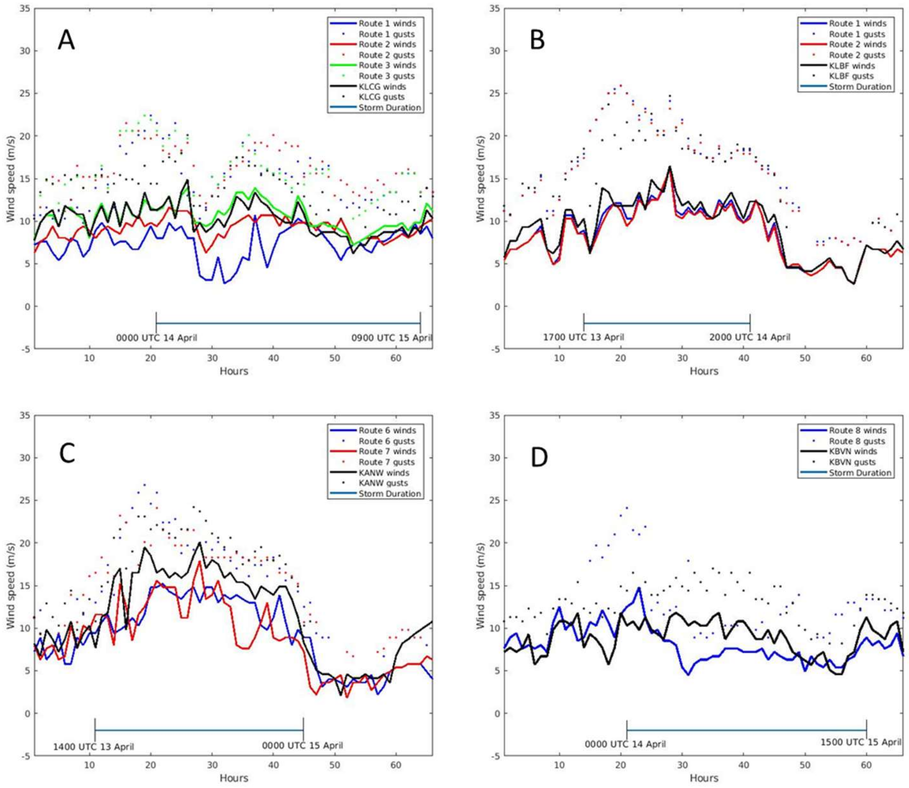

Figure 4.77: Sustained winds and wind gusts in the April storm. A) Route 1 (blue), Route 2 (red), Route 3 (green), and KLCG ASOS station (black). B) Route 4 (blue), Route 5 (red), KLBF ASOS station (black). C) Route 6 (blue), Route (7), and KBVN ASOS station (black). D) Route 8 (blue) and KANW ASOS station (black). The storm duration was plotted (light blue) to show when the storm was taking place per each route.

ASOS. The analysis from Routes 4 and 5 were in agreement within the NDOT-MDSS as well as with the ASOS station at KBLF (Figure 4.77b). There were no major differences in the sustained winds. From 9 to 17 hours out from the start of the storm, the KLBF ASOS was reporting considerably lower wind gusts than what was being outputted by the NDOT-MDSS in both Routes 4 and 5. Nine to ten hours after the storm started in Nebraska, the KLBF ASOS was reporting 7.5-9 m s^{-1} (14.6-17.5 kts) less than what the NDOT-MDSS was outputting. After this period, the wind gusts started to become more similar.

The analysis of the winds by the NDOT MSS at Route 7 shows that there were many spikes in the winds; however, these spikes rarely were greater than the winds reported by the KANW ASOS station (Figure 4.77c). The analysis of the winds by the NDOT-MDSS at Route 6 show a smoother increase and decrease in the speeds in comparison to Route 7. There is one large spike that occurs at 40 hours from the start of the saved storm. The winds and gusts follow the same overall pattern although, during the storm, the winds seem to not be as in agreement as when the storm is over. From the beginning of the saved storm to 13 hours from the start of the saved storm, the winds reported by the KBVN ASOS station and the analysis of the winds by the NDOT-MDSS were in good agreement (Figure 4.77d). The NDOT-MDSS analysis of the winds and gusts in Route 8 then increases by a few m s^{-1} until 27 hours from the start of the saved storm. The KBVN winds increase to greater than the Route 8 wind speed. This occurs for a majority of the time the storm is occurring. At approximately 47 hours from the start of the saved storm, the winds and gusts from the two sources are much more in agreement until the end of the saved storm. During the storm, Route 1 saw a large decrease in the winds and the KLCG ASOS station remained relatively constant while the storm was occurring. Other than Route 1's decrease in wind speed, there were no other notable differences between when the storm was occurring and when it was not.

During the April storm, the temperatures obtained from the KLCG ASOS station, Route 2 and Route 3 were all in agreement (Figure 4.78a). The temperatures in Route 1 were slightly lower and had more erratic changes from 45 to 66 hours from the start of the storm. The reason for the differences in Route 1 is unknown. The temperatures for Routes 4 and 5 were almost perfectly in agreement with each other as well as the KLBF ASOS station (Figure 4.78b). There are only minor differences present. The air temperatures reported by the KANW ASOS station agreed very well with the analysis of the air temperature by the NDOT-MDSS (Figure 4.78c). There are only minimal differences, which is expected because of the proximity of the routes to the ASOS station. The analysis done by the NDOT-MDSS has the exact same pattern as the air temperature reported by the KBVN ASOS station; however, the air temperatures reported by the KBVN ASOS station was approximately 2-3 °C higher than the analysis of the air temperatures by the NDOT-MDSS (Figure 4.78d). The reason for the difference in the temperatures is unknown. During the duration of the storm, Route 1 saw an interesting pattern of small temperature spikes that were not in the other routes nor at the KLCG ASOS station. In all other routes in the April storm, there were no major differences that occurred while the storm was taking place.

The pavement temperatures from Routes 1, 2, and 3 are in agreement during the April storm in the NDOT-MDSS, although pavement temperatures from Scriber peak 10 °C higher than both routes 17-23 hours from the start of the storm (Figure 4.79a). This

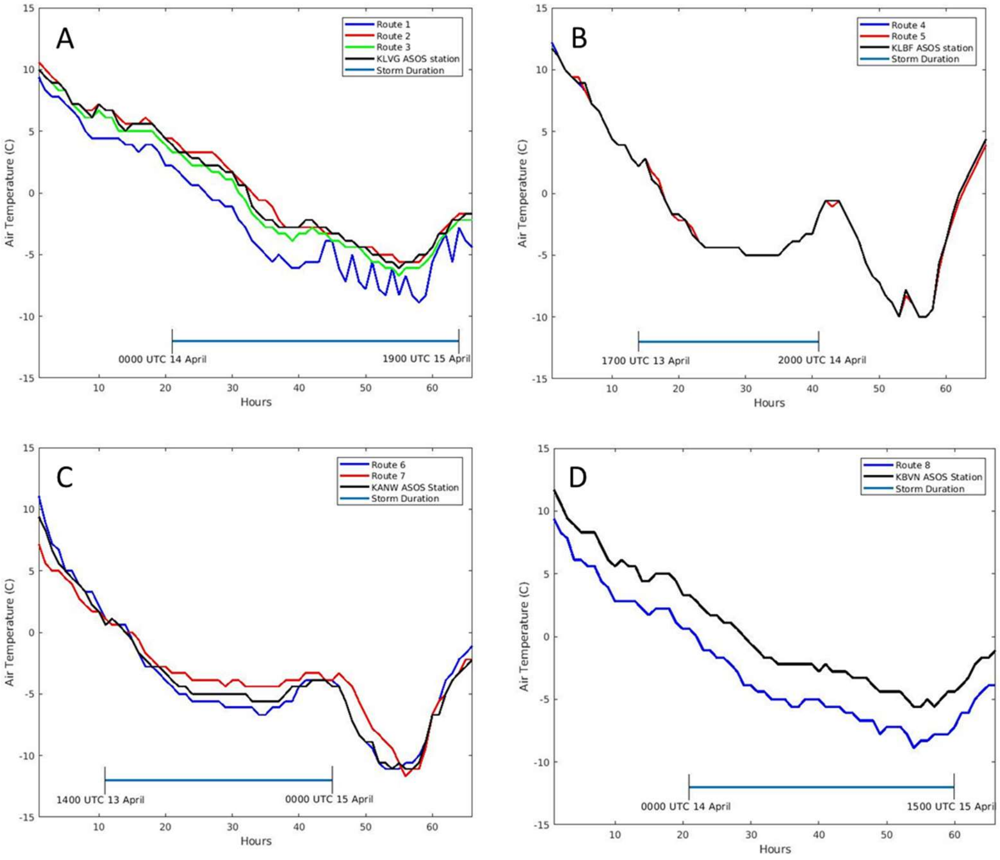

Figure 4.78: Temperatures during the April storm. A) Route 1 (blue), Route 2 (red), Route 3 (green), and KLCG ASOS station (black). B) Route 4 (blue), Route 5 (red), KLBF ASOS station (black). C) Route 6 (blue), Route (7), and KANW ASOS station (black). D) Route 8 (blue) and KBVN ASOS station (black). The storm duration was plotted (light blue) to show when the storm was taking place per each route.

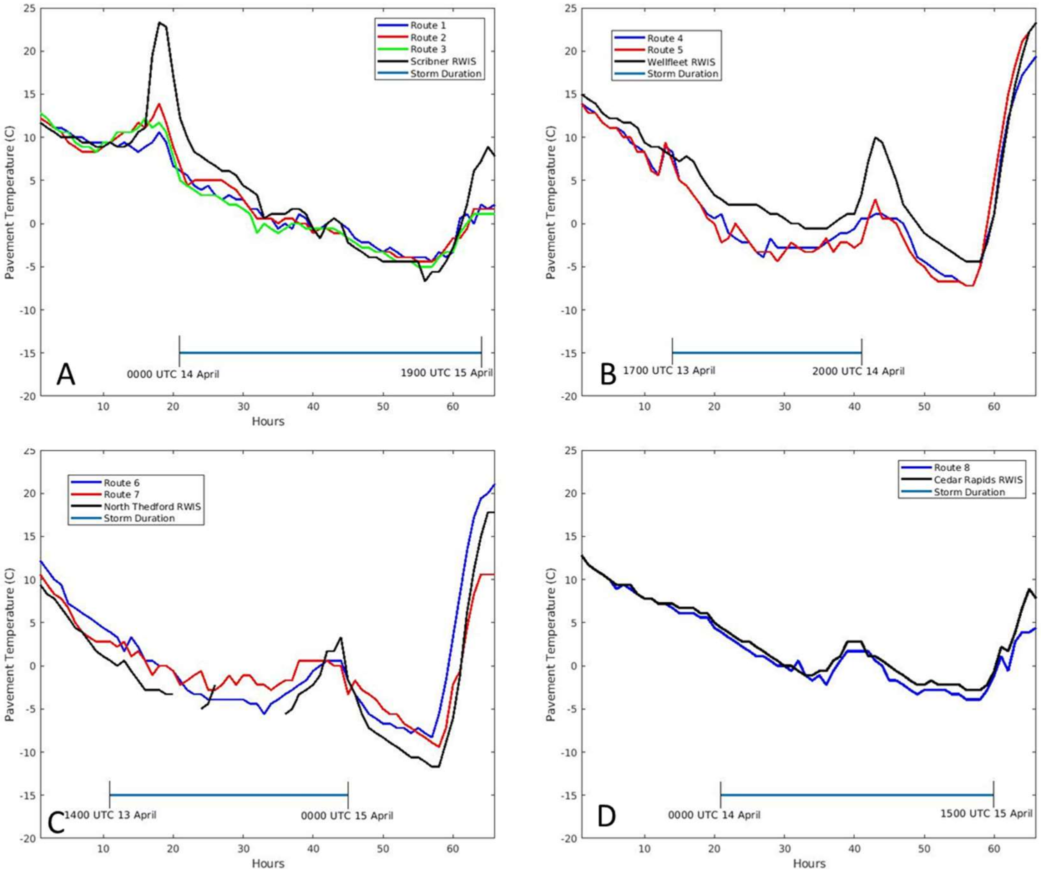

Figure 4.79: Pavement temperatures during the April storm. A) Route 1 (blue), Route 2 (red), Route 3 (green), and Scribner RWIS station (black). B) Route 4 (blue), Route 5 (red), and Wellfleet RWIS station (black). C) Route 6 (blue), Route (7), and North Thedford RWIS station (black). D) Route 8 (blue) and Cedar Rapids station (black). The storm duration was plotted (light blue) to show when the storm was taking place per each route.

could have been caused by the more southern location of the RWIS station. The pavement temperature in Routes 4 and 5 are very similar within the NDOT-MDSS (Figure 4.79b). The Wellfleet RWIS station pavement temperatures are slightly higher than both of the routes. This could be caused by the more southern location of the RWIS (Figure 3.2). The pavement temperature in Routes 6 and 7 within the NDOT-MDSS followed the pattern of the pavement temperatures of the North Thedford RWIS station relatively well (Figure 4.79c). There were a few areas of missing data from the RWIS station; however, most of the RWIS data saw the same peaks and dips as both routes. The inconsistency of the two routes and the RWIS station can most likely be attributed to the distance between them (Figure 3.2). Route 8's pavement temperatures matched the Cedar Rapids RWIS station very well in the April storm (Figure 4.79d). The only small inconsistency is present at the very end of the storm from hours 63 to 66 from the start of the storm. The April pavement temperatures from all routes and all ASOS stations had no major differences from the normal pattern observed when the storm was occurring to when it was not.

During the April storm, the RWIS and ASOS station temperatures agreed very well in most geographic locations. The Scribner RWIS station spiked at approximately 15 hours from the start of the storm while the KLCG ASOS temperature steadily decreased (Figure 4.80a).This was most likely caused by the more southern location of the Scribner RWIS station (Figure 3.2).The only other large difference occurred between the North Thedford RWIS station and the KBVN ASOS station (Figure 4.80c). Both stations have initial temperatures between 10-15 °C; however, the temperatures quickly diverge. The North Thedford RWIS reported much lower temperatures than what was being reported

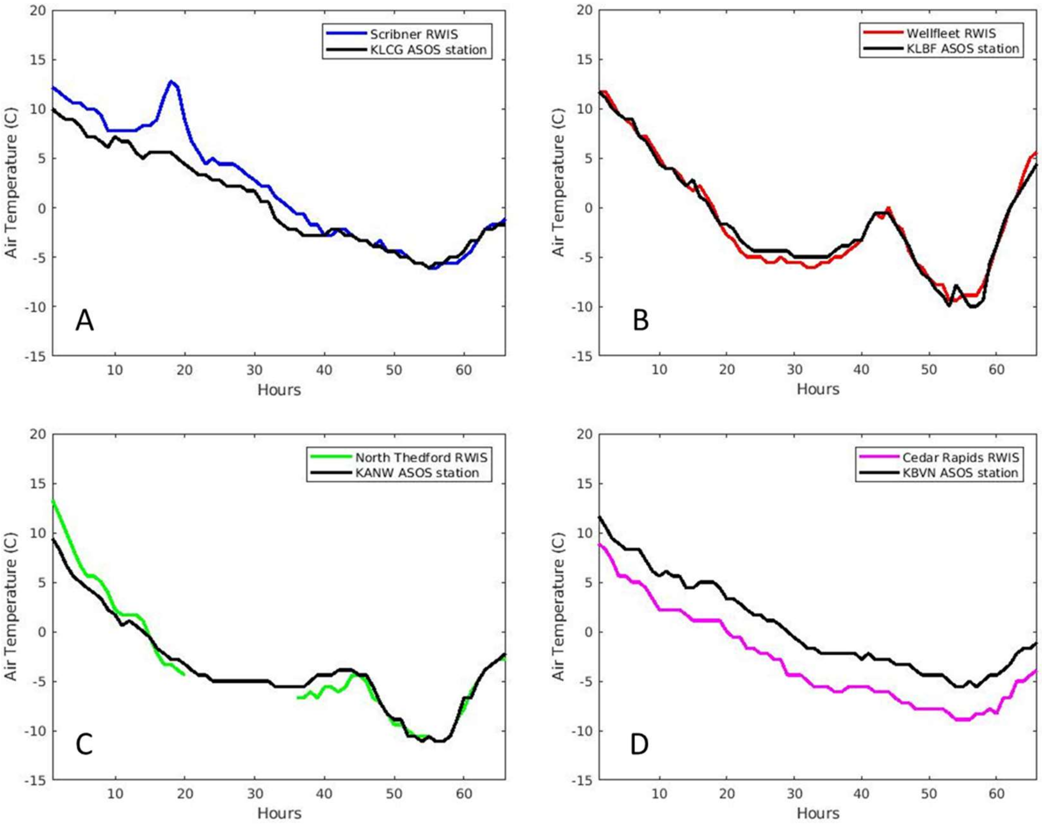

Figure 4.80: Air temperatures during the April Storm. A) Scribner RWIS station (blue) and KLCG ASOS station (black). B) Wellfleet RWIS station (red) and KLBF ASOS station (black). C) North Thedford RWIS station (green) and KBVN ASOS station (black). D) Cedar Rapids RWIS station (magenta) and KANW ASOS station (black).

at the KBVN ASOS station. There was also missing data from the North Thedford RWIS so comparisons weren't made from 21 to 35 hours from the start of the storm. The cause of the differences in temperature is unclear because there are varying distances between the stations and the routes (Figure 3.1), although the difference in temperatures should not be that much. The other ASOS and RWIS stations had very similar temperatures to one another.

4.5 Discussion

The January storm was a well forecasted storm as the storm got closer in both time and location; however, the forecasted low pressure center made major shifts due to a decrease in speed of the system prior to the event. The major shifts caused by a decrease in the speed of the system made the storm harder to forecast while it was still in the long-term forecast range. Freezing rain remained in the forecast in the days leading up to the event so there was confidence in that aspect of the forecast. A winter storm watch was issued in all 4 CWAs at around 1000 UTC 19 January. Winter storm warnings, blizzard warnings and winter weather advisories were issued by all 4 NWS offices responsible for the study routes for the January storm (Figure 4.81). NWS North Platte put out both a winter storm warning and a blizzard warning for their CWA. The winter storm warned areas were expected to see 10-18 cm (4-7 in) while the blizzard warned areas were expected to see 20-30.5 cm (8-12 in). Routes 4, 5, 6 and 7, which are all located in the NWS North Platte CWA, were forecasted to receive a range of 17-26 cm, which is well agreed with the forecast put out by the NWS for total snowfall accumulation. Routes 1, 2,

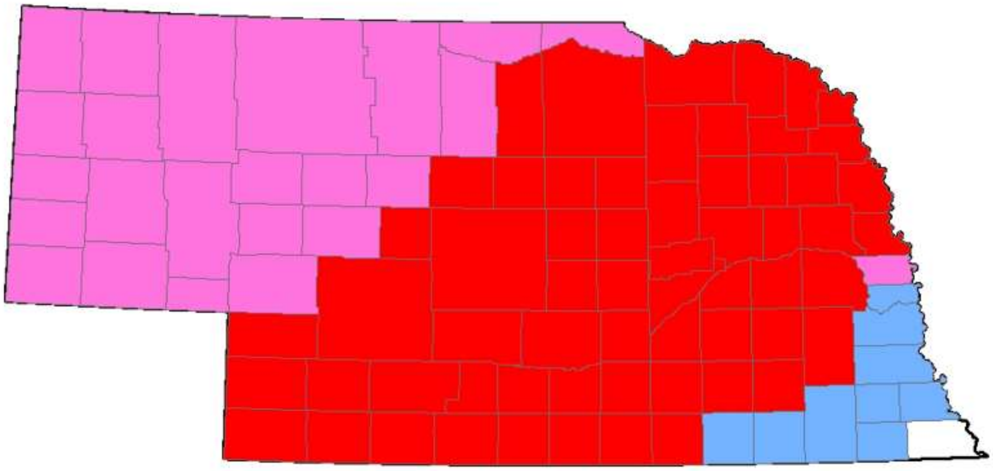

Figure 4.81: NWS Blizzard Warnings (red), Winter Storm Warnings (pink) and Winter Weather Advisories (blue) from 0000 UTC 22 January to 0000 UTC 23 January

3 and 8, located in either the NWS Omaha/Valley or Sioux Falls CWA, were forecasted in the NDOT-MDSS to see 30-33 cm (11.8-13 in), which is on the high side in comparison to the NWS prediction. At the end of the January storm, total snowfall accumulation was recorded from the NDOT-MDSS for each route as well as data from xmACIS which is compiled of various CO-OP and CoCoRaHS stations for areas on or near the routes (Table 4.13). Routes 1, 2, 4, 5 and 6 had differences of approximately 3 cm between the NWS total snowfall accumulation and the NDOT-MDSS total snowfall accumulation. Routes 3, 7, and 8 were not quite as accurate with the difference between the two snowfall accumulation totals amounting to 9-17 cm (3.5-6.7 in). xmACIS reported much higher amounts in Routes 3 (17 cm more) and 7 (8.8 cm more) and the analysis by NDOT-MDSS had a much higher amount in Route 8 (11.5 cm more). The snow reports collected from xmACIS (2019) were generally not directly on the routes; however, they were in the close vicinity so this could have led to some slight inconsistencies in the total snowfall accumulations.

The April storm was also a well forecasted storm, especially since the forecasted low pressure center is observed in the same location as was forecasted over the course of the few days prior to the storm impacting Nebraska. Heavy snow accumulations were predicted throughout Nebraska by each NWS office that contains a study route. Winter storm warnings, blizzard warnings and winter weather advisories were also issued by all 4 NWS offices for the April storm (Figure 4.82). The NDOT-MDSS forecasts were saved approximately 20 hours at the most before the storm impacted any route so a long-term forecast was not available for comparison against the NWS long-term forecasts. Areas in the CWA of NWS North Platte were expected to receive anywhere from 15.2-38.1 cm at

Table 4.13: Observed total snowfall accumulations from xmACIS and the NDOT-MDSS analysis for each route in the study for the January storm.

Route	xmACIS Total Snowfall Accumulation (cm)	NDOT-MDSS Total Snowfall Accumulation (cm)
1	17.8	15.8
2	17.8	17.0
3	38.1	21.1
4	26.7	23.9
5	26.7	23.6
6	26.7	26.2
7	27.9	19.1
8	10.1	21.6

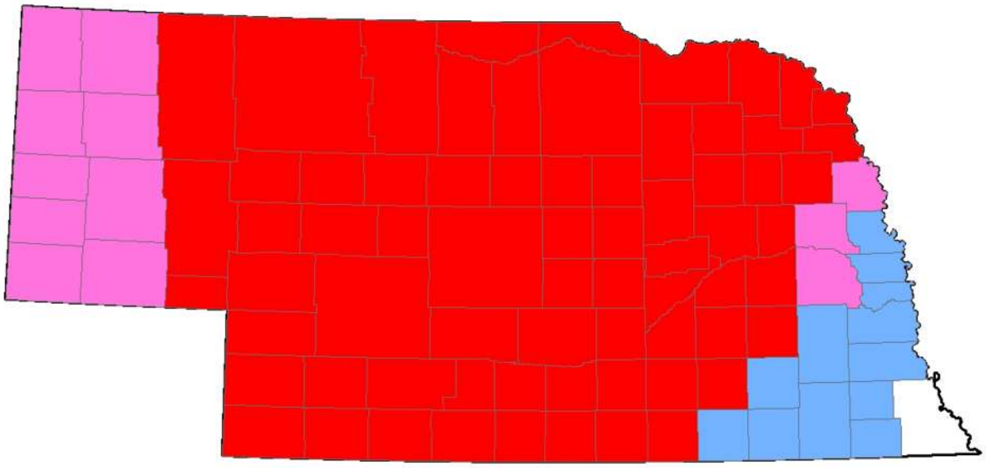

Figure 4.82: NWS Blizzard Warnings (red), Winter Storm Warnings (pink) and Winter Weather Advisories (blue) from 0000 UTC 14 April to 0000 UTC 15 April

2000 UTC 13 April, which was right before the beginning of the storm in the region. Within the NDOT-MDSS, the routes in the North Platte CWA had initial forecasted total snow accumulations ranging from approximately 21-24 cm and only had a Blizzard Warning put out. The NDOT-MDSS and NWS North Platte were very accurate with their range of total snowfall accumulations forecasted. NWS Omaha/Valley and NWS Sioux Falls had forecasted total snowfall accumulations ranging from 5.1-38.1 cm which included a winter weather advisory, blizzard warning and winter storm warning. Routes located in the NWS Sioux Falls or the NWS Omaha/Valley CWA had initial forecasted total snowfall accumulations ranging from 14-22 cm within the NDOT-MDSS. The range produced by the NDOT-MDSS was on the lower side of the NWS forecast. At the end of the April storm, both the NDOT-MDSS and the NWS along with various CO-OP and CoCoRaHS stations indicated totals snowfall accumulations for the event (Table 4.14). Total snowfall accumulation for all routes ranged from 3.1-25.4 cm. Most route's NDOT-MDSS total snowfall accumulations were within 5.08 cm of the total snowfall accumulations that were observed on the ground, with the exception of Route 2 which differed by 6.8 cm.

Each storm had major impacts across the state of Nebraska. Whiteout conditions were observed due to high winds that were produced by a tight pressure gradient. A shortwave formed over the Pacific Ocean and then traveled across the Rocky Mountains. Both of these storms went through lee-side cyclogenesis as they crossed the mountain barrier. They are both classified as Colorado lows or lee-side cyclones. They had very similar tracks with the April storm being located a little farther to the northwest. The pressure gradients were approximately the same magnitude. April's lowest pressure of

Table 4.14: Observed total snowfall accumulations from xmACIS and the NDOT-MDSS analysis for each route in the study for the April storm

Route	xmACIS Total Snowfall Accumulation (cm)	NDOT-MDSS Total Snowfall Accumulation (cm)
1	10.1	10.4
2	3.1	9.9
3	10.7	15.0
4	7.6	6.6
5	7.6	10.7
6	24.0	26.7
7	25.4	22.4
8	5.1	7.9

the storm was 988 hPa while January's lowest pressure was 996 hPa. The tightest part of the pressure gradient was located to the northwest of the center of the low pressure and situated over the state of Nebraska during each storm's peak intensity. The placement of the tightest part of the gradient led to high winds, producing blizzard conditions throughout the state. Each storm produced snowfalls with large ranges within the state of Nebraska. The April storm saw severe weather ahead of the snow. Convection occurs more often ahead of winter storms that take place in the spring due to the warmer temperatures that are associated with spring weather.

Although the two storms chosen for analysis are very similar, there are many different attributes present within them. The forecast for each storm had many challenges. The forecasted center of the low pressure for the January storm shifted from over the Great Lakes to over northwestern Kansas in the 7 days prior to the storm. The predicted location of the center of the center of the low pressure for April stayed in the same general area over western Iowa for the majority of the time starting at 7 days out. With the different locations of the low pressure centers for the storms, the predicted precipitation chances varied widely as well. The April storm took place overnight on 14 April to the 15 April in the eastern routes. In the more western routes, the brunt of the storm took place from midday 14 April to the morning of 15 April. The storm lasted anywhere from approximately 27-36 hours in the selected study routes. The January storm took place overnight on 20 January to the evening of 21 January in the eastern routes. In the more western routes, the storm began around midday on 20 January and ended around midday on 22 January. The storm lasted anywhere from 20-30 hours for the eight routes. The April storm was a few hours longer than the January storm; however, based on the NWS snowfall totals (Figures 4.1 and 4.42), this did not have that big of an impact on the total snowfall accumulation in Nebraska.

Freezing rain was seen in the January storm along the rain-snow line; however, the April storm had minimal to no freezing rain. The difference in the presence of freezing rain was mostly caused by a warmer layer in the atmosphere that allowed for partial melt of the ice crystals. The critical thicknesses at 2000 UTC 21 January were scattered across central Nebraska and were not completely in agreement. The surface and 1000-850 hPa critical thicknesses are located farther to the north. The location of the critical thicknesses are an indicator that some layers over Nebraska were above freezing which led to the melting of ice crystals. Freezing rain and rain were seen across the state prior to the precipitation changing over to all snow. The critical thicknesses at 0600 UTC 14 April were much more in agreement than the ones on 2000 UTC 21 January. As the storms progressed, the critical thickness lines move farther south, allowing for ice crystals to fall without melting in most of Nebraska.

Both of the storms had very similar characteristics of where rising motion was taking place. During the peak of the January storm, the center of the low pressure and the vorticity maximum was located over eastern Kansas. During the peak of the April storm, the center of the low pressure was also located in Kansas as was the center of vorticity, although it was slightly farther to the north than the January storm, crossing into Nebraska. The January storm had higher vorticity than the April storm so there was more rising motion associated with the January storm.

Chapter 5: CONCLUSIONS

This study provides insight into some the capabilities and limitations of the NDOT-MDSS based on data from two 2018 winter storms. The synoptic analysis of both storms shows how the storms compared and differed as events affecting the state of Nebraska. In addition, the two events are used as reference storms to evaluate how the NDOT-MDSS performed with different characteristics of the storms. The data collected from the NDOT-MDSS show the accuracies of the total snowfall accumulations, precipitation start and end times, and sustained winds and wind gusts of each storm. The results of this study provide valuable information to NDOT for use during winter events in the future.

The January and April storms had very similar storm tracks in Nebraska based on the synoptic analysis even though the forecasted tracks of the center of the low pressure system varied widely. The forecast for the January storm had many major shifts to its track due to timing differences while the April storm's forecast only had minor shifts. The center of the low pressure was located in slightly different locations during the peak intensity of the each storm which helped produce the different locations of heavy snow. Other variables contributed to the snowfall pattern as well, although both of these storms had similar intensities and values of the variables investigated in the study. The storms were very similar in overall structure and intensity. The impacts of both storms included road closures due to whiteout conditions caused by high winds and snow.

The NDOT-MDSS has many positive attributes; however, there are a few inconsistences and potential errors in the system. There were variations in the total snowfall accumulation forecasts produced by the NDOT-MDSS based on geographic location. The variations can be see when looking at how the forecasts of total snowfall accumulation changed throughout time and how each route compares to one another. During both the January and April storms, the routes located in eastern Nebraska always had an initial NDOT-MDSS total snowfall accumulation forecast that was much higher than what was observed. The accuracy of the initial total snowfall accumulation forecast also seems to have a geographic link, with the eastern Nebraska routes being more poorly predicted than the western routes within the NDOT-MDSS. The longer the forecasts, the greater the inconsistences were for the different regions.

The forecasts for total snowfall accumulation for Routes 1, 2, and 3 were very similar. The routes all started out with a forecasted high total snowfall accumulations, then the accumulations decreased as the storm progressed eastward. These routes are all located in eastern Nebraska. Routes 4 and 5, located in close proximity to one another in southwest Nebraska, were in agreement with most variables investigated in this study. There were very little differences in the winds and the start and end times but during the April storm, the total snowfall accumulations differed by over 4 cm which probably should not happen due to the limited distance between the two routes. The January storm had no issues with the total snowfall accumulations for these two routes.

The comparisons between the critical thickness values and precipitation types generated by the NDOT-MDSS showing the analysis of the conditions taking place at each route highlights the accuracy of the system in outputting the correct type of precipitation along with the rain-snow line. In each instant that was compared, the NDOT-MDSS had the rain-snow line in the correct place in the state. The freezing line was also used for verification since the critical thickness lines can sometimes be marginally accurate and the NDOT-MDSS was also very skillful in matching the location of the freezing line. Freezing rain was forecasted by NWS for the January storm and the NDOT-MDSS did show this precipitation type occurring throughout the storm.

Precipitation start and end times of the storms had varying accuracy for the routes. During both storms, Routes 1 and 3 had forecasting issues, although the NDOT-MDSS forecasted the January start times better than in April. The NDOT-MDSS forecasted the storm to begin both earlier and later than what was seen in the NDOT-MDSS analysis in January while it forecasted that the storm would begin later in every route in April. End times during the January storm were also better forecasted than the end times in April within the NDOT-MDSS. End times in January were forecasted to end earlier in every route by the NDOT-MDSS in comparison to the end time analysis while the storm was forecasted to end later in the April storm by the NDOT-MDSS in all routes. The NDOT-MDSS had trouble with Routes 1, 2 and 3 during the April storm and 1, 7, and 8 during the January storm. The April storm saw a decrease in track speed which explains the timing issues with the April storm since the routes are all in the same geographic location. The routes with problems in the January storm are not in the same geographic group as one another so the issues seen in the forecast have an unknown cause. The start times, in most instances, were better forecasted than the end times in each storm. There were only a few considerable differences between the total snowfall accumulation analysis by the NDOT-MDSS and by xmACIS. The largest difference during the April storm occurred in Route 2 with a difference of 6.8 cm. The largest difference was much greater during the January storm with Routes 3, 7, and 8 all having over 9 cm of difference in the total snowfall accumulation output by the NDOT-MDSS and xmACIS.

The overall accuracy of the wind variables in the NDOT-MDSS were good. There were only minor inconsistencies, some of which could have been caused by the proximity of the route to the ASOS station.

The temperatures outputted in the NDOT-MDSS during the January storm were generally less accurate than what was outputted in the April storm when compared to what was reported by the ASOS stations. Within the NDOT-MDSS, the temperatures outputted by the routes were very similar in the various geographic locations, especially in Routes 4 and 5. The NDOT-MDSS struggled to align with some of the larger temperature increases and decreases; however, it did do an acceptable job with matching the overall pattern of the temperatures being reported by the ASOS stations. The pavement temperatures in all routes were very accurate when compared to the RWIS station pavement temperatures. The biggest difference was seen between Routes 6 and 7 and the North Thedford RWIS pavement temperatures. The North Thedford RWIS station pavement temperatures were consistently 3-4 °C lower than the pavement temperatures of both routes. Many of the inconsistencies seen between RWIS stations and routes may have been caused by the proximity of the routes to the RWIS stations because the RWIS stations are relatively scarce in Nebraska. The comparisons between RWIS and ASOS stations show that they have very similar patterns in most geographic groups, although there are a few times where one station would have a peak of warmer temperatures while the other station did not. Minor temperature differences were seen; however, some of these differences could have been caused by the small distance between the two stations.

Throughout this study, there were various limitations that could have impacted the results or hindered the project. This study had the intentions of also looking at how well the forecasts in the NDOT-MDSS did in comparison to what was observed. Unfortunately, there were not long-term forecasts in the saved storms within the NDOT-MDSS, so it was not possible to see the long-term forecasting abilities of the NDOT-MDSS. Short term forecasts are more valuable to the maintenance crews, although knowing what to expect more than 24 hours out does help them decide on how to better handle an event. Another limitation was that the NDOT-MDSS accounts for melt, compaction and treatment application which could have affected the total snowfall accumulation. This would have most likely decreased the amount of snow in the analysis by the NDOT-MDSS, so it may have caused a few inconsistencies between the snowfall observed by the CoCoRAHS and CO-OP sites compared to the NDOT-MDSS. In addition, another limitation of the NDOT-MDSS were decreasing total snowfall accumulations in the analysis of total snowfall accumulation by NDOT-MDSS in April at times that had already occurred. It was thought that warmer road temperatures during the April storm had caused this; however, according to the NDOT-MDSS, the road temperatures during the April storm were relatively close to those of the January storm, although the January storms had slightly lower temperatures in most cases.

Ongoing collaboration with NDOT for similar studies will help to increase confidence of results found in this study. Future studies will consist of looking at different storms, including Colorado Lows and Alberta Clippers. Combining future studies with this study will help NDOT better understand any inconsistences with the NDOT-MDSS and lead them to make improvements where necessary. The overall goals of these studies are to help reduce road maintenance costs while increasing public safety during winter storms through the use of the NDOT-MDSS.

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