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Case Studies of Colorado Lows and the Impacts on Winter Weather Maintenance

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CASE STUDIES OF COLORADO LOWS AND THE IMPACTS ON WINTER WEATHER MAINTENANCE

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CASE STUDIES OF COLORADO LOWS AND THE IMPACTS ON WINTER WEATHER MAINTENANCE

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Winter storms of varying degrees plague the Plains each year, bringing with them ice, snow, wind, and cold temperatures which adversely affect public, commercial, and private transportation alike. The Nebraska Department of Transportation (NDOT) adopted a Maintenance Decision Support System (NDOT-MDSS) to aid in their winter weather maintenance practices. NDOT-MDSS ingests data from a variety of numerical weather models as well as real time surface and pavement observations to output both a weather forecast and winter road maintenance recommendation that can be taken into account by NDOT to finalize their maintenance decisions for a specific storm system or road segment. Two case studies of winter storm events, 24-25 November 2018 and 23-25 February 2019 that affected Lincoln, NE were analyzed. The case studies were chosen because they were both Colorado low systems that followed very similar synoptic scale trajectories yet produced very different results. An initial synoptic overview that preceded each system was conducted in order to understand the observed environment prior to snowfall onset for each case study. After the synoptic analysis, comparison of the NDOT-MDSS forecasts at 3, 6, 9, and 12 hours prior to snowfall intervals to the observed ASOS values at the Lincoln, NE airport (LNK) were conducted. Forecasted snowfall amount analysis of the NDOT-MDSS was analyzed against the Rapid Refresh model

(RAP), 12 km North American mesoscale model (12 km NAM), 4 km North American mesoscale model (4 km NAM), the global forecast system (GFS), and a derived model average, as well as National Weather Service and Weather Prediction Center computed accumulation forecasts. Ultimately, these analyses aided in a better understanding of the meteorological forecasts produced by the NDOT-MDSS and resulted in more insight for NDOT on the benefits and limitations of the NDOT-MDSS system that they have embraced.

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Chapter 1: Introduction

1. Introduction

Weather and risk management have long been tethered together in efforts to mitigate hazards while maximizing efficiency. Winter weather forecasts, specifically, play an essential role in the decision-making process for road maintenance. This research included a detailed analysis of the weather conditions within the Maintenance Decision Support System (MDSS) run by Iteris (Iteris, Inc. 2020) and used by the Nebraska Department of Transportation (NDOT), which will be identified as NDOT-MDSS, for several route segments across eastern Nebraska.

The first objective of the study was to analyze individual winter weather storms that affected eastern Nebraska during the 2018-2019 winter and determine how well the NDOT-MDSS forecasted the events. One of the main concerns within this objective is how well the NDOT-MDSS represents the weather conditions leading up to and during the winter weather event? For this study, the impacts of Colorado low winter weather systems are studied to analyze the forecast consistency of the NDOT-MDSS for a specific storm type. A Colorado low typically forms on the lee side of the Rockies in southeastern Colorado. In the winter and early spring, as the low progresses eastward, distinct warm and cold frontal boundaries develop. The positioning of these boundaries in collocation with upper air conditions can complicate the prediction of precipitation type possible with the associated storm. Nebraska lies within the uncertain region where the rain/snow line is difficult to predict. The variable position of this line during Colorado

low events often produces heavy, wet snowfall conditions once the precipitation type has transitioned to snow.

The second objective examined how the NDOT-MDSS forecasted for snowfall accumulation totals prior to and during the event. This objective investigates how and if the NDOT-MDSS is adjusting snowfall accumulation totals in conjunction with other model output and real-time observations. The precipitation type complications associated with Colorado low systems can lead to issues with any forecast system that is trying to forecast snowfall. The final objective compares the two case study events to explore the consistencies and discrepancies that accompany the NDOT-MDSS from storm to storm. The case studies analyzed are of the same Colorado low sub-category, yet can have different weather conditions as they progress.

The NDOT-MDSS was recently implemented to integrate meteorological information with winter maintenance operations to examine winter weather conditions from a variety of angles. The primary utilization of the NDOT-MDSS is to aid the NDOT in its road maintenance practices. To provide quality road maintenance recommendations, the NDOT-MDSS must first have a sound understanding of the observed weather conditions as well as the future complications that will accompany an incoming storm.

Two case study events that fit the Colorado low criteria were selected from the 2018-2019 winter season. The first event spanned 24 - 25 November 2018 and brought snowfall totals of 0.5 – 10.5 inches (1.3 – 26.7 cm) and blizzard conditions to much of eastern Nebraska. The second event occurred between 23 - 25 February 2019 and began with a transition from freezing rain and sleet to snow and then blizzard conditions,

producing snowfall totals from 3.0 – 12.0 inches (7.6 – 30.5 cm) that affected eastern Nebraska. Both of the weather systems caused road closures due to low visibility and slick road conditions. Before the occurrence of the weather systems, both were also denoted as “Pathfinder events”, where collaboration between the NDOT and National Weather Service (NWS) occurred in order to relay consistent messages to the public. The Pathfinder initiative was created by the Federal Highway Administration (FHWA) with the initial pilot project demonstration conducted in 2014 (Helsel et al. 2016). The goal was to provide consistent messaging for the traveling public during adverse weather conditions to improve safety and inconveniences through collaborations between state Departments of Transportation (DOTs), private companies, and the NWS. The Pathfinder initiative began development in 2016 (Helsel et al. 2016) and was put into motion in Nebraska during the 2018-2019 winter (Moritz 2018). While there have yet to be any retrospective studies that examined the effectiveness of the Pathfinder initiative, public reception thus far has been mostly positive (J. Schulz 2019, personal communication). Pathfinder efforts were especially applauded for the messaging that was imparted to the public during the Thanksgiving weekend 2018 blizzard (24 – 25 November 2018 case study) that urged travelers to adjust their holiday travel plans around the storm.

Along the same lines with the Pathfinder initiative, the NDOT-MDSS was created to improve road maintenance practices while mitigating road weather hazards. The overall reception around the use of MDSS is positive in that the system lowers the necessary labor hours and materials used while still providing practical maintenance efforts. One of the more recent reviews on the implementation of a MDSS system by the

South Dakota Department of Transportation (SDDOT) was to investigate the cost-benefit analysis of the system. The answers yielded promising results economically as the benefits to cost of implementation ratios for the three case study states observed were all calculated to be greater than 1 (Table 1.1). Alongside the monetary benefits, the MDSS system implementation forced DOTs to evaluate their performance standards.

Very little has been done to assess the credibility of the forecasting that the system utilizes from a meteorological standpoint. Meteorologically speaking, most forecasting entities are appraised by how well the forecast verifies. Therefore, the main focus of this study on Colorado low impacts on winter weather road maintenance was to verify NDOT-MDSS forecasts for this type of event. The 2018-2019 winter saw a high frequency of winter weather events that affected eastern Nebraska. On average, the Lincoln area receives 25.9 inches (65.8 cm) of snowfall per year (NWS 2005). The 2018-2019 winter season was the second snowiest on record with 55.5 inches (141.0 cm) of snowfall recorded, which was only 3.9 inches (9.9 cm) behind the all-time record observed during the 1914-1915 winter (Dewey 2020).

A review of the atmospheric conditions from the upper air observations (300, 500, 700, 850 hPa) down to the surface is included to provide a picture of the observed conditions prior to and during the snowfall event. An examination of air temperature, dewpoint temperature, wind speed, snowfall accumulation, and visibility was conducted to observe the forecastability of the system. Representative routes were chosen near Lincoln, NE, for the NDOT-MDSS analysis. Understandably, difficulties in the verification of the snowfall accumulation values along the many different routes was

Table 1.1: Summary table of cost-benefit analysis that was conducted by the South Dakota Department of Transportation (from Ye et al. 2009).

Case State	Scenario	Benefits	Percent of User Savings (%)	Percent of Agency Savings (%)	Costs	B-C Ratio
New Hampshire	Same Condition	$2,367,409	50	50	$332,879	7.11
	Same Resources	$2,884,904	99	1		8.67
Minnesota	Same Condition	$3,179,828	51	49	$496,952	6.40
	Same Resources	$1,369,035	187	-87		2.75
Colorado	Same Condition	$3,367,810	49	51	$1,497,985	2.25
	Same Resources	$1,985,069	90	10		1.33

challenging due to the limited spatial extent of observation networks. The NDOT-MDSS was compared against surface observations as well as other forecasting models such as the Rapid Refresh (RAP), global forecast system (GFS), 12 km North American mesoscale model (12 km NAM), and 4 km North American mesoscale model (4 km NAM) to roughly classify the skill that the NDOT-MDSS had comparatively.

Chapter 2: Background

Winter weather can cause widespread impacts. Colorado low systems especially can create hazardous driving conditions with high wind speeds, high snowfall totals, and precipitation type transitions as the system progresses. These varying meteorological conditions are difficult to forecast and need to be understood well to thoroughly analyze any forecast system. Winter weather forecasting complexities in turn affect road maintenance as crews must be prepared for the many different scenarios that may accompany an impending winter storm. The NDOT-MDSS is a proprietary forecast system that was created as a response to the need for a road weather forecast system. The analysis of the NDOT-MDSS during Colorado low type events will combine the complexities of forecasting for winter weather and examine the reliability of the NDOT-MDSS during such events.

2.1 Winter Weather Prediction

Any upper level wave that traverses the western United States usually encounters the Rocky Mountains. Interactions with the topography can produce an orographically forced low. Analysis of lee side cyclogenesis from a dynamical perspective provides useful insights into the formation of these orographically forced lows. Potential vorticity conservation is the governing equation for this process and is introduced as:

$$\frac{D_h}{Dt}\left[\frac{\zeta+f}{h}\right]=0 \qquad (1)$$

Westerly flow occurring over a topographic barrier within a fluid depth between two constant isentropic surfaces is a typical process that occurs along the Rocky Mountains (Figure 2.1). As the flow advects the air mass eastward, nearing the topographic barrier, the fluid columns stretch vertically. This process causes the relative vorticity (ζ) to increase alongside the Coriolis parameter (f) as the depth of the column decreases. Positive cyclonic vorticity will in turn produce cyclonic flow as the column begins its ascent up the topography. This induces a slight northward trajectory which manifests as an increase in f. Since the poleward drift increases f and the depth is still constant, the relative vorticity will slowly decrease in magnitude. Next, the column interacts with the topographic barrier and works to decrease the overall depth of the column. Since the poleward extent of the column is still consistently rising initially, the only parameter that can compensate for the sudden decrease in depth is the relative vorticity which takes on a negative value. This negative relative vorticity will induce anticyclonic vorticity and begin to move the column southward, thus decreasing f. This attendant decrease in f, yet again, leads to the relative vorticity taking on a positive sign. Holton and Hakim (2012) state that steady westerly flow over a large-scale topographic ridge will result in anticyclonic flow over the mountain, a cyclonic flow pattern to the east of the barrier, followed by a wavetrain downstream. This means that an area of low pressure will form along the lee side of the Rocky Mountains in response to an area of anticyclonic flow over the mountains and will induce smaller eddy-like circulations from the attendant wavetrain farther downstream. This also lays the blueprint for the maturation of the low

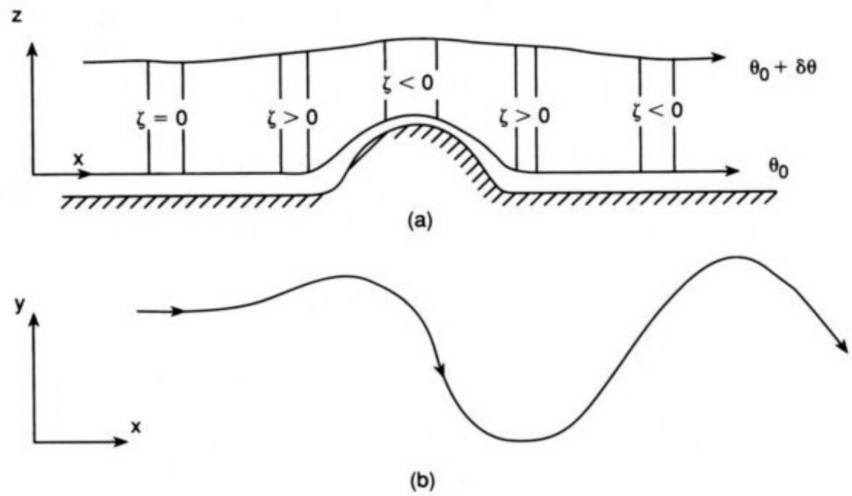

Figure 2.1: Schematic of westerly flow over a topographic barrier a) depth of the fluid column as a function of x and b) the trajectory of a parcel in the (x, y) plane (from Holton and Hakim 2012).

pressure system as it progresses because of the area of low pressure that forms over the mountains as a result of this process.

Colorado and Alberta Clipper lows are two winter, orographically forced, low pressure synoptic systems that occur via lee cyclogenesis throughout the northern and central Plains. A Colorado low is a specific subset of synoptic systems that forms off the lee side of the Rocky Mountains, especially in eastern Colorado and locations southward. A Colorado low trajectory will generally progress on an eastward or, initially, even southeastward trajectory, then continue on a northeastward trajectory after its formation in the lee of the Rockies (Figure 2.2). The Alberta Clipper system forms in the same manner as a Colorado low and differs by forming on the lee side of the Canadian Rockies in Alberta or south to Montana. An Alberta Clipper will dip down from Canada on a southeasterly trajectory, clipping states in the northern and central Plains as well as the Midwest, and quickly progressing along a northeastward trajectory (Figure 2.3). Initial differences between the two systems are directly related to their starting locations, trajectory, and their attendant moisture content as they traverse the continent.

Typically, a Colorado low, when compared to an Alberta Clipper, will produce a heavier, denser snow that accumulates in much higher amounts than the Alberta Clipper. The main reasons for this are due to the availability of and access to Gulf of Mexico moisture, temperature differences, and stronger upper air support. More moisture allows for higher liquid content snowfalls. As the system intakes air from the Gulf, it advects warmer temperatures which allow for greater moisture content in the region prior to cold frontal passage. A general pattern of increasing cloud-level air temperature yielding

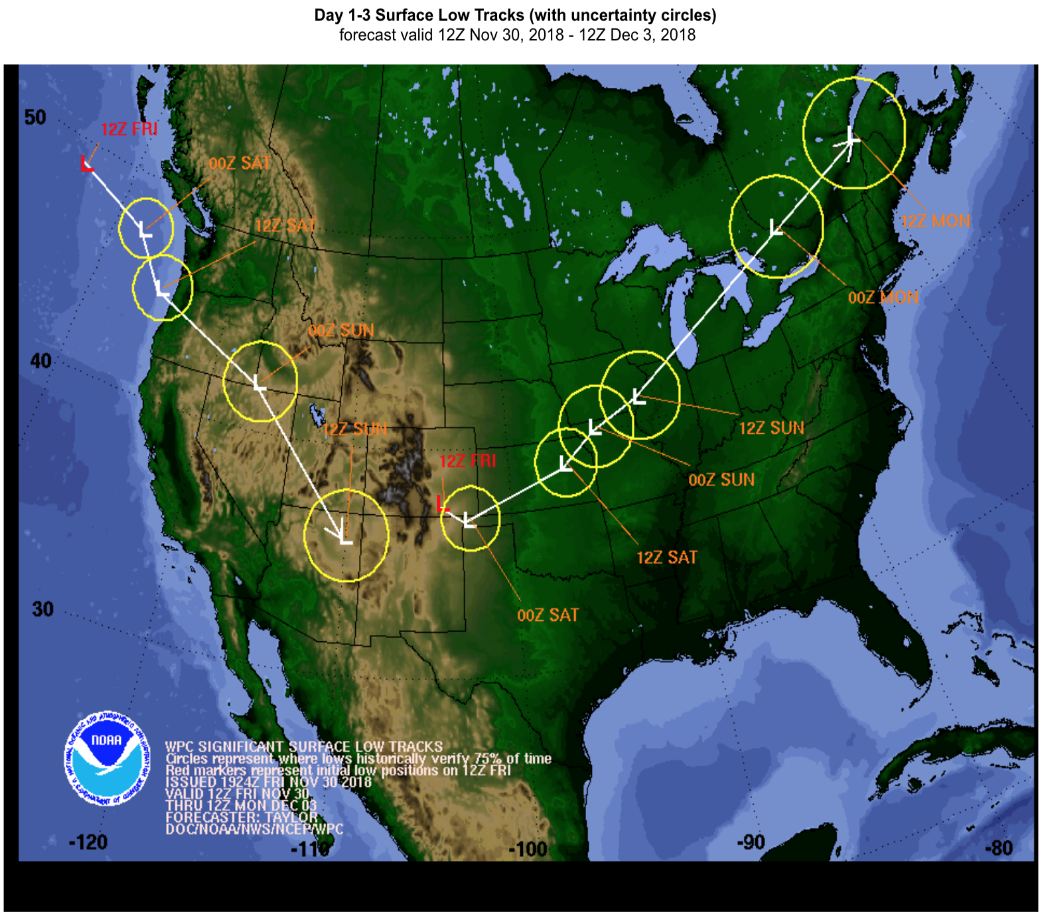

Figure 2.2: General formation area and trajectory of a Colorado low system (from WPCWW 2019)

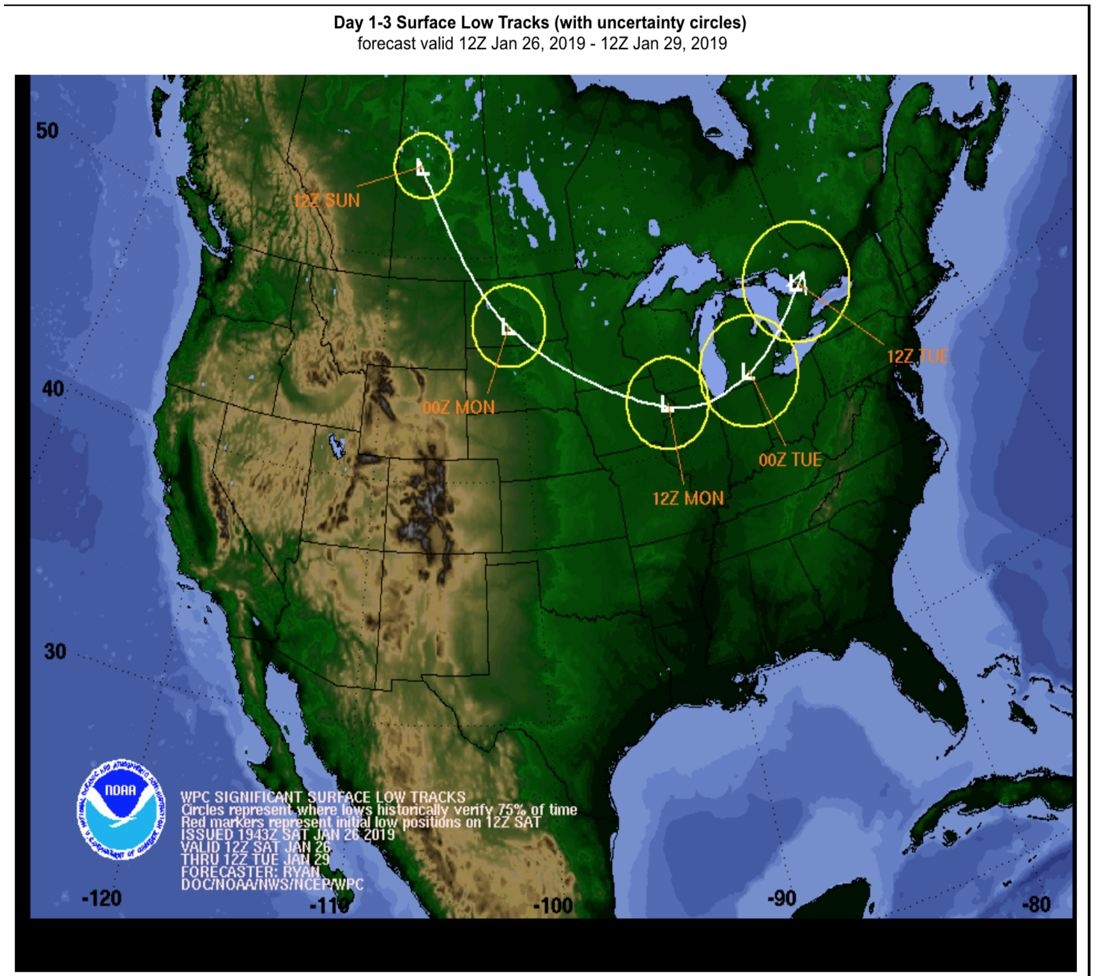

Figure 2.3: General formation area and trajectory of an Alberta Clipper system (from WPCWW 2019)

higher values of snow density was found by Judson and Doesken (2000) during their comparison of prior case studies. This relationship in conjunction with the warm air advection along the southeastern quadrant of a system infers the presence of higher density snowfall with Colorado lows. The upper level support means that the system is usually stronger dynamically and will have greater vertical velocities also aiding in snowfall production. An Alberta Clipper relies upon carrying Pacific moisture across the continent as well as local moisture sources provided by lakes, which are typically frozen, along its path during the winter. This contrast in moisture will naturally bring about a differential in total snowfall potential for both of these systems. Blowing and drifting can occur with both systems; however, the drifting occurs during a Colorado low's snowfall period. Usually after the snowfall stops, there is less drifting due to higher liquid content of the snow. During an Alberta Clipper, blowing and drifting associated with high winds will occur during and after the snowfall period, since the snow is typically drier and is more susceptible to blowing and drifting even after the snowfall has stopped.

The speed of the system also affects total snowfall accumulations. The Colorado low tends to move slower which allows for higher snowfall accumulations while the Alberta Clipper is generally a faster moving system that limits its own snowfall accumulation potential. A Colorado low can expect to drop anywhere between 1.0 - 12.0 inches (2.5 - 30.5 cm) of snow depending on location and proximity to the center of the low pressure system, with larger snowfall amounts falling on the northern or northwestern side of the low pressure system if temperature conditions are favorable. An Alberta Clipper will usually yield lower snowfall accumulations of 2.0 – 5.0 inches

(5.1 - 12.7 cm) due to the lack of available moisture. Instances of heavier snowfall for both types of systems can also be observed in conjunction with the presence of a deformation zone. These higher associated snowfall accumulation amounts typically fall within an area about 1° of latitude south-southeast of the tight temperature gradient that can be seen on satellite infrared (IR) imagery (Steigerwaldt 1986). Deformation zones can occur with very few analogs to surface and upper air observations. Therefore, this tight temperature gradient better depicts the movement and transformation of the deformation zone over time and can aid in pinpointing where locations of heavier snowfall may occur.

One of the forecasting difficulties for a Colorado low compared to the Alberta Clipper type systems in the wintertime is the ability to correctly determine the location of the rain-snow line. Usually in winter, the temperatures for an Alberta Clipper type system are below freezing and all precipitation would be snow. Colorado type lows often advect warmer temperatures into the storm system creating a rain-snow line. Forecasting for the region where this transition occurs can be difficult. In addition, the greatest snowfalls are usually found close to the rain-snow line. The greater snowfalls are characterized by higher moisture contents, temperature differences through the vertical extent of the system, and vertical velocity distributions. Therefore, the greater snowfalls are typically to the west and north of the rain-snow line. Colorado low type systems tend to move more slowly, allowing the warmer air to advect farther to the north.

One common method used to determine the rain-snow line location is to associate the transition line with the position of the geopotential thickness between two set pressure

layers. The 1000-500 hPa, 1000-850 hPa, and 850-700 hPa partial thickness analyses can all be used to identify precipitation type with varying degrees of accuracy. The thicknesses are a function of the average temperature and moisture content of the air between the two levels (Haby 2004). One of the largest issues with using thickness and partial thickness methods is that shallow warm layers above the surface are typically not well represented (Junker 2000) and often these shallow warm layers contribute to the change in precipitation type. The most commonly used thickness is the 5400 m contour from the 1000-500 hPa thickness layers. The 5400 m contour is a rough threshold where the thickness is shallow enough that snow should be able to reach the surface (Glahn and Bocchieri 1975). During precipitation, one current approach for observationally estimating the rain-snow line position utilizes the newly implemented dual-pol radar upgrades. Differential reflectivity (Z_{DR}) and correlation coefficient (CC) are used to identify regions dominated by non-spherical, heterogeneous hydrometeors. These regions are indicative of the presence of mixed precipitation which denote where the rain-snow transition is taking place (NWS Louisville 2015).

Weather prediction is still a young and evolving science. Frick and Wernli (2012) state that many prior studies have been conducted on numerical weather prediction (NWP) and have found that models of both a synoptic and mesoscale nature are very sensitive to initial environmental parameters. More accurate forecasts are being produced with increased knowledge of the atmosphere and more efficient modelling capabilities. Difficulties in snowfall forecasting can be traced back to the challenging circumstances of tracking an ice particle throughout its descent through ever-changing atmospheric

conditions. The main conditions necessary for snow production are water vapor (with supersaturation the ideal mode), ice nuclei presence, and cloud droplets with a temperature less than freezing present (Gray and Male 1981). Furthermore, snow and ice particle growth mechanisms can occur depending upon the attendant conditions. Ice crystals form primarily by vapor depositional growth and once large enough, can grow further by collisions with other ice crystals or supercooled droplets within the column it is falling through. Growth mechanisms such as aggregation, sublimation, and riming can all work to alter snowflake size and density and, inherently, snowfall intensity.

With regards to snow prediction there are many methods that produce a variety of forecasting results. For example, some of the current methods used are the Quantitative Precipitation Forecast (QPF) method (Henry 1917; LaChappelle 1962; Potter 1965; Grant and Rhea 1974; Doesken and Judson 1996; Super and Holroyd 1997; Roebber et al. 2003, Baxter et al. 2005), the Cook method (Cook 1980), the Magic Chart (Sangster 1985; Chaston 1989), the Garcia method (Garcia 1994), and the Cobb method (Cobb and Waldstreicher 2005). The Garcia and Cobb methods rely upon a collocation of environmental conditions with lifting mechanisms to produce a snowfall forecast, while the basic QPF prediction method calculates a deterministic snow-to-liquid ratio (SLR) (inches of snow to inches of water) based upon model guided QPF forecasts. A 30-year climatology of SLR within the United States presented by Baxter et al. (2005) will be used to further analyze QPF forecasts based upon SLR values.

Around 1875, the National Weather Service stated that a moderately useful analog for snowfall prediction that could be used was the 10:1 ratio (Henry 1917). As time

passed, further investigation into snowfall prediction noted that a 10:1 forecast would not be indicative of universal conditions and should only be used as a base approximation. A new study was therefore conducted in order to create a climatology of SLRs that take into account geographic and microphysical processes (Baxter et al. 2005). Statistically, the average SLR distribution for Nebraska is 13:1 for the three NWS offices (North Platte, Hastings, Omaha/Valley). Variability within the mean SLR values for Nebraska shows that early October and November (Figure 2.4) as well as late March and April (Figure 2.5) snowfall will have SLR between 11:1 and 14:1. As could be easily deduced, the SLR during the peak winter season for the Central Plains, December through February (Figure 2.6), increases to a range between 13:1 and 18:1. These distributions are logical since colder, drier air intrudes during winter, thus bumping up the SLRs for the time period, while warmer temperatures and more moist conditions comparatively will overtake the region both earlier and later in the snowfall season.

2.2 Winter Weather Transportation Impacts

A study by Carriere et al. (2000) notes that freezing precipitation comprises roughly 0.5-1% of all reported precipitation events across central and western Europe. Cortinas et al. (2004) expanded on this notion finding that freezing rain, freezing drizzle, and ice particles are most common throughout the central and eastern United States as well as Canada. The common presence of freezing rain, freezing drizzle, and ice pellets throughout the United States and Canada causes hazards for transportation. Often,

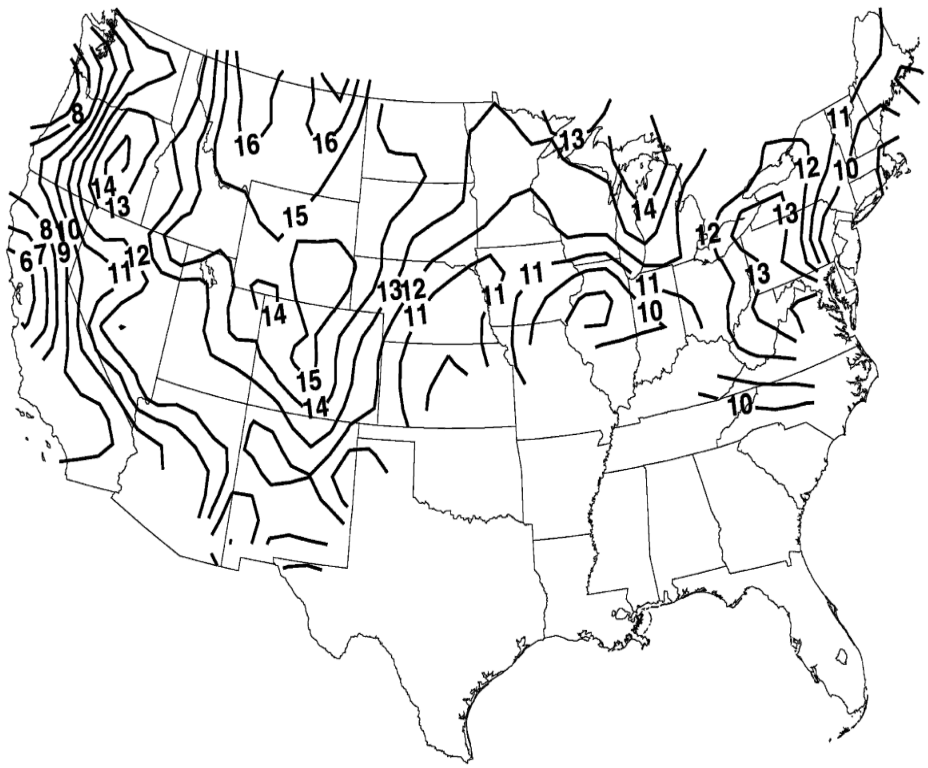

Figure 2.4: Mean snow-to-liquid ratio (1971-2000) values for October and November (from Baxter et. al. 2004).

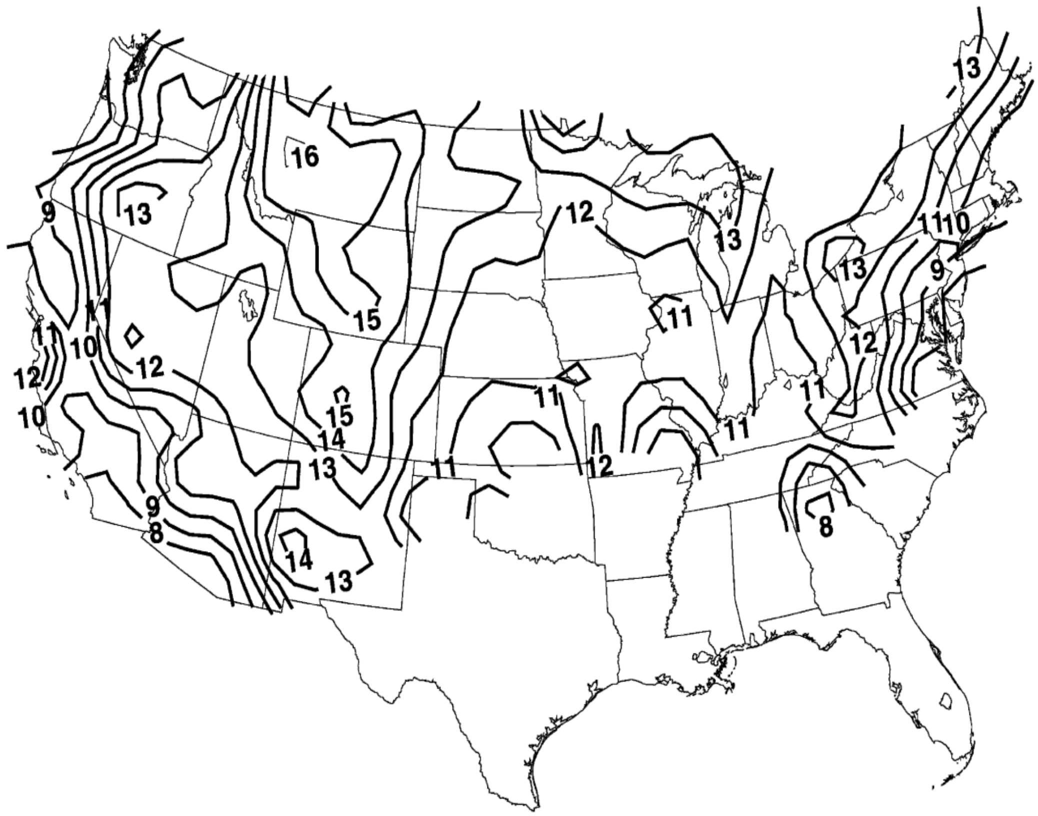

Figure 2.5: Mean snow-to-liquid ratio (1971-2000) values for March and April (from Baxter et. al. 2004).

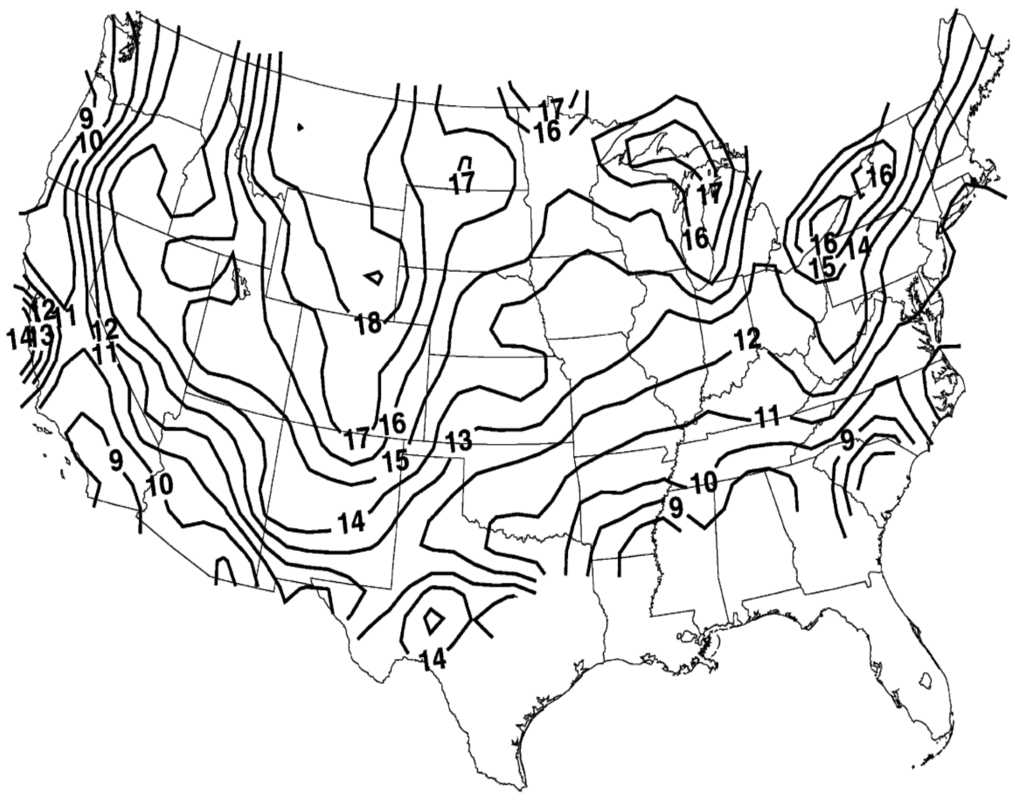

Figure 2.6: Mean snow-to-liquid ratio (1971-2000) values for December, January, and February (from Baxter et. al. 2004).

Colorado low snowfall events are preceded by freezing precipitation which can lead to quickly deteriorating road conditions even before snowfall begins.

A study (Black and Mote 2015) that analyzed 36 years of traffic fatalities related to winter precipitation events determined that winter weather far outweighs any other meteorological phenomena for fatalities (Figure 2.7). Despite this clear discrepancy, Black and Mote (2015) noticed that most winter weather fatalities are indirect, or a product of a situation caused by the weather rather than occurring as a direct result from the storm, and therefore tend to be glossed over more often than fatalities linked with tornadoes, flooding, and extreme temperature events. A study conducted by Andrey et al. (2005) discovered that winter precipitation resulted in the majority of crashes involving injuries across 27 cities in Canada. From 1949-2000, Changnon (2003) reported that 87 catastrophic (denoted by property losses of $1 million or greater) freezing rainstorms resulted in over $16.3 billion in damages collectively. A second study conducted by Changnon (2007) reported that six of the fourteen storms which affected the Midwest during the 2006-2007 winter seasons' each surpassed $25 million in property damages. All six of these events were labelled as catastrophes by the property insurance industry and a total of $1.5 billion of total insured property loss was recorded for the 2006-2007 winter season. Changnon (2007) also detailed that the top areas of economic loss were due to property loss, power outages, major transportation, and business. Furthermore, the top contributions to differentiation from a similar study comprised for 1977-1979 were an uptick in the number of major ice storms as well as general societal differences such as population growth and density as well as a higher number of automobiles per household.

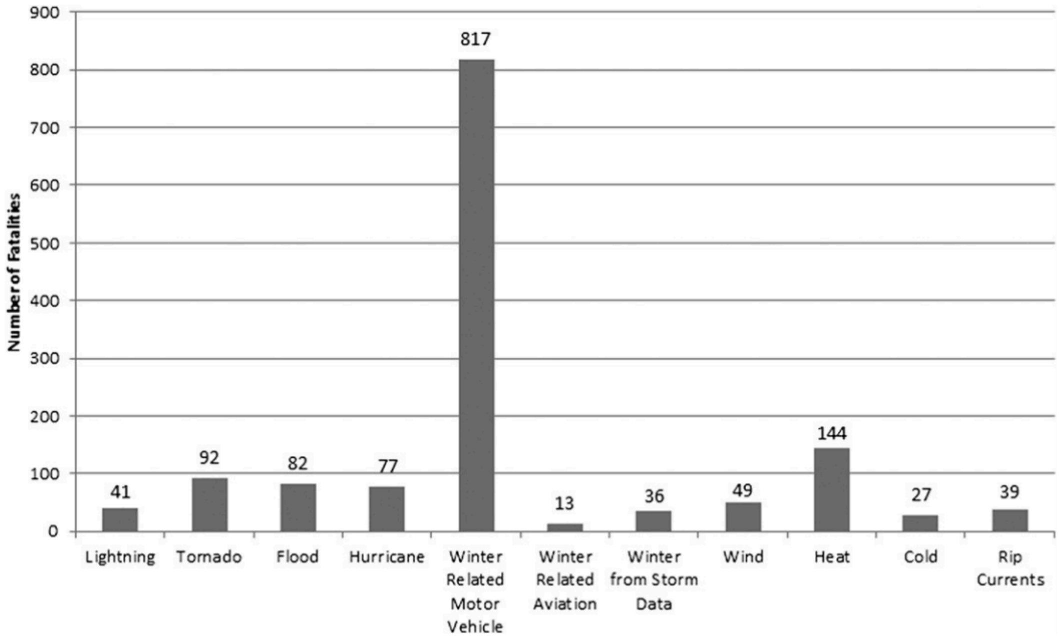

Figure 2.7: Average number of fatalities per year from various meteorological hazards for the period 1996-2011. Totals for all hazard except winter-related motor vehicle and winter-related aviation fatalities are from Storm Data (from Black and Mote 2015).

Changnon (2003) found earlier that in the southern United States when freezing rain occurred, it was more likely to be catastrophic and the region had more ice accumulation comparatively to counterparts in the northeast United States, where ice storms are less prevalent. Nine ice storm-related events were declared as major disasters in the southern United States between the years of 2000-2010, which comprises 31% of the 29 total disaster declarations during this time (Grout et al. 2012). Even though the density of winter storms affecting Oklahoma is relatively small, the number of high impact events that disrupt socioeconomic activities are considerable. In total, FEMA aid disbursed for the state of Oklahoma for these disastrous events was $795 million. While this study presented a good snapshot of monetary and general weather impacts, the article does fail to define how the funds were allocated with respect to disaster relief.

Another issue concerning winter weather are the effects of what have been coined “high intensity (impact), sub-advisory” storms (Devoir 2004). When these systems fail to meet the National Weather Service requirements (NWS Omaha 2018) of a typical, 6 inches (15.2 cm) in 12 hours or 8 inches (20.3 cm) in 24 hours, snowfall threshold for a winter storm watch/warning, a winter weather advisory may be issued for accumulations of 3 - 5 inches (7.6 – 12.7 cm). An advisory may also be issued for instances where a sub-advisory storm will have a definitive impact such as high intensity snowfall over a short duration or snowfall occurrences during peak rush hour times (NWS Omaha 2018). Much work has been done by the NWS in order to relay the messages of high impact, sub-advisory events since Devoir (2004) published his study; however, there are still

considerable strides that need to be made in order to effectively and concisely communicate these hazards to the general public.

2.3 MDSS

Throughout the 1990's the United States Department of Transportation Federal Highway Administration (FHWA) understood that efficient road weather management was crucial for societal and environmental considerations (Pisano et al. 2005). In 2001 the FHWA initiated a development plan to the National Center for Atmospheric Research (NCAR) to develop the first ever operational MDSS. A functional prototype was presented to the FHWA in 2002 (Petty and Mahoney 2008). Further iterations were developed in later releases as advances were made technologically and operationally. Reports were constructed by various DOTs as well as within the private weather enterprise that reviewed the positive and negative feedback associated with the implementation of the system (Block et al. 2003; Pisano et al. 2005; Linden and Petty 2008; Ye et al. 2009; McClellan et al. 2009).

An internal report of the background processes within the MDSS during its early stages was published by Block et al. (2003). The main motivation behind the creation of this new forecasting system was a result of the necessity for timely winter road maintenance forecasts within various DOT entities during the winter months. Ultimately the end result of the MDSS implementation was to efficiently relay meteorological information in a universally understandable format that could be incorporated into road maintenance. Block et al. (2003) further discussed the many facets of data acquisition,

numerical weather prediction, grid-based forecast creation and alteration, dissemination and alerts, and monitoring and maintaining alerts behind the actual system that culminate in the final user-friendly interface. An in-house satellite broadcast network (NOAAPORT) system was constructed by Meridian (Meridian Environmental Technology, Inc. 2020) as well as general data acquisition from state DOTs and mesonets. NOAAPORT effectively communicates real time NOAA environmental data via commercial satellite C-band transmission (NWS 2008). Once all of the pertinent data are obtained, the data are input into several different numerical weather prediction models. These models were said to include NOAA's National Center of Environmental Prediction (NCEP), mesoscale modeling system Version 5.0 (MM5), and advanced regional prediction system (ARPS). This spread of models was intended to provide the most current short and long-term models of varying resolution in order to emulate an ensemble forecasting system.

Once the numerical weather data are gridded, a gridded forecast can be created. As with any forecast, the forecaster may make limited, subjective modifications such as subjective analysis, model blending, or site-specific editing to ensure that the forecast accurately accommodates for the local conditions of the forecast area. At the time, the highway condition analysis and prediction system (HiCAPS) road surface model was implemented in order to assess and forecast the road surface conditions. The HiCAPS model was managed internally by Meridian and utilized a unique approach for the time. Rather than relying on balanced fluxes and the general iterative approach that many models prior had used, HiCAPS assimilated hourly location-specific weather data from

the gridded forecasts, depths and phases of water on the pavement, and latent heat and mass exchanges from phase changes, hydrologic processes, and maintenance practices (Block et al. 2003).

According to Linden and Petty (2008), the MDSS system had been using the snow thermal model (SNTHERM) which was developed by the Cold Regions Research and Engineering Lab (CRREL) in Hanover, NH. Simply stated, SNTHERM (Jordan 1991) is a physically based ground condition model that is defined by surface fluxes (Frankenstein 2012). In 2007 the SNTHERM model discontinued active development and opened discussions as to which road temperature model should become the successor. The top candidates were fast all-season soil strength (FASST) model (Frankenstein and Koenig 2004), Engineer Research and Development Laboratory (ERDC)/CRREL's newest energy balance model, and model of the environment and temperature of roads (METRo), a Canadian energy balance model developed by Crevier and Delage (2001). The 2008 report from NCAR (Linden and Petty 2008) outlined the strengths and weaknesses of each new system and concluded that METRo outperformed FASST from a forecasting standpoint and was recommended as the successor to SNTHERM.

Ultimately, this forecast system utilizes iterative processes to reach a finalized, usable winter road weather forecast. The MDSS relies on a substantial data ingest from a variety of sources. Real time observational data from ASOS and Road Weather Information System (RWIS) stations throughout a designated area are collected and assimilated into various publicly available weather models such as the NAM, GFS, and

NWS forecasts. Once the initial environmental forecasts are aggregated, one final ensemble-like forecast, produced by a statistical weighting of the models, is output by the MDSS. After the environmental forecast is finalized it is run through the road condition and treatment module (RCTM). This RCTM module creates the road treatment recommendations that are ultimately used by the road maintenance crew members. With any sort of preliminary forecast system there are bound to be pros and cons. These features have the ability to make or break the product. The MDSS has been no stranger to this process and outside evaluations of the system (Ye et al. 2009; McClellan et al. 2009) outlined improvements that should be made in the product as well as fiscal year reports outlining the monetary benefits of the MDSS. Two main case studies were also conducted between 2005 and 2008 in Iowa (Pisano et al. 2005) and Colorado (Chapman et al. 2008) respectively in order to test the MDSS in the field.

The initial case studies conducted by Pisano et al. (2005) and Chapman et al. (2008) were organized as a metric to illustrate what changes had been introduced to the functional prototype developed by NCAR between its public release in 2003 and subsequent reports. The most notable comparative report was the implementation of the MDSS in and around the city of Denver, CO for a Colorado Field Demonstration which spanned the winter of 2007-2008 (Chapman et al. 2008). The case that this report was compared against was the Iowa implementation, which was conducted for the winters of 2003-2004 (Pisano et al. 2005). The initial Iowa case study recommended changes to the weights of the model input that the MDSS had been using and the review by NCAR (Chapman et al. 2008) examined how well the recommended implementations performed.

Both of these original studies were conducted and monitored by scientists at NCAR in Boulder, CO.

The first field demonstration for the MDSS covered a period from 3 February 2003 to 7 April 2003 and involved the crews of three maintenance garages around Ames and Des Moines, Iowa (Pisano et al. 2005). Maintenance crews were under immense pressure to have plows at the ready as soon as snow began and also to clear roads to the public's liking in a timely manner. Pisano et al. (2005) described the status and progress that the MDSS has undergone. As this system was created by NCAR, the main goals of the overall project were to showcase the positive benefits of the MDSS implementation as well as to reveal the availability of a privatized market for this type of forecast system Success for the entire MDSS project was defined by the FHWA as when private sector implementation was achieved and private companies integrated the MDSS components into usable products.

Of the six recommendations for the MDSS system improvements, there were two objectively meteorological issues that were addressed. The first issue was the difficulty of forecasting for light precipitation events. The MDSS did not predict these events well because the system requires highly specific precipitation forecasts (Pisano et al 2005). Often these events had high impacts that were poorly forecast and had maintenance crews scrambling to get out and maintain the roads. The other main meteorological issue was more directly correlated with the available instrumentation at the time. The problem described the inadequacy of RWIS sensors to observe freezing or frozen precipitation accumulation and the lack of accurate observations of precipitation from ASOS stations.

These poor representations of observed precipitation often inhibited the MDSS's ability to provide sound verification of events (Pisano et al. 2005).

The 2003-2004 field demonstration campaign introduced a multitude of upgrades including a time-lagged ensemble of the mesoscale road weather forecast system (RWFS) model and the installation of global positioning system/automated vehicle location (GPS/AVL) on eight plow trucks (Pisano et al. 2005). Sensors for measuring precipitation, temperature, humidity, shortwave solar radiation, and wind were also installed at the Ames yard to provide more accurate verification observations. The biggest finding in the report was that Iowa DOT estimated that an operational MDSS has the potential of saving the DOT between 10% and 15% of their annual maintenance costs (materials and manpower), which equates to approximately $3.5 million (in USD from 2005) per year (Pisano et al. 2005). This positive net savings just from the MDSS utilization was one of the many positive impacts that this forecast system could feasibly produce for maintenance crews moving into the future.

The test site was moved to central CO for the winter of 2004-2005 observation to better assess the system's ability to forecast for mountainous regions, improve forecasting and treatment of black ice, blowing snow, and frost conditions, and understand multiple treatments on a single road segment (Chapman et al. 2008). SNTHERM used a one dimensional mass and energy balance model and was being upgraded to METRo, which is a Canadian mass/energy balance model. The MDSS changed QPF forecast weights from 60% for the NAM, 30% for the Rapid Update Cycle (RUC), and 10% for the GFS to 60% for the NAM, 20% for the RUC, and 20% for the GFS. The final RWFS forecast

outputs a precipitation forecast based upon a QPF threshold of 0.05 mm hr^{-1} and probability of precipitation (POP) threshold of at least 15% forecasted. RWFS also includes NWS Aviation (GFS short range, also depicted as MAVMOS) MOS, NAM MOS, GFS MOS, and RUC MOS into their forecast system. Newly introduced statistical techniques for the RWFS improved the predictions of all parameters. However, no singular model showed confidence in increased accuracy over all parameters, therefore the blended ensemble forecast method was the most logical solution for this issue (Chapman et al. 2008).

A review by NCAR (Chapman et al. 2008) was conducted to document how well the new implementations aided in the forecasts at the testbed in Colorado. Four case studies of differing snowfall intensity were chosen: 20 November 2007 (moderate snow), 7 December 2007 (light snow), 25 December 2007 (moderate/heavy snow), and 16 March 2008 (light/moderate snow). Predictably, overall model performance was highly volatile from case to case. The NAM was observed to be significantly less accurate with regards to QPF comparatively to the 2006-2007 winter season as well. Since the RWFS is heavily weighted (60%) towards the NAM output forecasts, this proved to be a drastic issue. The researchers recommended that the model should possibly be revised to decrease dependence upon NAM forecasts if the inaccurate trend continues (Chapman et al. 2008).

Ultimately, the MDSS was created as a supplement for maintenance crews to combine pertinent road weather data with road maintenance recommendations into one easy to use module. One of the main issues with the model stems from the dependence

upon the accuracy of weather models and observations for both ambient and pavement parameters. A 2006-2007 case study in Colorado was conducted to determine the top replacement for the SNTHERM model. The 2007-2008 case study was the first to implement the new METRo energy balance model and reported improved MDSS road temperature and road conditions forecasts, along with better recommended treatments. The addition of road and truck cameras as well as the GPS/AVL modules into the MDSS system also incorporated a new level of assessment for the observed conditions and point forecasts provided by the MDSS.

Chapter 3: Data and Methodology

3.1 Data

An analysis was conducted using a top-down approach in order to understand the synoptic setup for the two case studies, which affected Nebraska. The top-down approach is used to analyze the atmosphere at differing pressure levels, starting at the 300 hPa level and proceeding down to the surface level. This analysis can be used to gain a more thorough understanding of the atmosphere by visualizing where moisture and lift may be most prevalent for snowfall. Upper air maps were obtained from the NWS's Storm Prediction Center (SPC) surface and upper air maps page (SPC 2019) and surface maps were obtained from the NWS's Weather Prediction Center (WPC) surface analysis archive page (WPC 2019).

The primary datasets that will be compared against the upper air and surface observations are the generated forecast and 24-hour post-storm verification from the NDOT-MDSS for the chosen routes. The two observed storms being analyzed as Colorado lows mainly impacted eastern Nebraska. To highlight the impacts, five routes were selected in and around the Lincoln, NE region (Figure 3.1) will be investigated for both events. Two of the routes examined were along Interstate 80 (I-80): the first is from the Waverly I-80 interchange to the I-180 interchange (W80) and the second is from the I-180 interchange to the Pleasant Dale I-80 interchange (P80) and are denoted as having Super Commuter and Urban Commuter levels of service (LOS) respectively (Table 3.1).

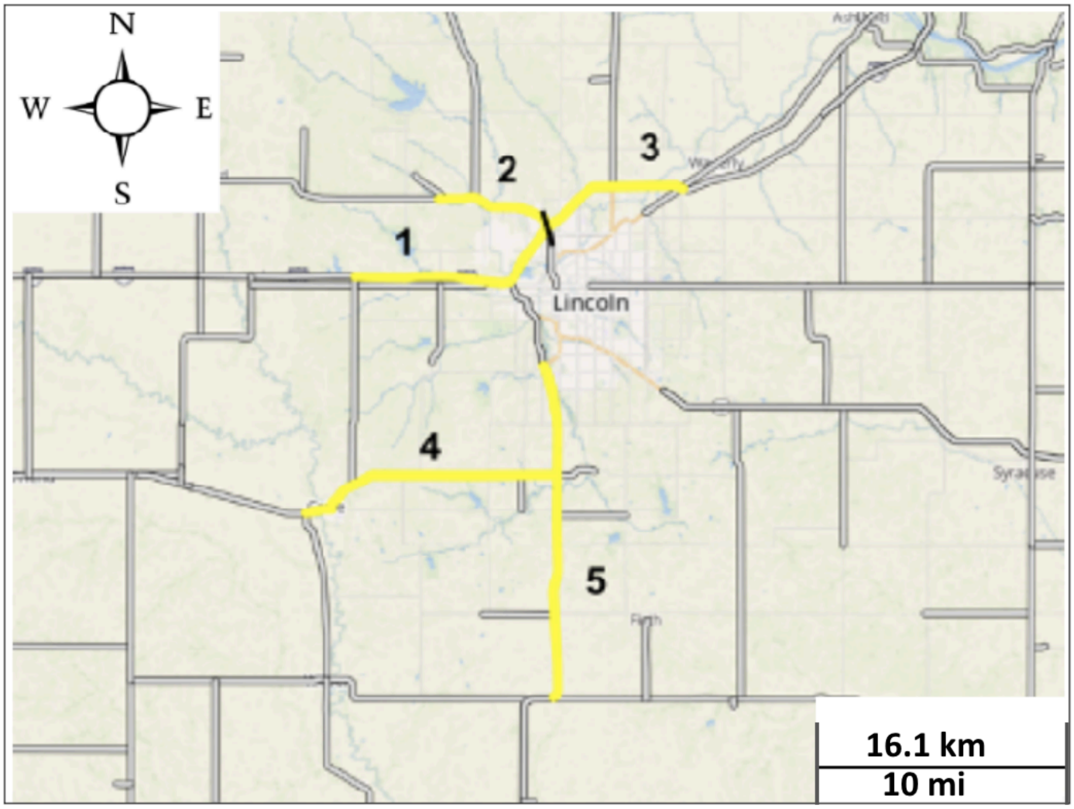

Figure 3.1: The five selected routes (1) P80, (2) HW34, (3) W80, (4) HW33, (5) HW77 for observation within the NDOT-MDSS system for both case study events (23-26 November 2018 and 21-25 February 2019) (from *WebMDSS*)

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

Route Designation	Traffic Level (Average Daily Traffic Count)	Regain Time (bare lane) (hrs)	Routes
Super Commuter	> 50,000	4	W80
Urban Commuter	20,000 - 50,000	6	P80
Rural Commuter	7,000 - 20,000	8	HW34, HW77
Primary	2,500 - 7,000	12	HW33
Secondary	1,000 - 2,500	24	N/a
Low Volume	< 1,000	48	N/a

The remaining three routes include Highway 34 (HW34), which is an east-west route from near Malcolm to the I-180 interchange, roughly paralleling the Pleasant Dale interstate route. Highway 77 (HW77) is a north-south route from Lincoln to Beatrice. Both routes are notated as Rural Commuter. The last route is Highway 33 (HW33), an east-west route from Highway 77 to Crete, which carries a Primary LOS. This broad variety of road section LOS was selected in order to examine if there were any differences in MDSS forecasts comparatively due to the LOS.

With more insight into the LOS that dictated the maintenance protocols for the events, data could then be obtained for the selected routes from the NDOT-MDSS. The saved storm data for the November system ran from 1800 UTC 23 November 2018 to 1750 UTC 26 November 2018. The saved storm data for the February system ran from 2300 UTC 21 February 2019 to 350 UTC 25 February 2019. Since the NDOT-MDSS is utilized primarily for winter weather maintenance, the variables used for data analysis were temperature, snowfall accumulation, dewpoint, wind speed, and the start/end times for the snowfall events. The start and end times are equally important to the NDOT personnel in order to know when maintenance should begin for a particular system and as an estimate of how long maintenance crews may need to be out maintaining roads towards the end or even after the event.

Data were extracted from the *WebMDSS*^{TM} (2019) user interface for the environmental parameters as well as snowfall forecasts. Hourly forecast data from NDOT-MDSS were obtained by selecting a specific time and date to obtain the observed values. All of the values for the forecasted environmental parameters were taken at

hourly intervals, between the NDOT-MDSS derived snowfall start and end times, from the 3 hourly forecast run intervals prior to snowfall onset. The snowfall accumulation totals were recorded as the maximum accumulation values at the hourly forecast intervals. Once the date and time were selected for a forecast time, the individual route could be selected within the user interface for current and forecasted road conditions and treatments. From this location, the observed and forecasted meteorological and maintenance values were also generated in tabular format. The tabular format values for the environmental parameters were copied by hand into comma-separated-values (.csv) files. Visual representations of the extracted data were then constructed in Python using the Pandas and Matplotlib modules.

The NDOT's MDSS was compared against other forecast entities such as the modeled average consensus between the RAP, GFS, 12 km NAM, and 4 km NAM at the appropriate snow-to-liquid ratio from automated surface observing system (ASOS) observations obtained from the Iowa State Environmental Mesonet website (Iowa State 2019). Point forecast products for the city of Lincoln were obtained via NWS Omaha/Valley (2019) for the selected case study dates. Observed data from ASOS for the Lincoln Airport, which is near the selected routes, were obtained from the National Center for Environmental Information's (NCEI) Local Climatological Data (LCD) (NCEI 2019). These observed data were examined against temperature, dewpoint, wind speed, visibility, and snowfall accumulation from the NDOT-MDSS. Analyses were conducted for these environmental parameters as well as for the duration of snowfall at each section of roadway.

3.2 Methodology

Upper air analysis of each system was done starting with a top-down analysis. The top-down analysis looked at the atmosphere from multiple levels (300, 500, 700, and 850 hPa) to investigate the storm systems from a broader perspective outside of the Lincoln, NE region. Upper level observations generally show what the upper level flow pattern, which affects the speed and direction of the surface feature, looks like. Areas of divergence aloft are also associated with convergence at the surface and the net column of divergence aloft leads to the intensification of a progressing storm system. In the mid to lower levels such as 850 and 700 hPa, regions of saturation may collocate with areas of vertical lift to produce a preferred precipitation region. The temperature profile derived from these levels was also important in diagnosing the precipitation type as hydrometeors fall through these levels toward the surface.

The November event upper air analyses were conducted for 12 UTC 24 November – 12 UTC 25 November, which covers 20 hours prior to snowfall onset. The February event upper air analyses were conducted for 12 UTC 22 February – 12 UTC 23 February 2019, which covers 29 hours prior to snowfall onset. It is helpful to identify how the storm systems evolved synoptically, up to and during the event, in order to accurately assess how the NDOT-MDSS handled the initialization and movement of the system.

The three environmental parameters at the surface from the NDOT-MDSS (air temperature, dewpoint temperature, and wind speed) were investigated at intervals of 3, 6, 9, and 12 hours prior to snowfall onset. The hour of snowfall onset within the model

was determined as the hour when the snowfall rate increased above 0.0 inches hr^{-1} (0.0 cm hr^{-1}) and the end of snowfall was the hour after the snowfall rate fell to 0.0 inches hr^{-1} (0.0 cm hr^{-1}) and snowfall accumulation did not increase. Analysis of the surface environmental parameters was conducted for the time period between the snowfall start and end times. These forecasted environmental parameters were then compared against the observed values from the ASOS station at the Lincoln airport (KLNK) for the same period to visualize how well the NDOT-MDSS was forecasting during the event. Difference graphs were also created to further visualize the accuracy of the forecasts generated by the NDOT-MDSS.

From the NDOT-MDSS, forecasted snowfall accumulation is compared to observed snowfall accumulation within the NDOT-MDSS. This analysis spans a time period of 24 hours prior to snowfall onset up until the end of the snowfall. Forecasted snowfall accumulation from the NDOT-MDSS is also compared against the RAP, 12 km NAM, 4 km NAM, GFS, and NWS forecasts, as well as the ASOS observed total snowfall accumulation. The forecasted model comparisons are all compared at hourly increments of forecast runs from 24 hours prior to snowfall up until snowfall onset. A more comparative analysis of forecasted snowfall accumulations across models is conducted in the final section of the results. NDOT-MDSS snowfall graphs were produced from the same data as used in the prior analyses; however, the end times displayed for the routes on this graph corresponds with the snowfall start at each of the five routes. This new approach to the graphs illustrates the true forecast of the NDOT-MDSS before the snowfall began, which eliminates the possible corrections that

take place as the NDOT-MDSS sees the snowfall in real-time. Visibility is used as an approximation for snowfall intensity and accumulation within the NDOT-MDSS, so a comparison of the NDOT-MDSS recorded visibility during the snowfall period was compared against the ASOS observed visibility values to assess the accuracy of the NDOT-MDSS snowfall accumulation methods.

For the event length analysis, the snowfall start time was defined as when snow rate increased and by the next hour snow accumulation had increased in the NDOT-MDSS. The end time was defined as the hour after snow rate fell to 0.0 inches hr^{-1} (0.0 cm hr^{-1}) and snowfall accumulation did not increase. From the start and end times per forecast run, a composite of the event length was created for each forecast run. A difference graph between the observed and forecasted end time was also developed to examine the forecasted event length.

3.3 Limitations

The MDSS was developed as a decision support system intentionally. While the product may offer helpful guidance to maintenance managers, the MDSS is certainly not perfect and comes with its own list of limitations that must be stated in order to develop a thorough and intuitive understanding of the system. The main outright limitation, from the perspective of a meteorologist researcher, was the general black box methodology that surrounds the system as a whole. Knowing that this limitation existed was crucial to molding the examination of the system. We could only know what information was disclosed to us from the private company and so the forecast data then had to be taken at

face value without an extensive knowledge as to how it was developed and utilized throughout the model.

Chapter 4: Results and Discussion

4.1 Case Study I: 24-25 November 2018

4.1a) Synoptic Analysis

At 1200 UTC 24 November 2018, a strong area of divergence aloft (Figure 4.1a) was observed on the lee side of the Rockies. The area of divergence is noted along the Front Range in central Colorado on the southeastern side of the upper level trough. Divergence aloft is indicative of surface convergence and the balance of net divergence between surface convergence and divergence aloft results in stronger vertical motions that can lead to increased precipitation intensity. A favorable region of lee cyclogenesis is beginning to manifest across the Colorado Rockies. An upper level trough (300 and 500 hPa) with a branch of the polar jet stream is observed over the Pacific Northwest, which results in zonal flow over the Rocky Mountains in Wyoming and Colorado (Figure 4.2a). At this time, the lower levels (850 and 700 hPa) observe lowering heights in response to the beginning of lee cyclogenesis (Figures 4.3a, 4.4a). At the surface, pressure falls are already being observed across the Central Plains up to the Front Range in Colorado and a modest region of moisture is also in place (Figure 4.5a).

The upper level trough has progressed farther eastward while also deepening by the 0000 UTC 25 November 2018 observation period (Figures 4.1b, 4.2b). Accompanying this eastward drift of the upper level trough is the continued presence of strong upper level divergence (Figure 4.1b) over southeastern Colorado and Nebraska. Analysis at 700 hPa (Figure 4.3b) shows the southeastward progression of the system. The 850 hPa level (Figure 4.4b) exhibits a drastic change as a region of lowered heights

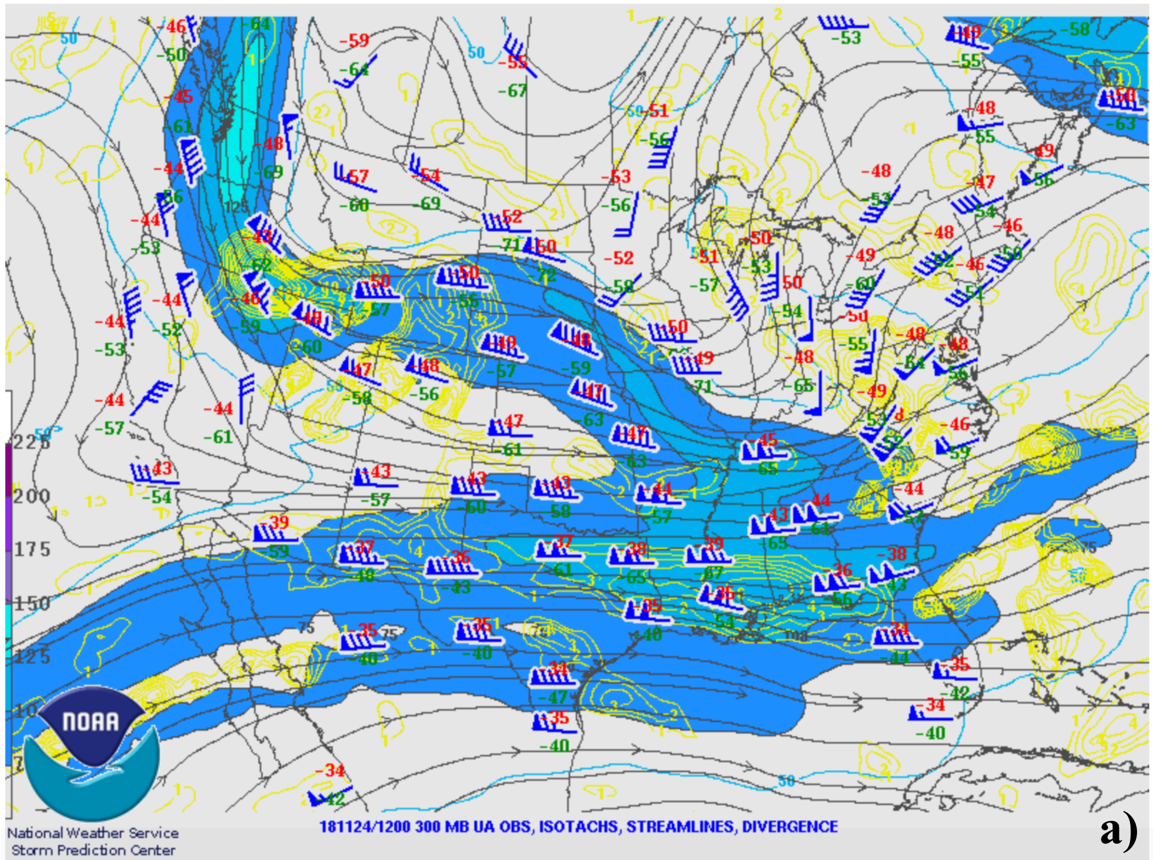

Figure 4.1a: 300 hPa analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

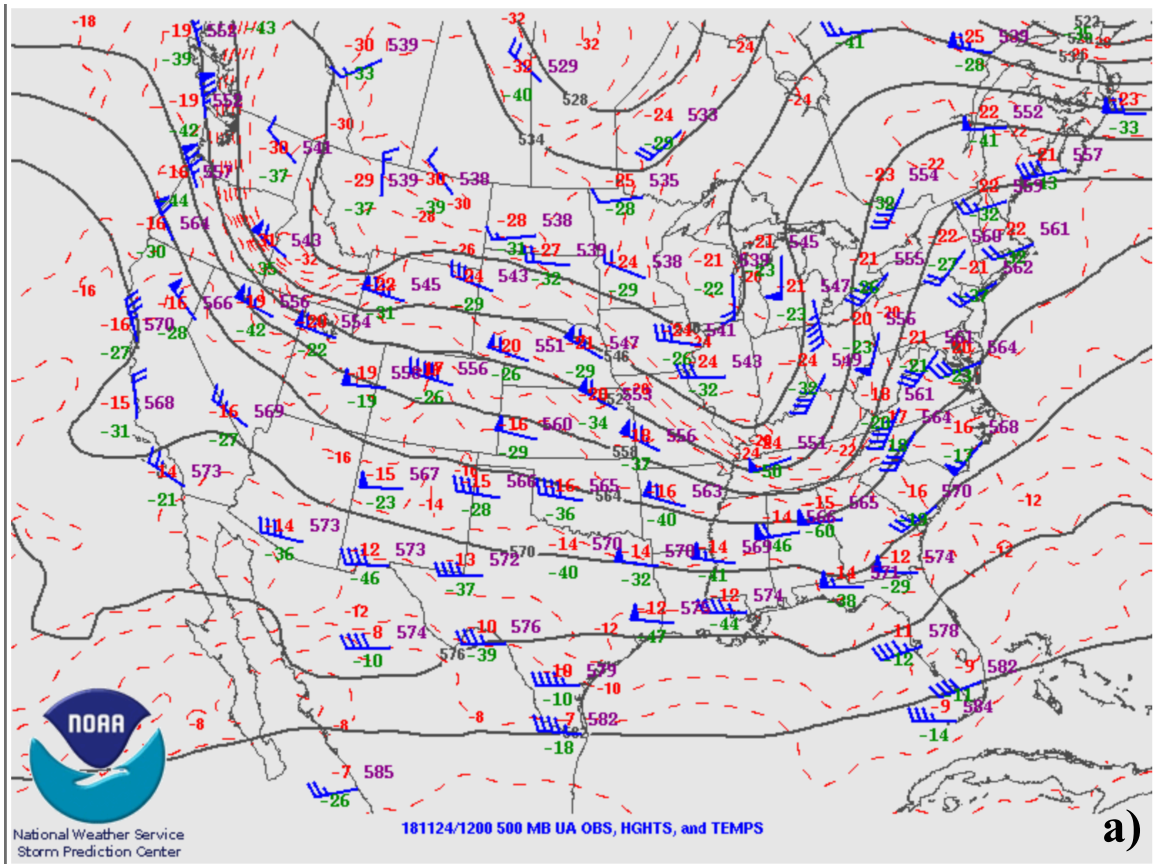

Figure 4.2a: 500 hPa analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

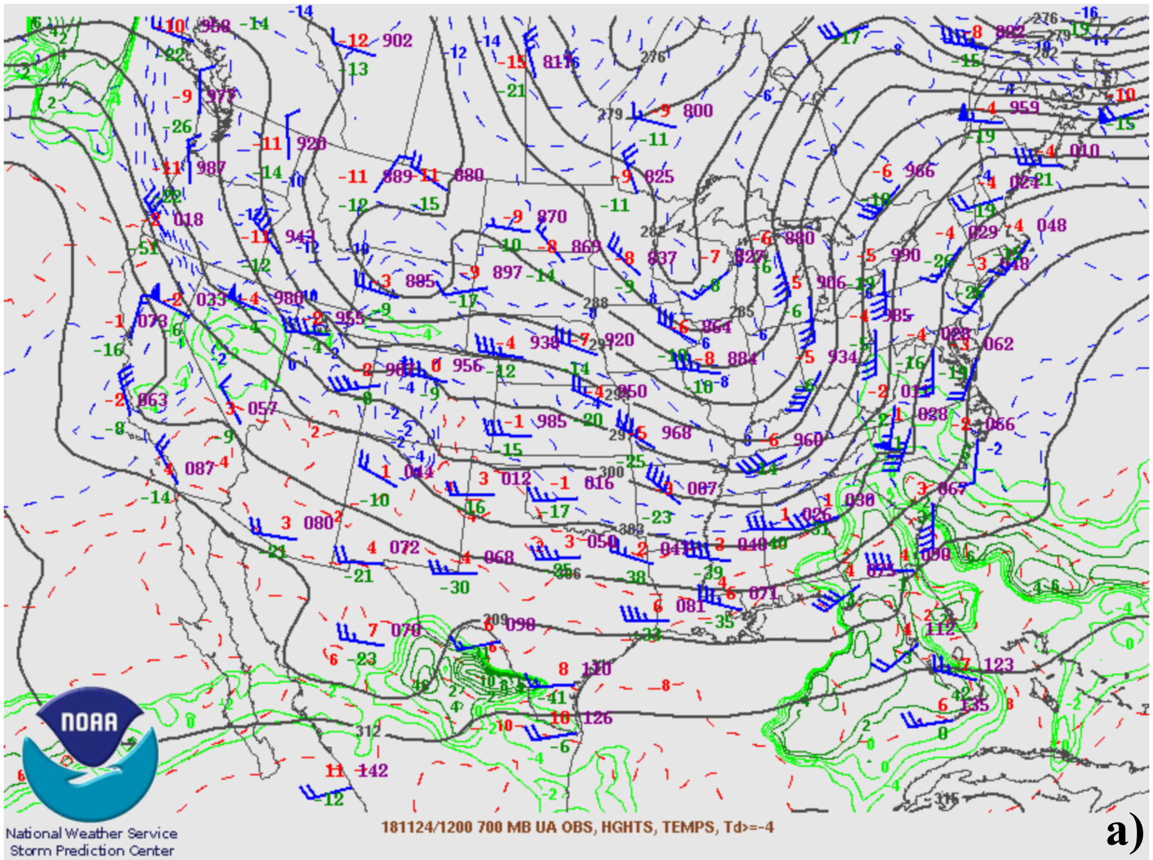

Figure 4.3a: 700 hPa analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

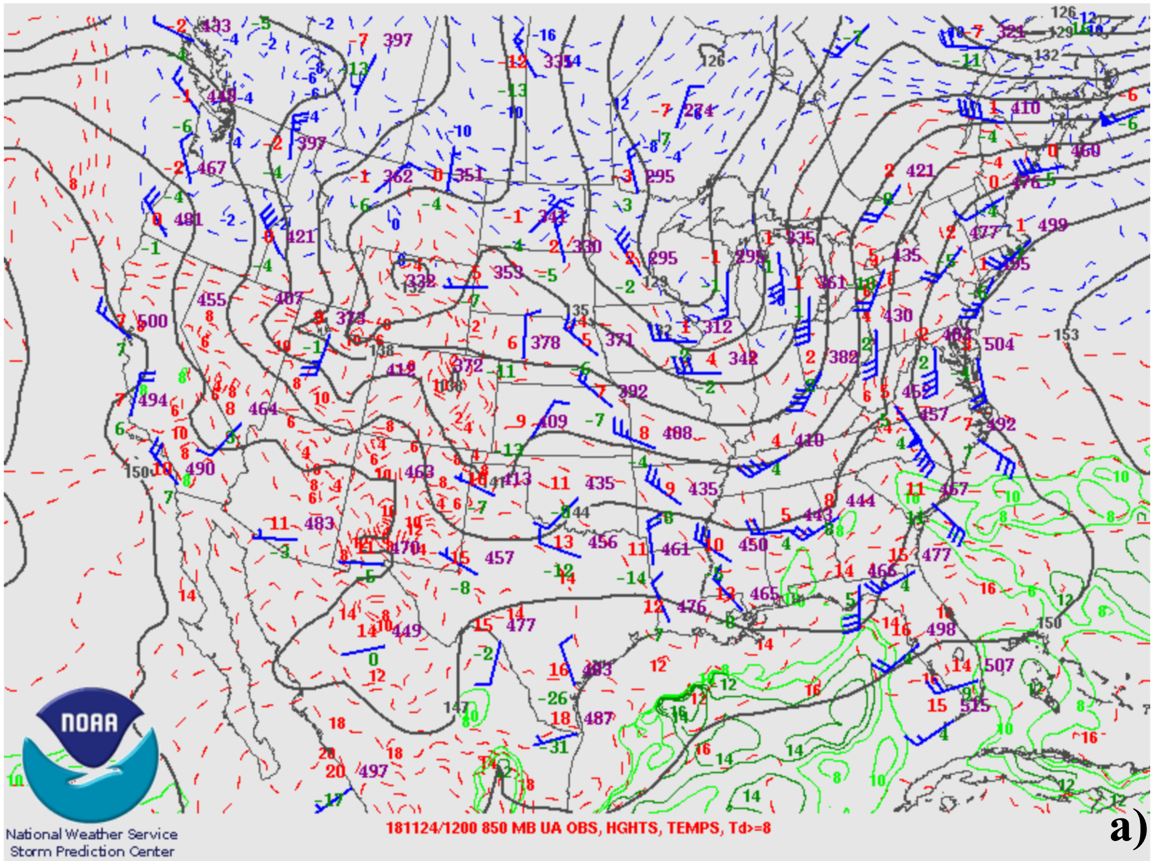

Figure 4.4a: 850 hPa analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

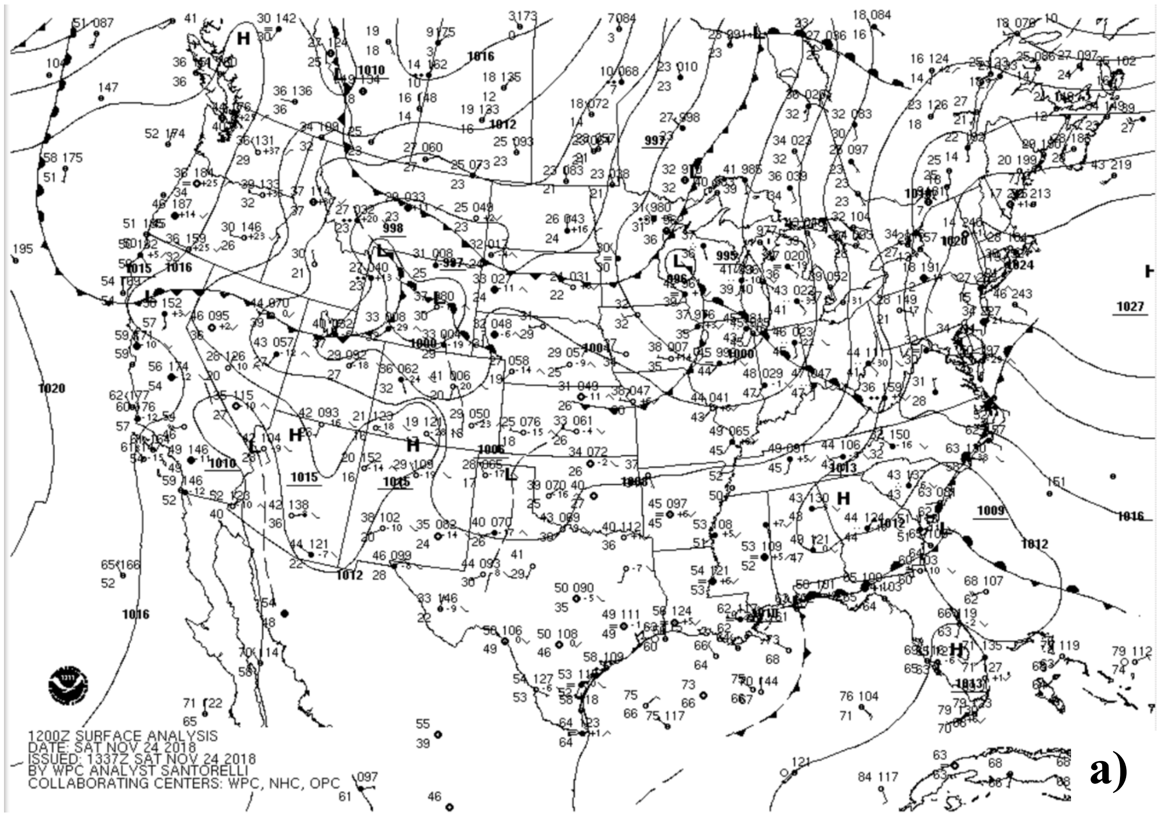

Figure 4.5a: Surface analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

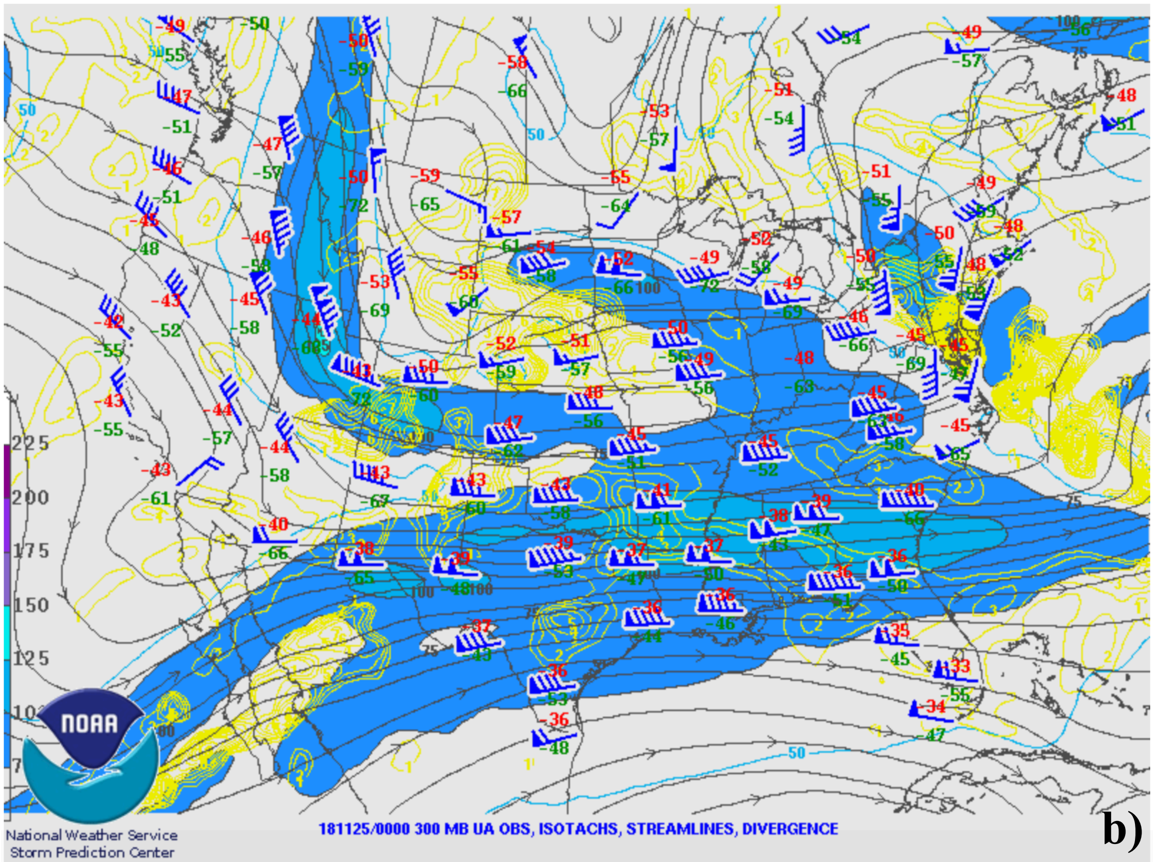

Figure 4.1b: 300 hPa analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

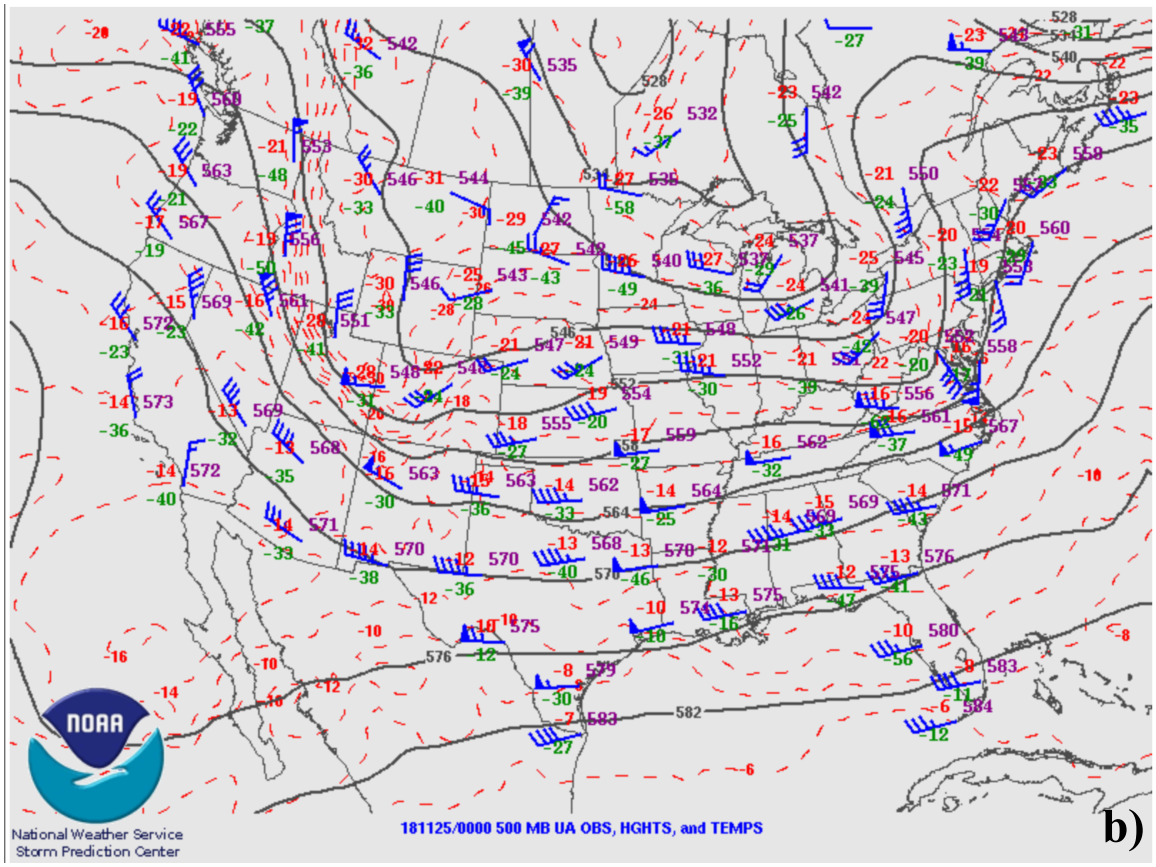

Figure 4.2b: 500 hPa analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

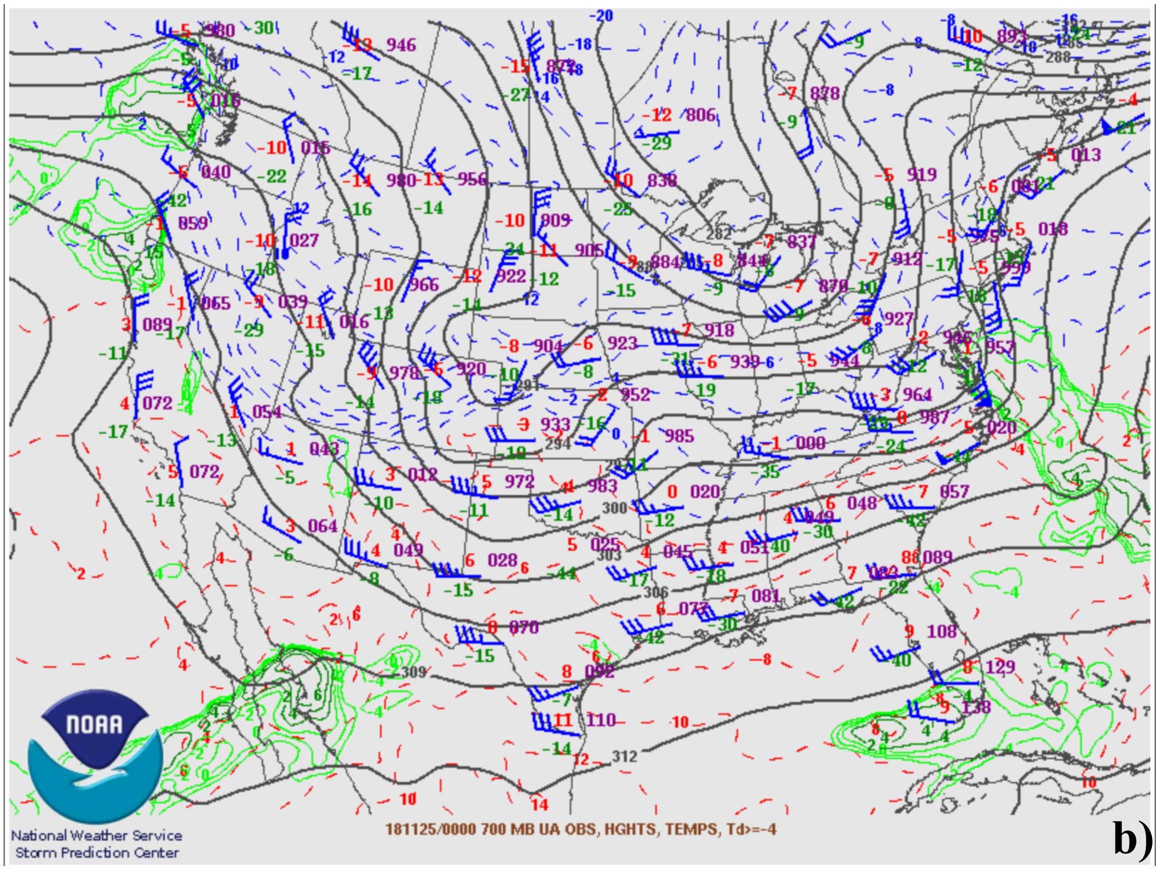

Figure 4.3b: 700 hPa analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

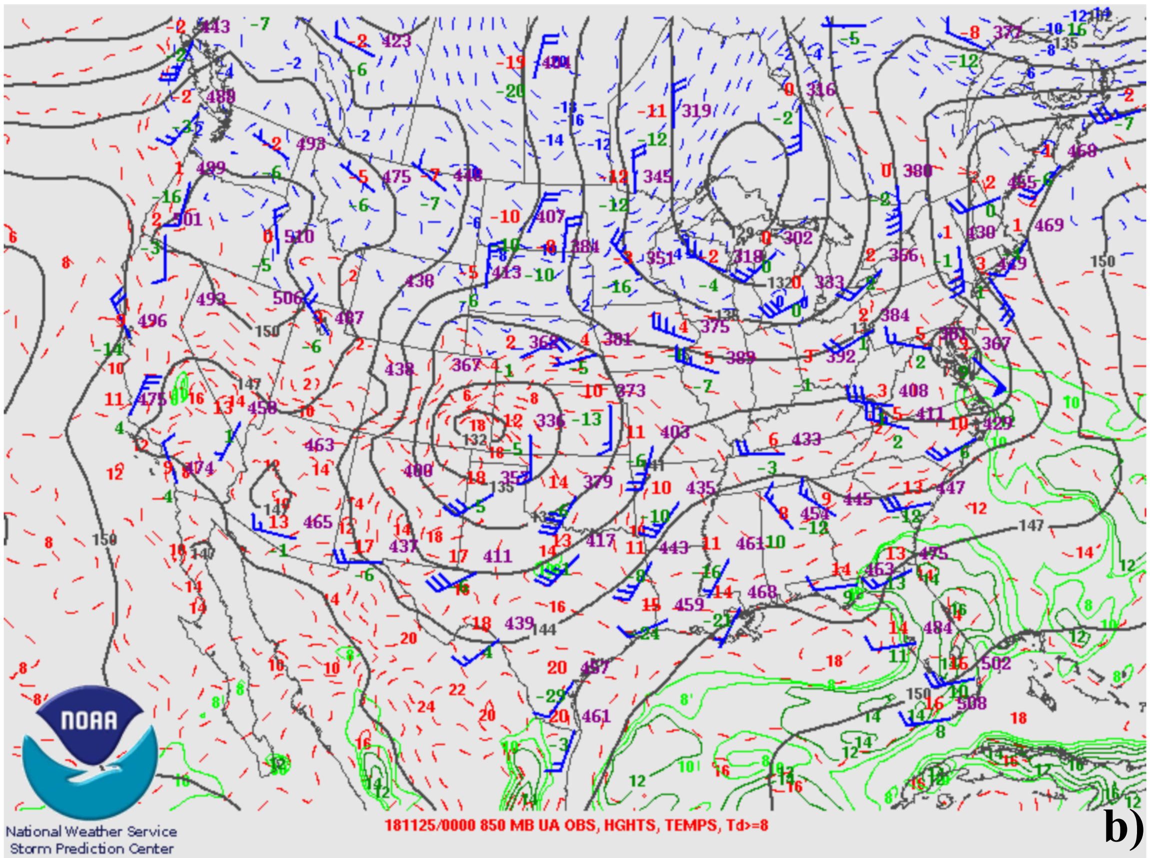

Figure 4.4b: 850 hPa analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

associated with a cutoff is observed along the lee side of the Rockies. Even more noteworthy is the lack of moisture at the lower levels. The introduction of a southerly wind component from the lee cyclogenesis indicates that as time moves on, slight warm air advection and, more importantly, Gulf moisture advection will be taking place soon. A closed low pressure system is observed over southeastern Kansas as well as a polar cold front advancing through the region (Figure 4.5b). This polar front is working to inhibit moisture at the surface while also decreasing temperatures toward the freezing level. The polar front can also be interpreted from the 1000-500 hPa thickness map. The 5400 m contour is observed to be over northern Nebraska at the time (Figure 4.6a).

The area of upper level divergence (Figure 4.1c) is observed moving farther east with the system, yet a band is still present over much of eastern Nebraska at 1200 UTC 25 November 2018. The upper level longwave trough is enveloping much of the Central Plains with closed height contours observed at the 500 hPa level (Figure 4.2c). Southeastern Nebraska is also in the vicinity of the left exit region of the upper level jet streak, which adds another mechanism for lift in the area. Defined regions of closed height contours are observed at both of the lower levels as the storm becomes nearly vertically stacked (Figure 4.3c, 4.4c). The surface analysis outlines decreasing temperatures across the region with strengthening northerly winds along with observations of snowfall occurring across the state (Figure 4.5c). These all match up well with the increasingly northerly winds in the lower levels as well as the strong concentration of moisture from the surface up to 700 hPa. The 5400 m contour

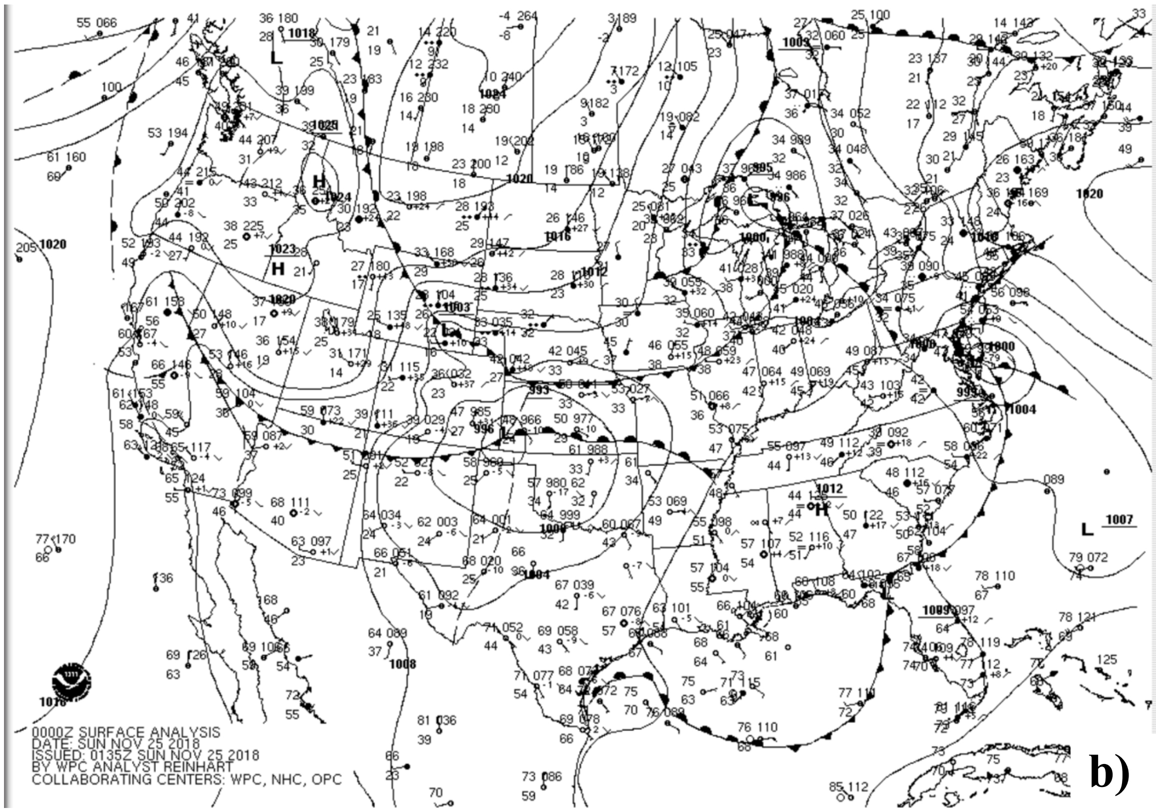

Figure 4.5b: Surface analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

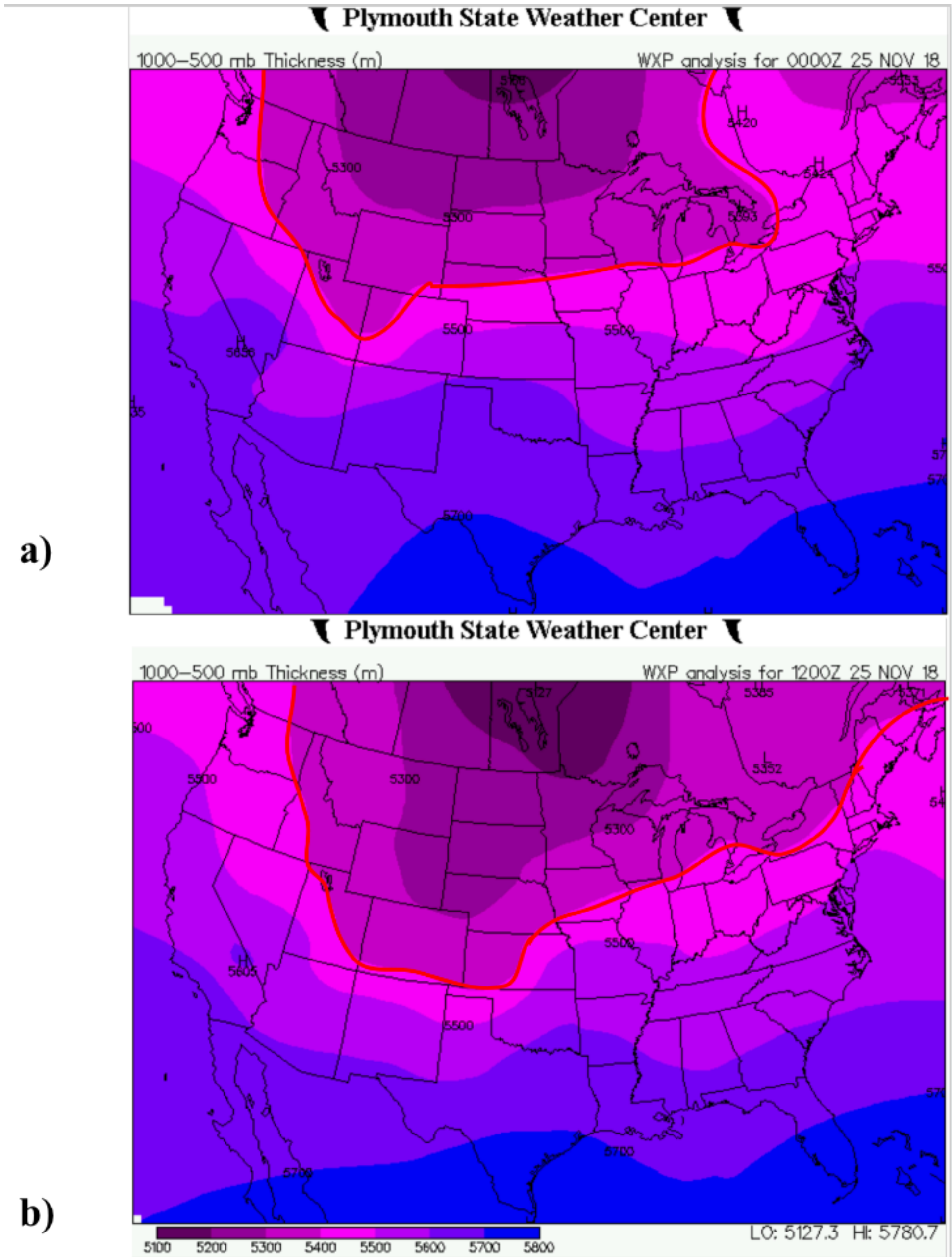

Figure 4.6: 1000-500 hPa partial thickness analysis with 5400 m critical thickness level outline (red) at: a) 0000 UTC 25 November 2018 and b) 1200 UTC 25 November 2018 (from Plymouth State 2020)

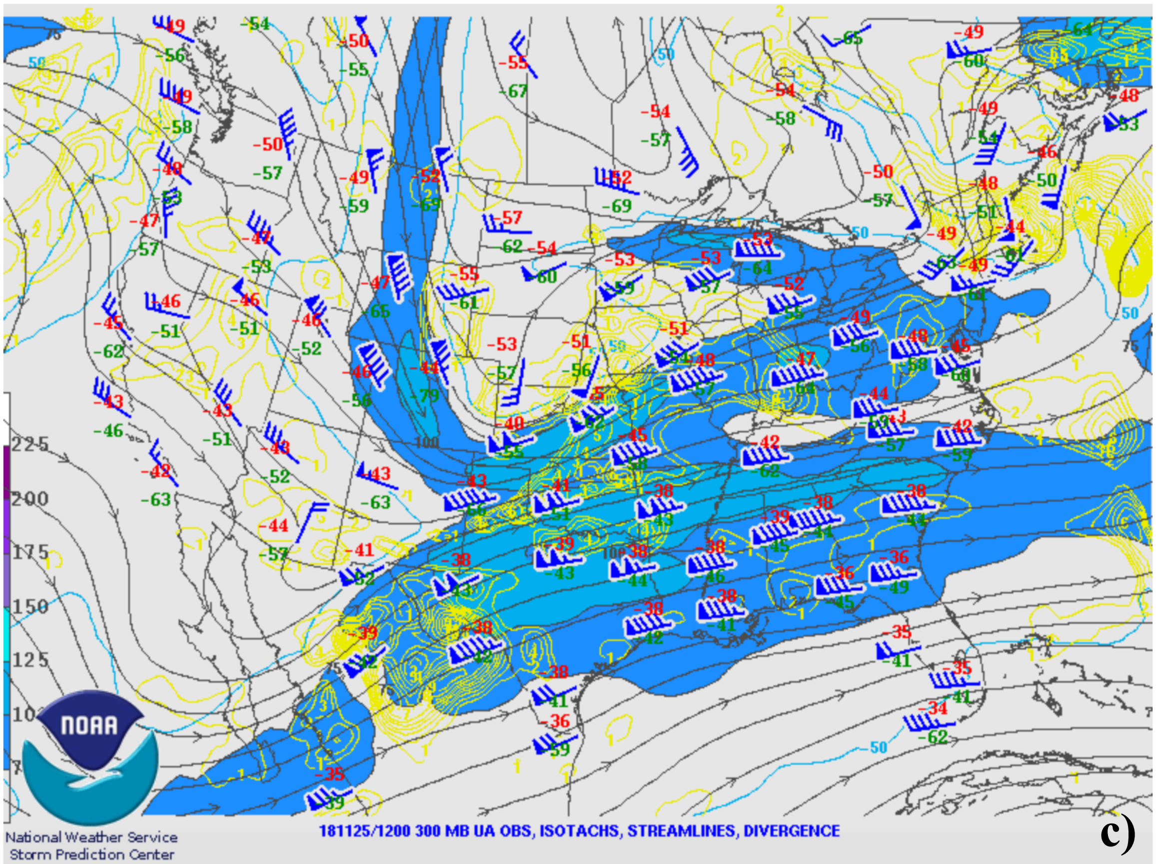

Figure 4.1c: 300 hPa analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

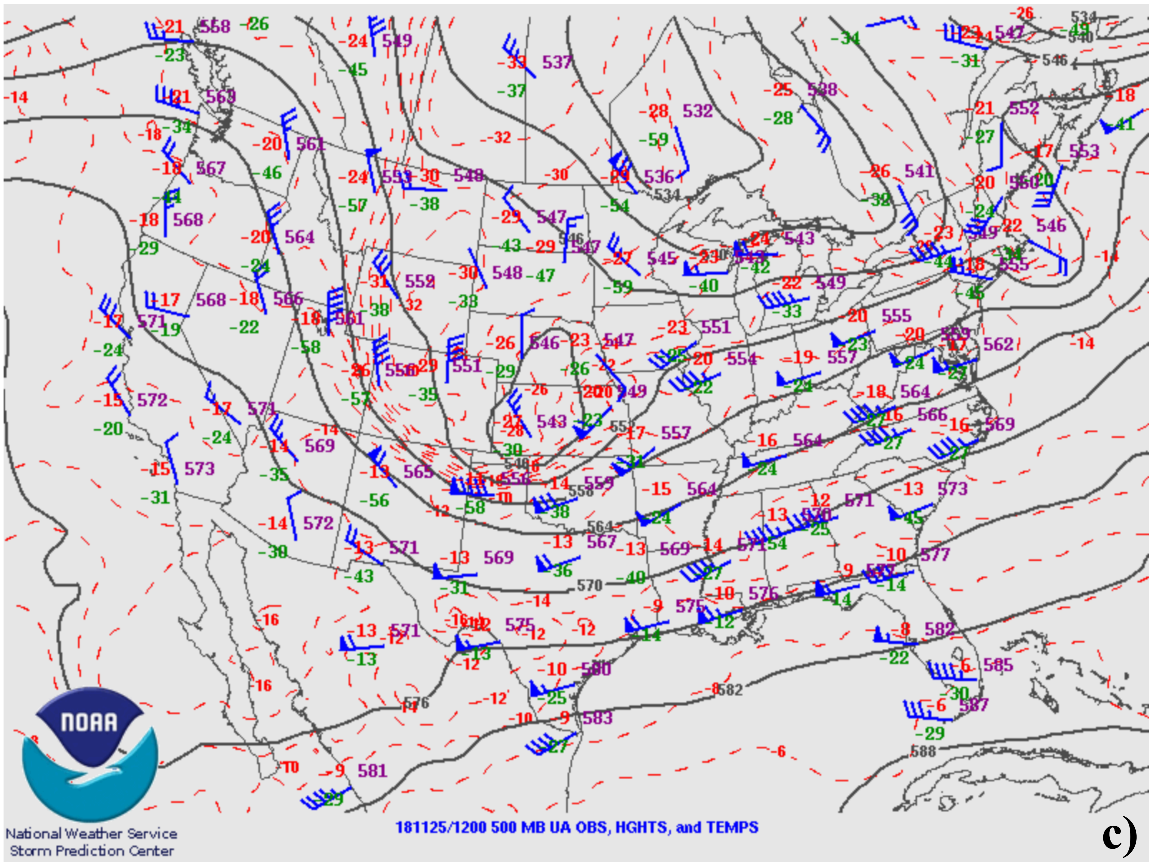

Figure 4.2c: 500 hPa analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

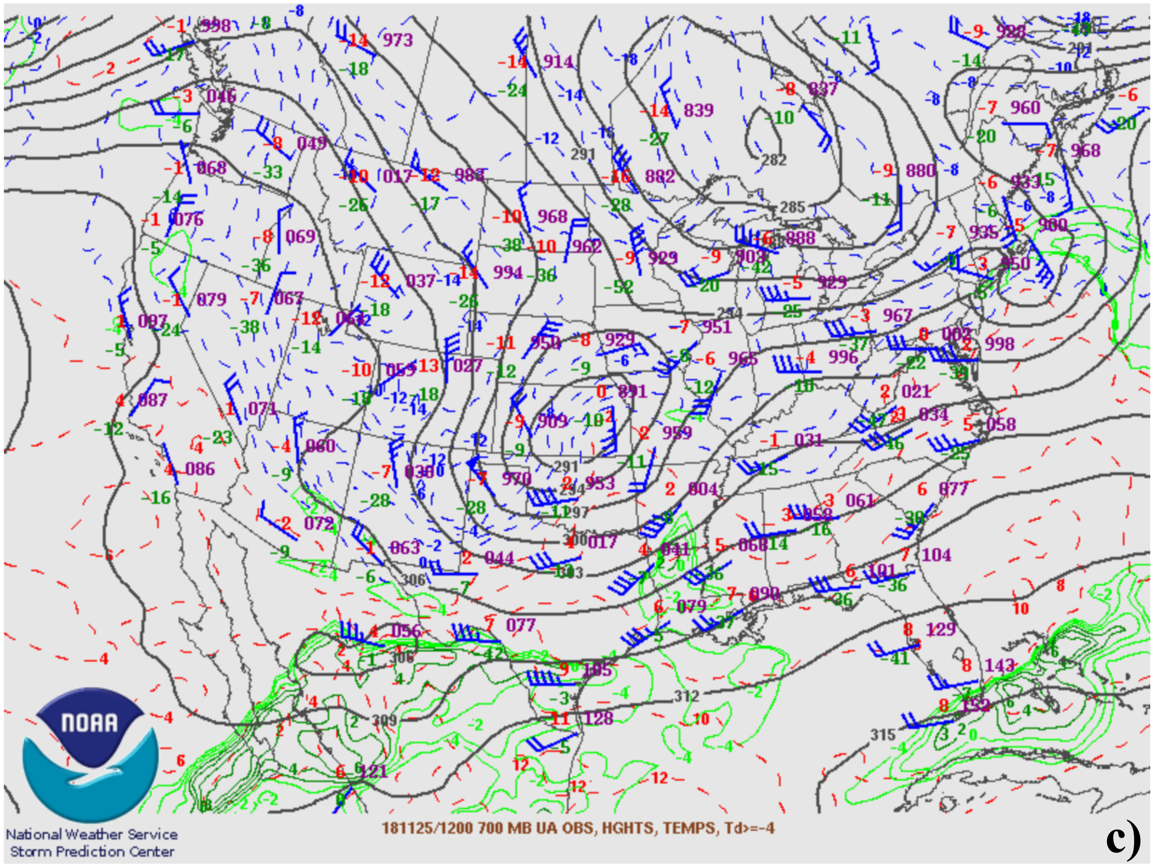

Figure 4.3c: 700 hPa analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

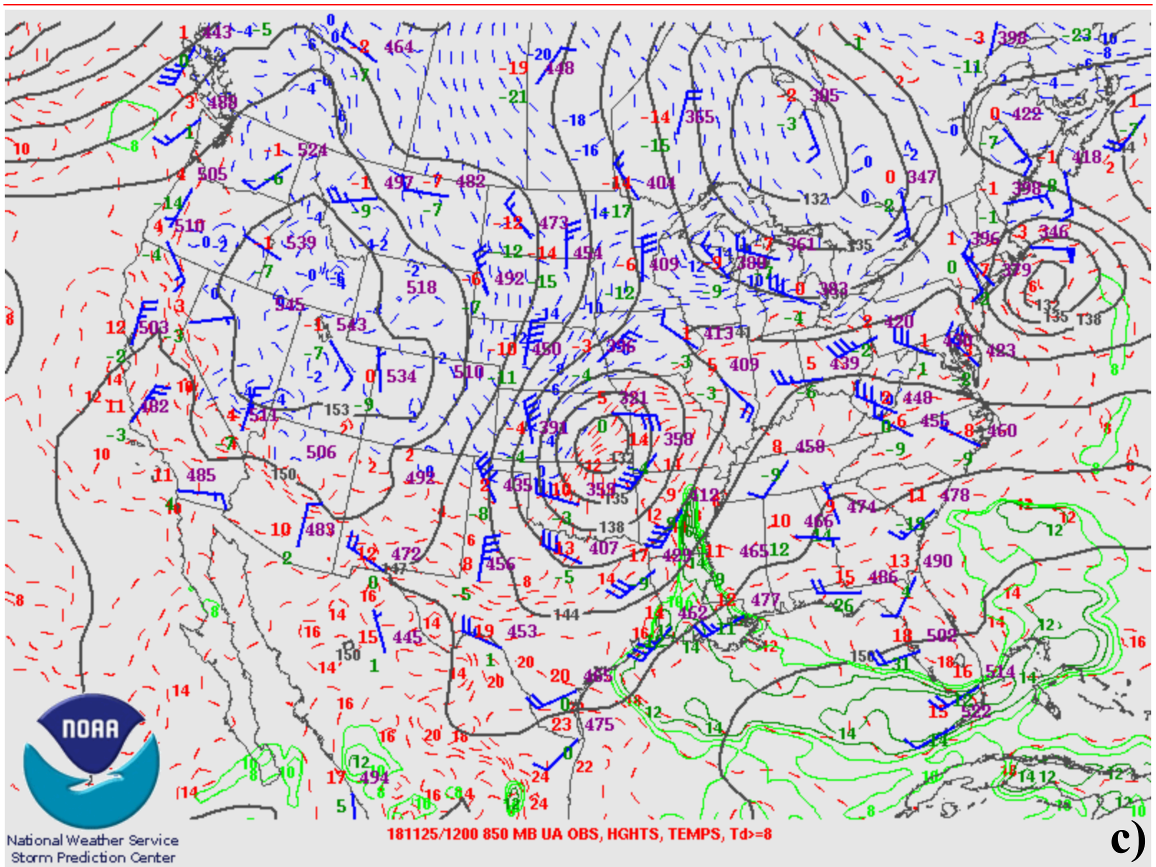

Figure 4.4c: 850 hPa analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

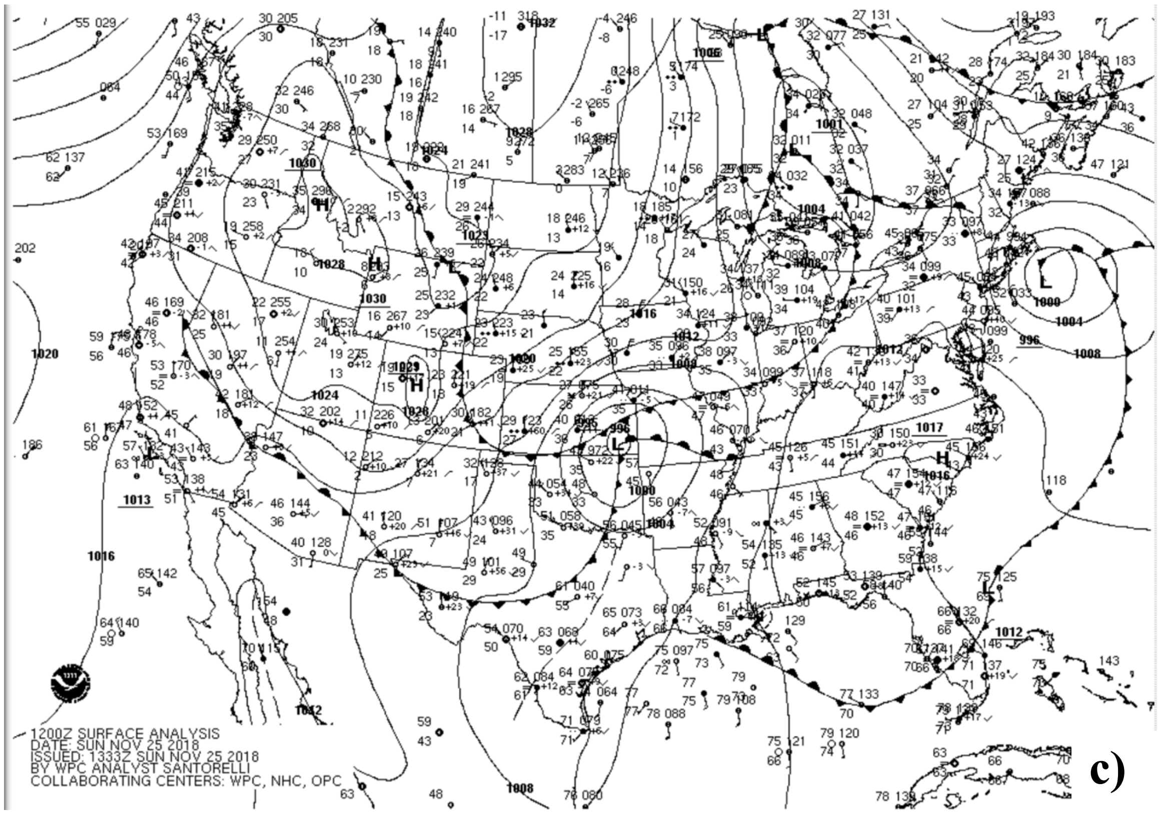

Figure 4.5c: Surface analysis at: a) 1200 UTC 24 November 2018 b) 0000 UTC 25 November 2018 c) 1200 UTC 25 November 2018 (from SPC 2019).

(Figure 4.6b) shows the clear cold frontal gradient that is moving across eastern Nebraska and the Lincoln, NE area, is on the northern side of the line. It can be inferred that the primary precipitation type for this event is snow due to the position of the 5400 m contour. By 0300 UTC 26 November 2018 (SPC 2019), snowfall ceased across Nebraska, and the low pressure system progressed eastward over Illinois. While the low pressure system had fully matured and become occluded at this time, high pressure sets in over the Central Plains with slowly weakening winds observed over the region.

4.1b) MDSS Analysis:

The 25-26 November 2018 case study event is a Colorado low that moves over eastern Nebraska, produces heavy snowfall, causes blowing and drifting snow, and has a large impact on transportation. While the original forecast had the event moving farther to the north over Lincoln, the actual storm track was a little farther to the south and east of Lincoln. Lincoln still receives a large snowfall; however, conditions could have been much worse with a more northerly track. The resulting change in storm track can be seen in the NDOT-MDSS forecasts. Atmospheric parameters of temperature, dewpoint temperature, and wind speeds, are analyzed at 3, 6, 9, and 12 hour prior intervals within NDOT-MDSS and compared to ASOS observed values, which spans snowfall start (08 UTC) to snowfall end (15 UTC), on the morning of 25 November 2018. In addition, hourly forecasts for snow conditions from the NDOT-MDSS are obtained and analyzed for each event.

Air temperature forecasts from the NDOT-MDSS are consistently low compared to ASOS observed values across the majority of the forecast runs (Figure 4.7), though air temperature forecasts for the three highway routes performed very well with most forecasts increasing in accuracy as the snowfall came to an end. The most accurate air temperature forecast at the P80 road section is the 12 hour prior forecast. The 12 hour prior forecast is almost perfectly collocated with the ASOS observed air temperature, which indicates that the 12 hour prior forecast by the NDOT-MDSS may be more accurate than the forecasts closer to the event start time. In comparison, routes HW33 and HW77 are more accurate at the 9 hour forecast time frames. The largest deficit between the NDOT-MDSS and ASOS for air temperature was 5 °F (2.8 °C) occurring at the W80 section of the interstate during the 9 hour prior forecast period. Observed ASOS minus the NDOT-MDSS forecast shows that the northernmost routes (W80, P80, HW34) all exhibit a similar pattern of under-forecasting across much of the time period with increasing accuracy at the end of the time period (Figure 4.8). In contrast, the southernmost routes all over-forecast air temperatures. This illustrates a situation of possible cold and warm bias at the northernmost and southernmost routes, respectively. Some of the inaccuracies within the NDOT-MDSS could be caused by the more southerly track taken by the storm system and may not be a result of a forecasting issue within the NDOT-MDSS. The higher forecasted temperatures at HW77 may be representative of the shift in the storm track. The length of the route might also be responsible for the difference in forecasted air temperatures. HW77 is a north-south oriented route and could easily stretch along a gradient of increasing air temperatures at

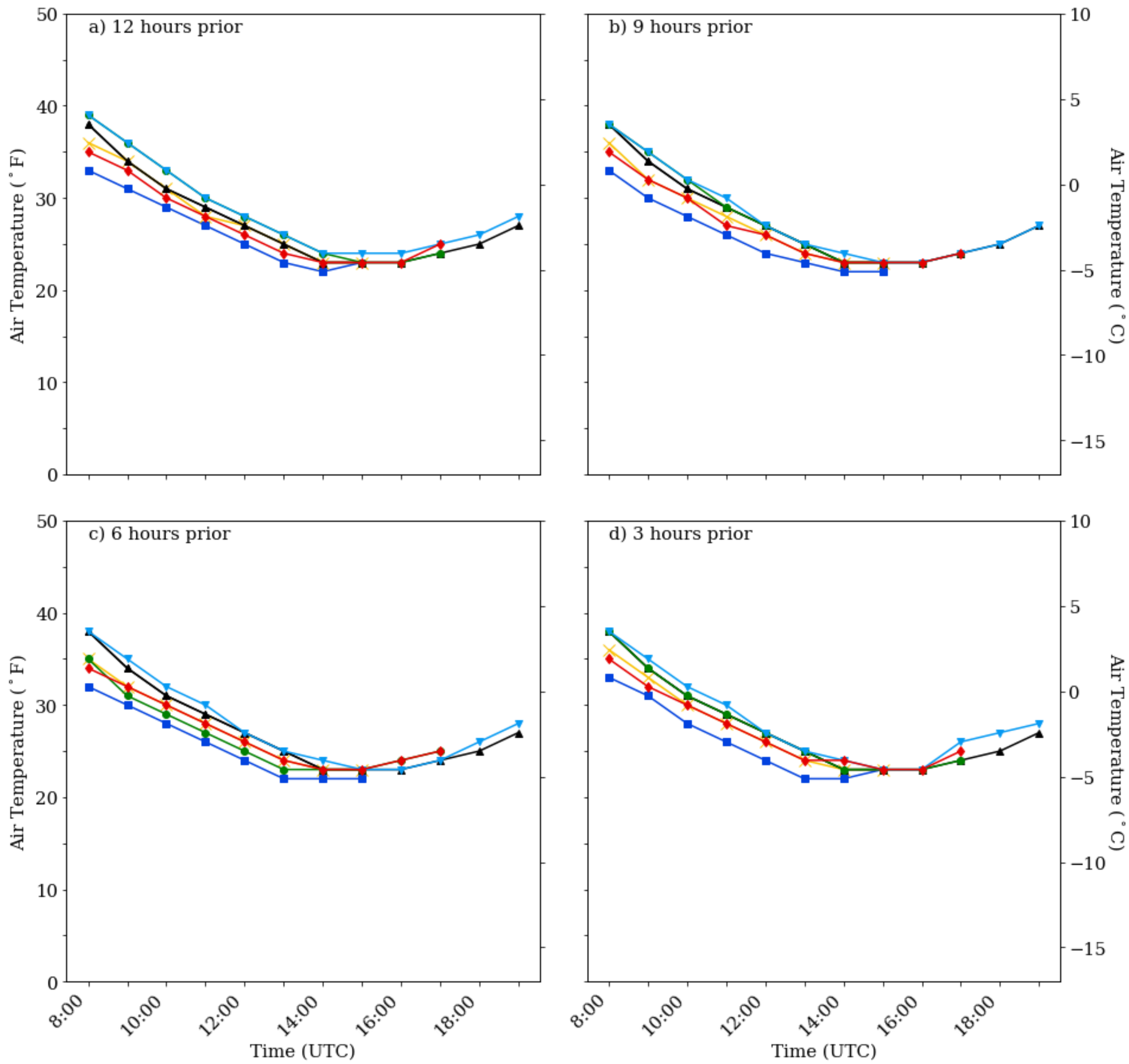

Figure 4.7: 24 November 2018 hourly temperature forecasted by MDSS at (a) 2000 UTC forecast run (12 hours prior to snowfall start), (b) 2300 UTC forecast run (9 hours prior to snowfall start), (c) 0200 UTC forecast run (6 hours prior to snowfall start), and (d) 0500 UTC forecast run (3 hours prior to snowfall start) for W80 (yellow), P80 (blue), HW34 (red), HW33 (green), and HW77 (light blue) compared to ASOS observed (black). Date and time run from the start of snowfall to the end of snowfall.

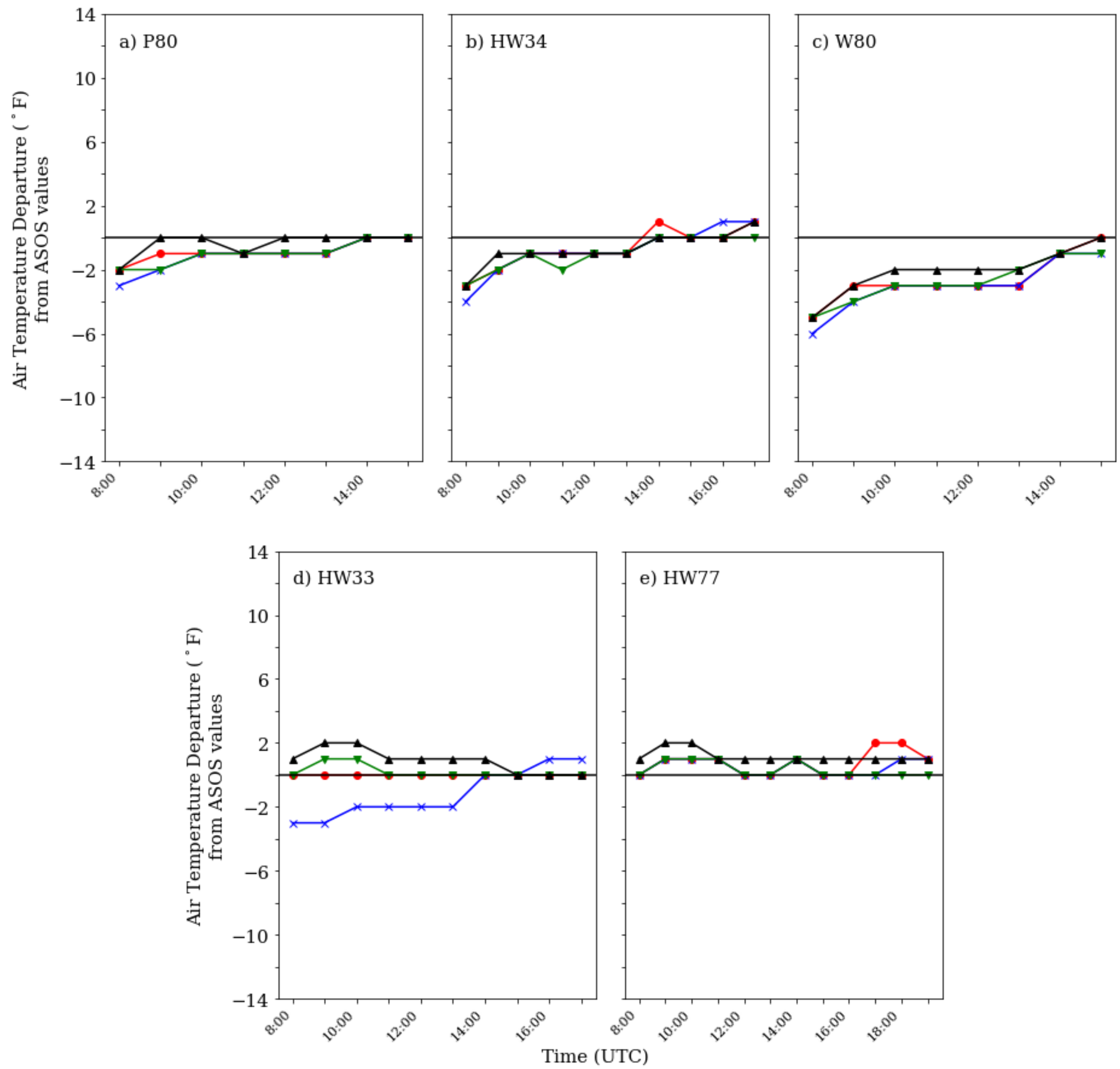

Figure 4.8: Difference graphs of the NDOT-MDSS forecasted temperature departure for 24 November 2018 from the observed ASOS values at (a) P80, (b) HW34, (c) W80, (d) HW33, and (e) HW77 for 3 hours (red), 6 hours (blue), 9 hours (green), 12 hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

its southern extent. It should also be pointed out that air temperatures calculated in the NDOT-MDSS are averaged over the length of the route and the number of grid points averaged to create the route value may be causing differences. Therefore, any averaging across HW77 may be skewed because of its southern extent. HW34 is closest to the Lincoln Airport, the forecast verification location, so proximity to the ASOS site might also produce some of the differences.

Dewpoint temperature forecasts by the NDOT-MDSS have much smaller variation across the board with regards to all the routes (Figure 4.9). Again, the most accurate forecast by the NDOT-MDSS system is for the P80 section 12 hour prior forecast. This 12 hour prior forecast correctly forecasted the dewpoint for P80 and is only 2 ^{o}F (1.1 ^{o}C) under-forecasted for the W80 route. The dewpoint temperature forecasts follow the air temperature differences closely. All of the forecast runs are within a reasonable degree of variation of 2 ^{o}F (1.1 ^{o}C) except for the forecast from 9 hours prior to snowfall start. Notable under-forecasting throughout all of the forecast runs for the three routes is observed. The largest comparative deficit of -8 ^{o}F (-4.5 ^{o}C) is recorded at all three of the routes at 18 UTC 25 November 2018. The dewpoint temperature and air temperature are both under-forecasted, although the presence of a smaller margin of variation for the dewpoint temperature would indicate that the NDOT-MDSS is predicting a slightly more saturated lower atmosphere than was verified. The dewpoint temperature differences (Figure 4.10) all follow the same pattern as the air temperature with regards to under and over-forecasting, which illustrates consistency across routes by the NDOT-MDSS. Whether the forecasted presence of marginally more moisture led to

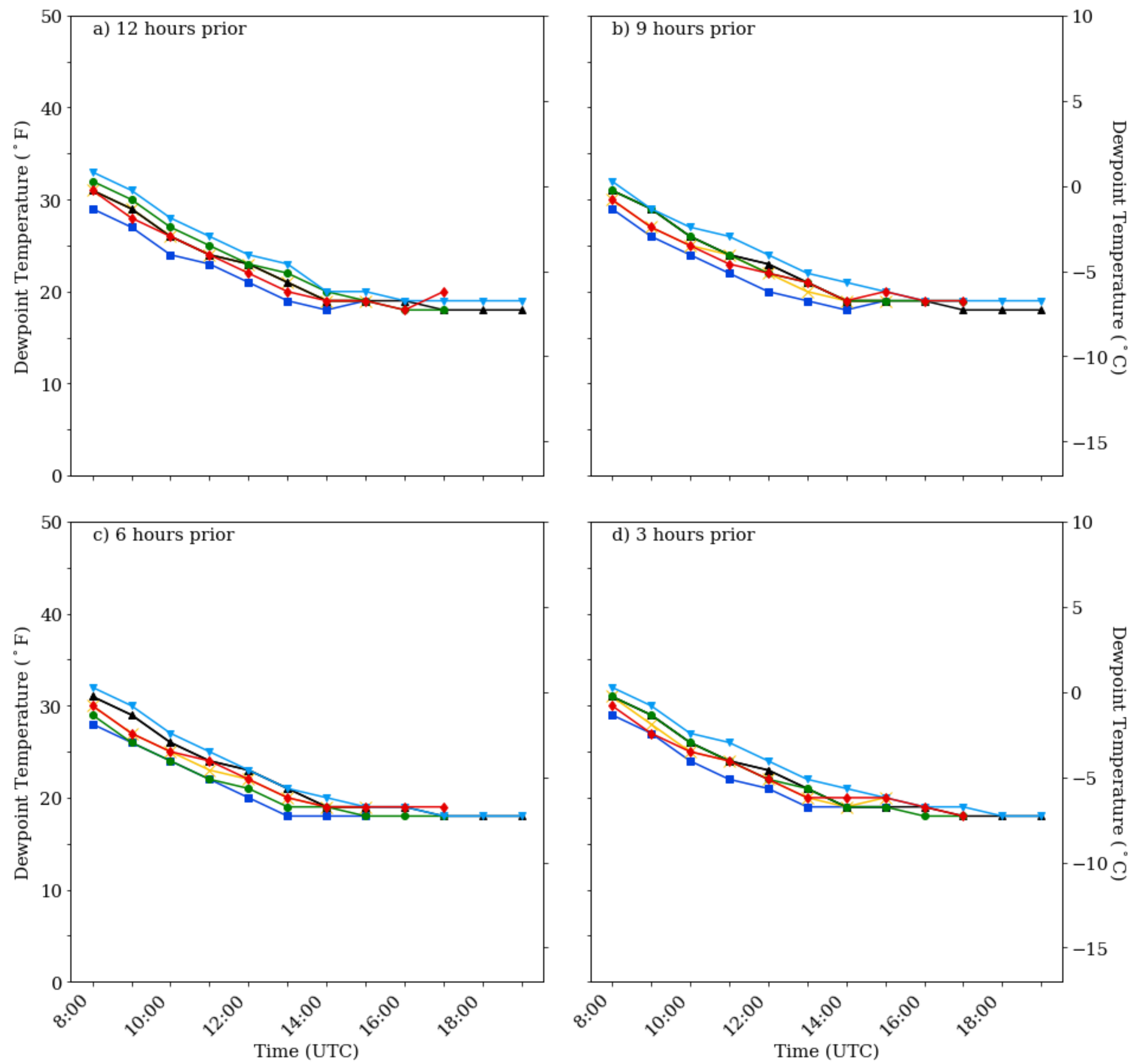

Figure 4.9: 24 November 2018 hourly dewpoint temperature forecasted by MDSS at (a) 2000 UTC forecast run (12 hours prior to snowfall start), (b) 2300 UTC forecast run (9 hours prior to snowfall start), (c) 0200 UTC forecast run (6 hours prior to snowfall start), and (d) 0500 UTC forecast run (3 hours prior to snowfall start) for W80 (yellow), P80 (blue), HW34 (red), HW33 (green), and HW77 (light blue) compared to ASOS observed (black). Date and time run from the start of snowfall to the end of snowfall.

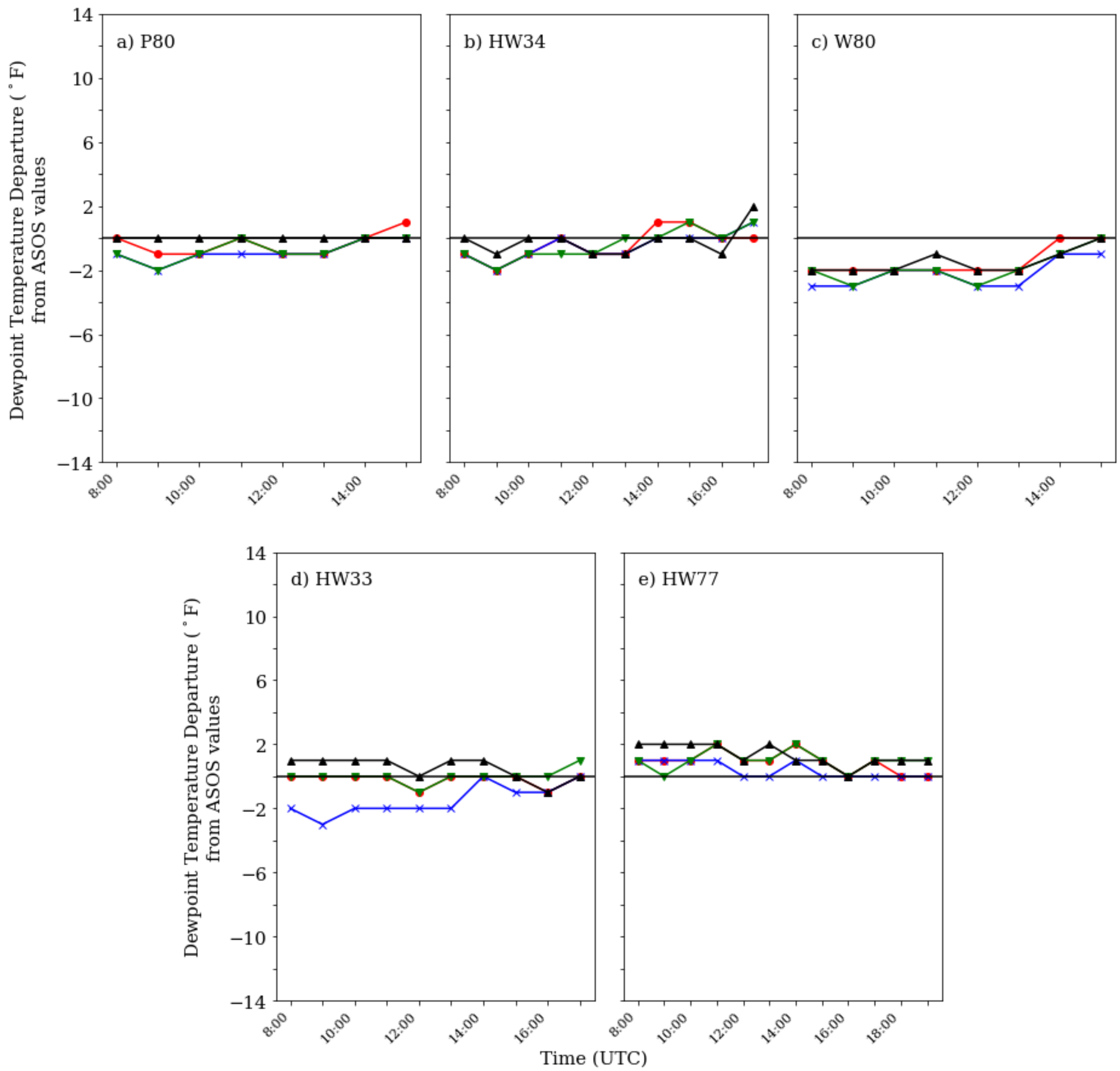

Figure 4.10: Difference graphs of the NDOT-MDSS forecasted dewpoint temperature departure for 24 November 2018 from the observed ASOS values at (a) P80, (b) HW34, (c) W80, (d) HW33, and (e) HW77 for 3 hours (red) for 3 hours (red), 6 hours (blue), 9 hours (green), 12 hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

the spikes in snowfall accumulation prior to and during the event is an analog that could be investigated in future research.

At first glance, the NDOT-MDSS seems to have issues predicting wind speeds (Figure 4.11). However, the largest deficits for W80 and P80 are 5.0 kt (2.6 m s^{-1}) and 3.0 kt (1.5 m s^{-1}), respectively. Both of these deficits, in contrast to the air temperature and dewpoint temperature, occur at the 12 hour prior forecast period with increasing accuracy for the P80 route as the forecast period moves closer to the event start time. The most accurate forecasts for HW33 and HW77 occur during the 9 hour prior forecast run, while the most accurate forecast for HW34 occurs 12 hours prior to the event start. The most accurate route was HW77. At 3 hours prior, HW77 is nearly perfectly aligned with the ASOS values. Notably, though, HW34 and HW33 wind speeds are both under and over-forecasted, respectively. HW33 boasts a maximum over-forecast value of 5.0 kt (2.6 m s^{-1}), while HW34 reports a deficit of 3.0 kt (1.5 m s^{-1}). The forecast variations are rather nominal and did not indicate any preference for forecast time. The representation of wind speed forecasts in the difference graphs (Figure 4.12) shows how well the NDOT-MDSS performed. The one route that has considerable variation across forecast runs is HW33. One reason for this could be the orientation and length of the route. In very specialized cases, the small discrepancies could play a part in the decisions that are made by maintenance crews, such as wet vs. dry salt applications. Otherwise, the wind speed forecast provided by the NDOT-MDSS performed well.

Further analysis of the forecasted air temperatures (Figure 4.8), dewpoint temperatures (Figure 4.10), and wind speeds (Figure 4.12) depicts a subtle spatial

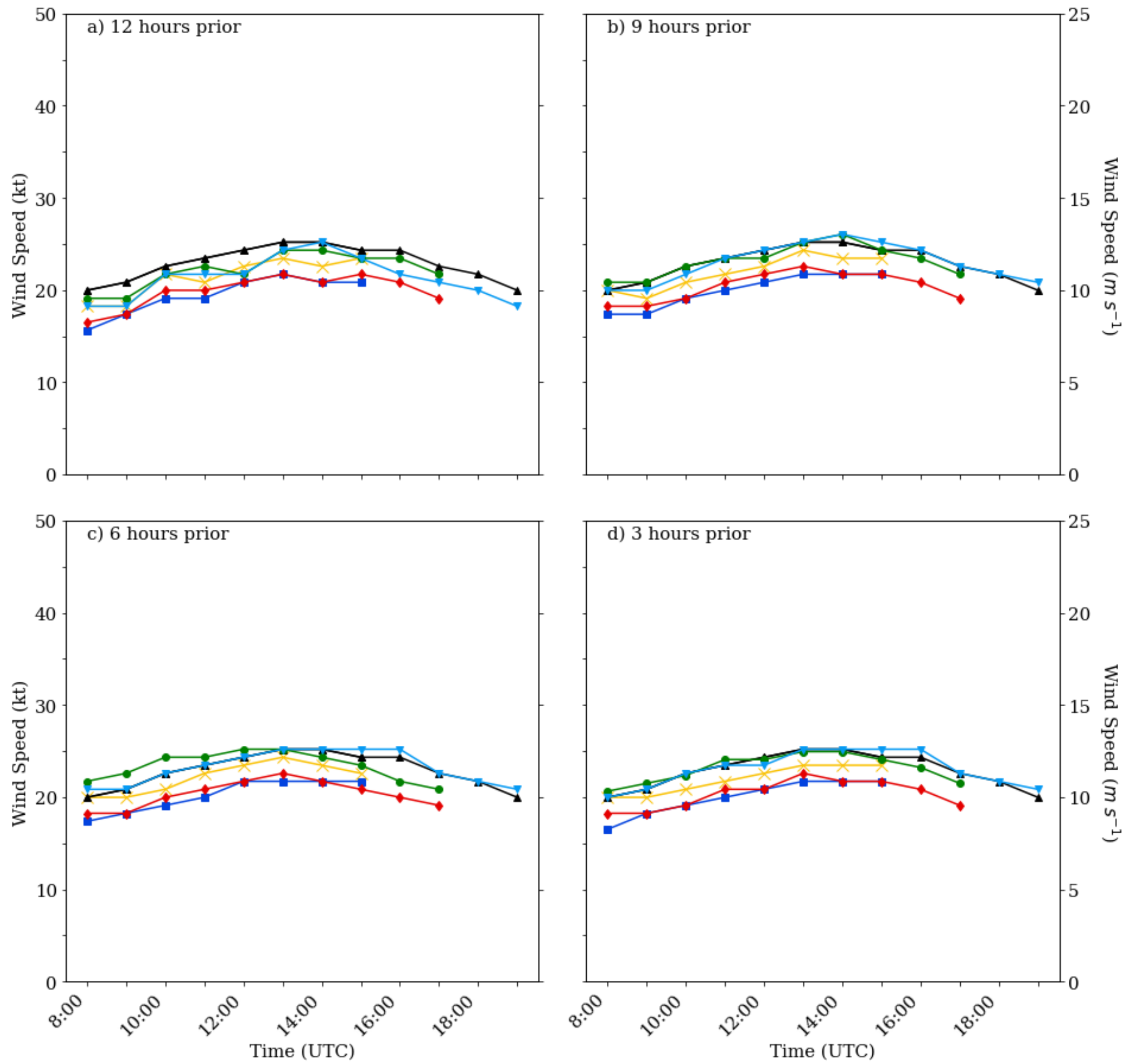

Figure 4.11: 24 November 2018 hourly wind speed forecasted by MDSS at (a) 2000 UTC forecast run (12 hours prior to snowfall start), (b) 2300 UTC forecast run (9 hours prior to snowfall start), (c) 0200 UTC forecast run (6 hours prior to snowfall start), and (d) 0500 UTC forecast run (3 hours prior to snowfall start) for W80 (yellow), P80 (blue), HW34 (red), HW33 (green), and HW77 (light blue) compared to ASOS observed (black). Date and time run from the start of snowfall to the end of snowfall.

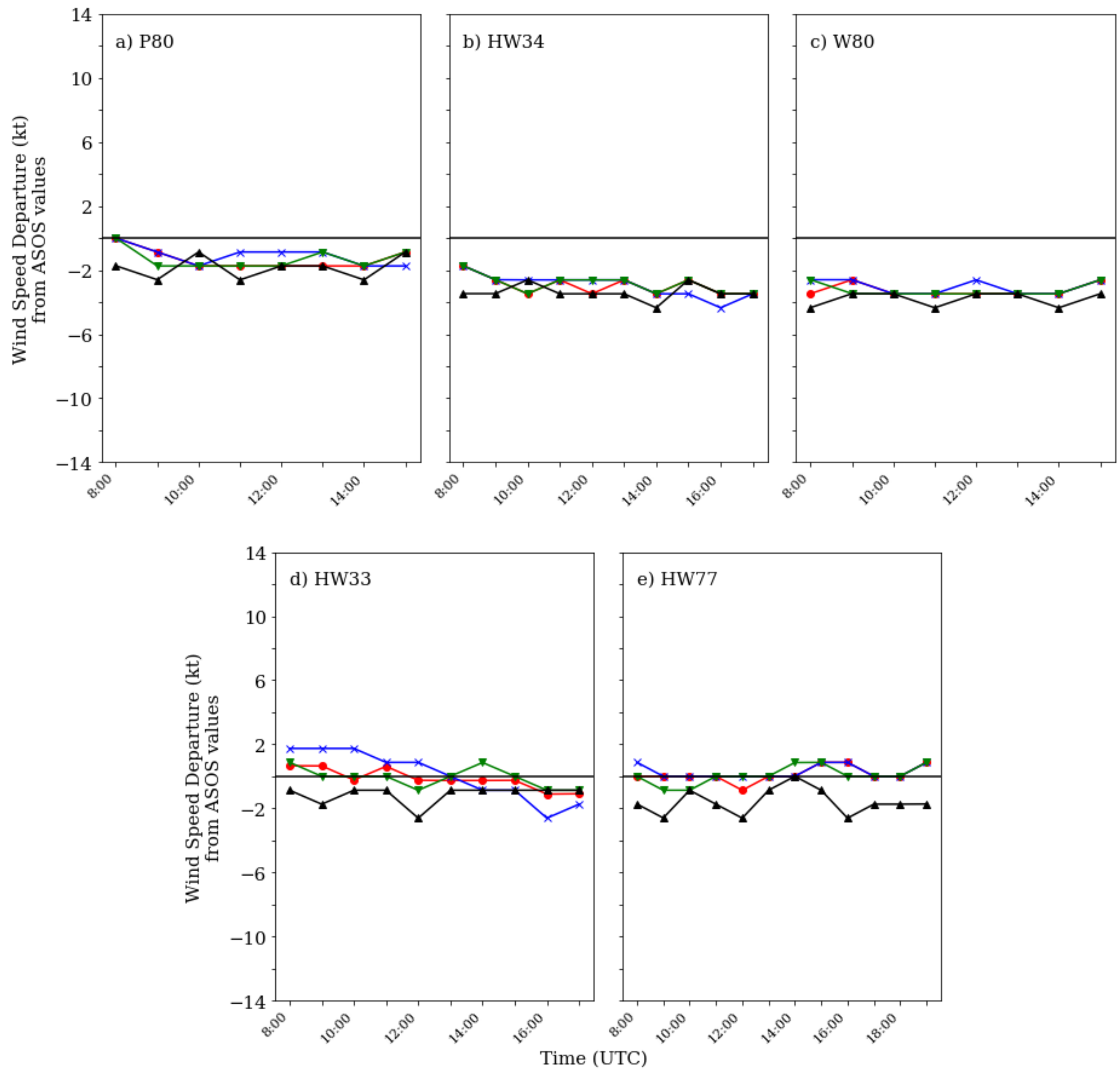

Figure 4.12: Difference graphs of the NDOT-MDSS forecasted wind speed departure for 24 November 2018 from the observed ASOS values at (a) P80, (b) HW34, (c) W80, (d) HW33, and (e) HW77 for 3 hours (red) for 3 hours (red), 6 hours (blue), 9 hours (green), 12 hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

variation of forecasts across the five routes. At W80, it can be seen that all three of the variables are under-forecasted for the route. Air temperature and dewpoint temperature forecasts both improve as they converge toward the end of the event. On the other hand, wind speed is consistently under-forecasted and never rebounds or increases in accuracy towards the ASOS values with time. Forecasted values for temperature and dewpoint temperature at P80 fell near a departure value of zero with increasing accuracy across all runs as the event came to a close. The wind speed differential demonstrates the same consistency trend as W80 yet, output values much closer to zero than the W80 wind speed forecast. The consistent under-forecasting of these values may be connected to the issue of the NDOT-MDSS averaging values across the length of the route or the proximity to the ASOS observation station. HW34 produces the most consistent forecasts of temperature and dewpoint temperature with the largest departures of -4 ^{o}F (-2.2 ^{o}C) represented at the beginning of the snowfall event. HW33 and HW77 did have accurate forecasts of temperature and dewpoint temperature. The variance between forecasts per forecast run is much greater. However, as far as wind speed forecasts are concerned, the NDOT-MDSS forecasts for HW77 are the most accurate with a maximum departure of 3.0 kt (1.5 m s^{-1}). Wind speed forecasts at HW34 are the most consistent, varying between 2.0 kt (1 m s^{-1}) and 4.0 kt (2.1 m s^{-1}) departures. The departures from ASOS for wind speed for the HW33 section are quite variable with a spread of variation of 8.0 kt (4.1 m s^{-1}) ranging from a positive 5.0 kt (2.6 m s^{-1}) overage to a deficit of 3.0 kt (1.5 m s^{-1}). While the variance in wind speed is only slight, it may be linked to the

orientation of the road to the wind vectors and also the distance from the ASOS observing station.

The final aspect of the NDOT-MDSS analysis compiles the NDOT-MDSS snowfall accumulation forecasts (Figure 4.13) and forecasted event length (Figures 4.14, 4.15). One of the most noteworthy aspects that can be seen on the snowfall accumulation plot is the consistency between routes. While the snowfall total accumulation values differ from route to route, the incremental increases and decreases by the forecast run follow a nearly identical pattern. The spike in forecasted snowfall accumulation totals six hours prior to snowfall onset is consistent across the routes and the NDOT-MDSS began to more accurately predict final snowfall accumulation through the duration of the event. This uptick in accuracy is directly caused by the NDOT-MDSS adjusting its forecast based upon real-time observations. The generally similar correlations between the highway and interstate road sections are a positive signal that accentuates the consistency of the NDOT-MDSS to produce analogous forecasts for different routes in the same area. Even more so, the NDOT-MDSS forecast follows the gradient of actual snowfall accumulation rather well with totals increasing from south to north (Figure 4.16).

For this November event, the NDOT-MDSS forecasts snowfall accumulation (Figure 4.13) well prior to the onset of snowfall. A spike in accumulation values between 02 UTC and 05 UTC 25 November 2018, six hours prior to snowfall onset, is observed at both sections producing variation margins between 2.0 – 3.0 inches (5.1 - 7.6 cm). The forecasted snowfall totals for W80 and P80 are very similar and the routes are within

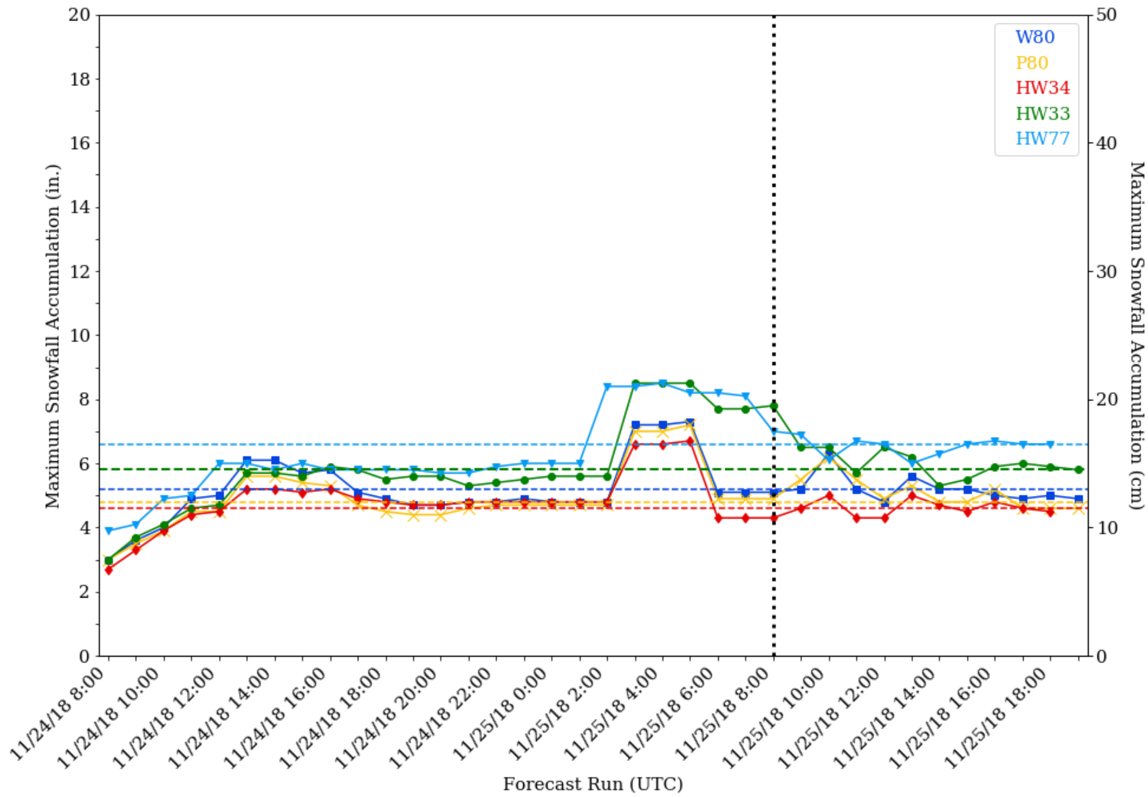

Figure 4.13: Maximum MDSS forecasted snowfall accumulation for the individually observed routes per forecast run. The vertical dotted line denotes snowfall start time. The color-coded horizontal lines denote the final snowfall accumulation totals recorded at the snowfall end time for their corresponding routes.

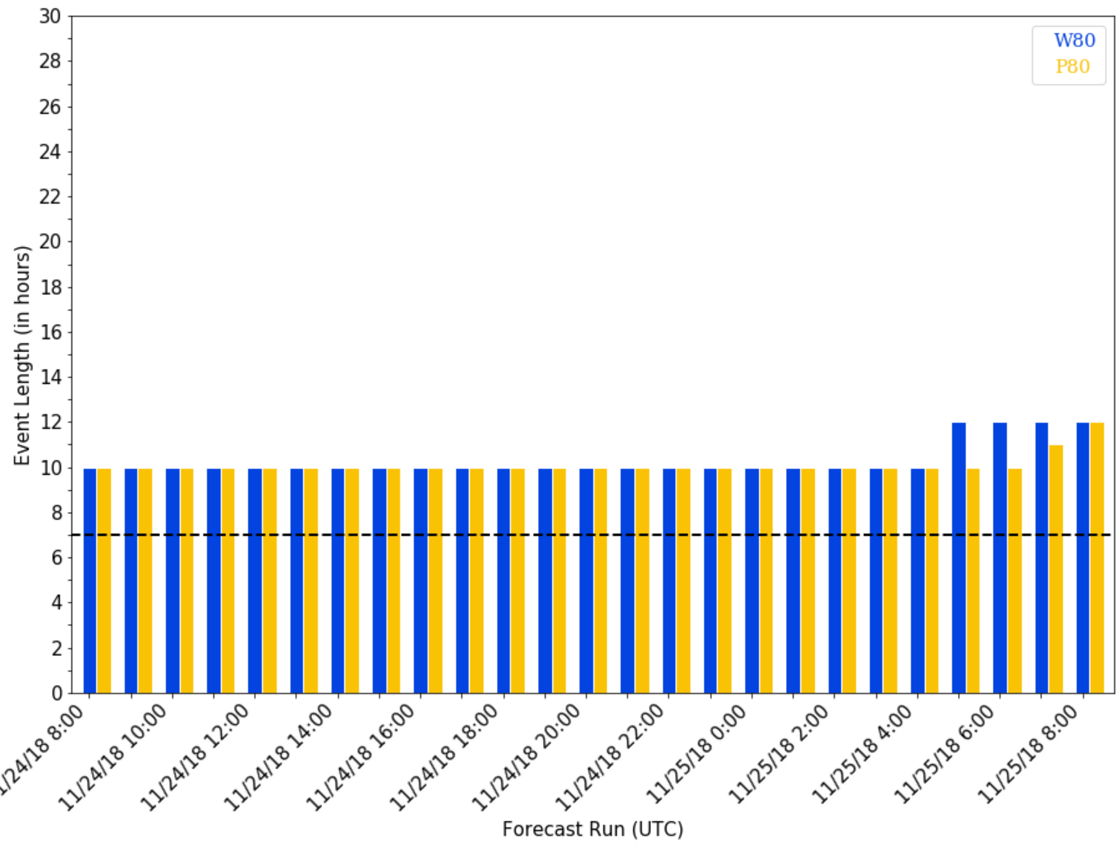

Figure 4.14: MDSS forecasted event length for the W80 (yellow) and P80 (blue) I-80 interchanges per forecast run. The horizontal dashed line denotes the final recorded event length for the corresponding routes.

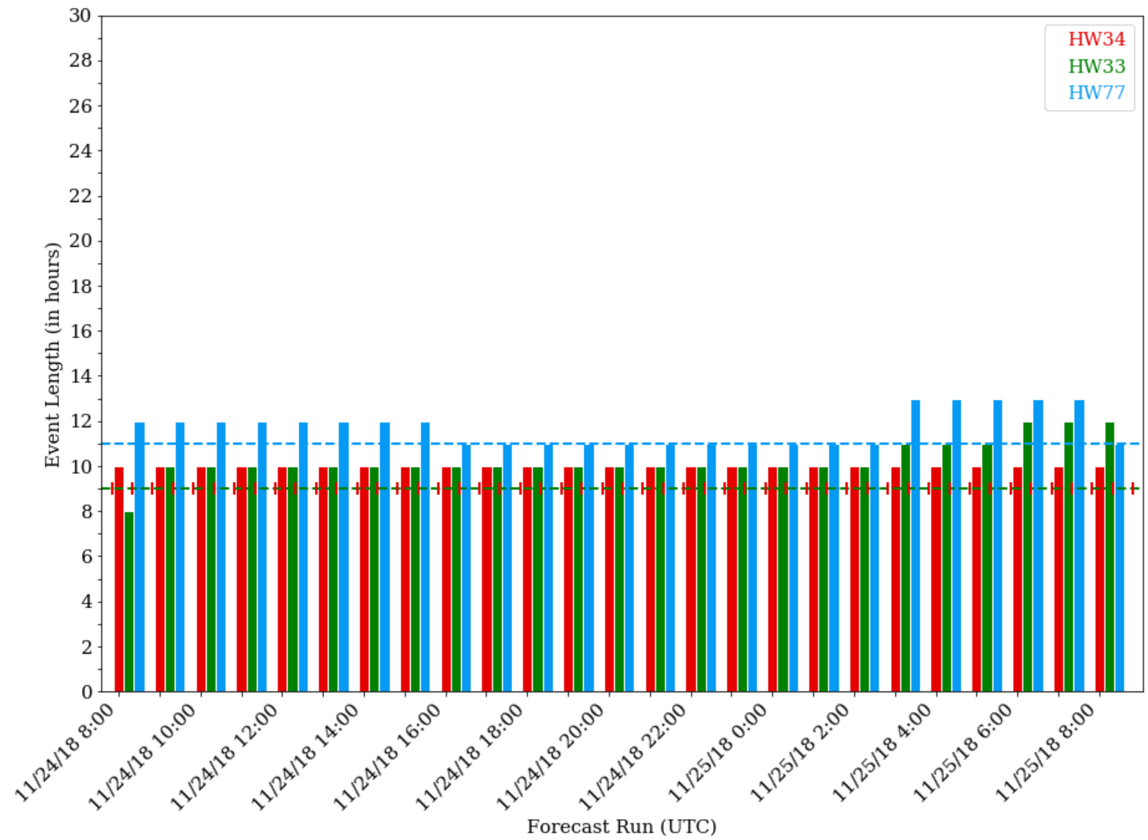

Figure 4.15: MDSS forecasted event length for HW34 (red), HW33 (green), and HW77 (light blue) per forecast run. The color-coded horizontal lines and vertical ticks denote the final recorded event length for the corresponding routes.

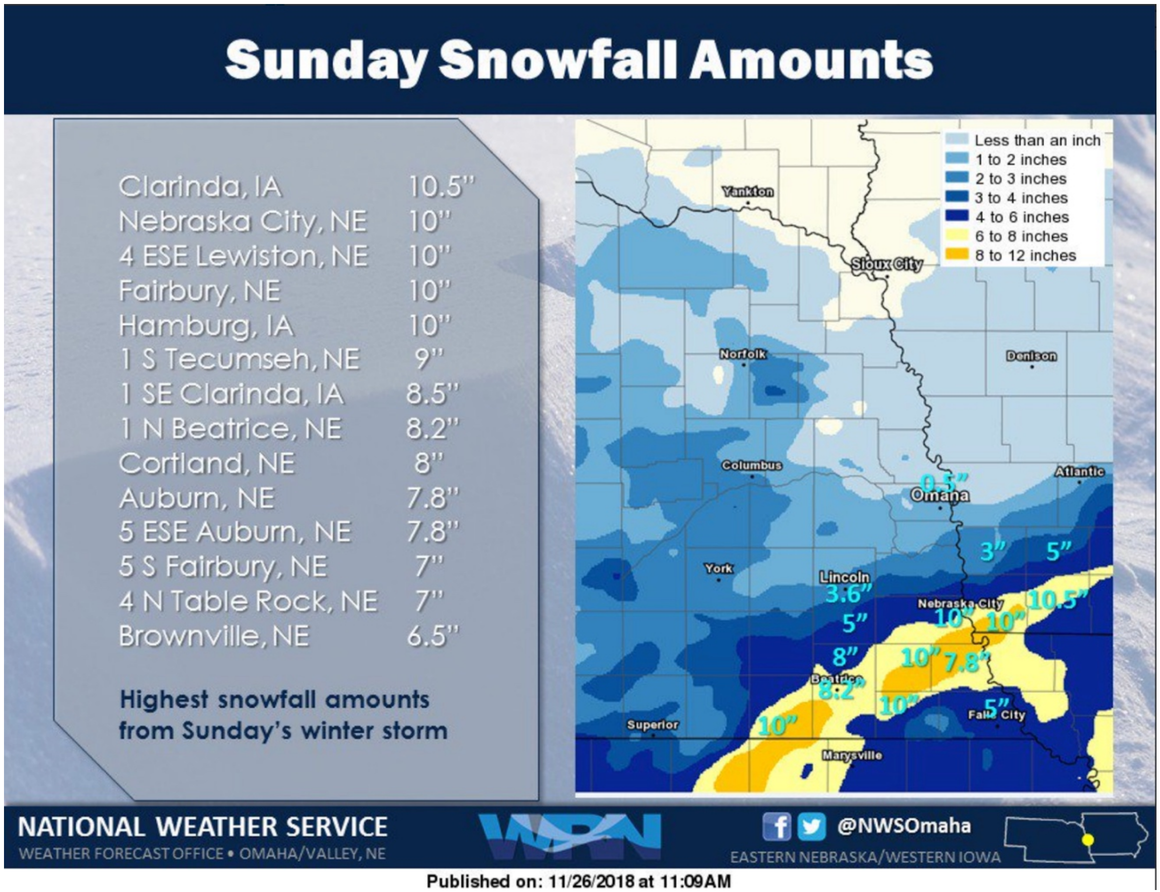

Figure 4.16: Total snowfall accumulation map across the NWS Omaha CWA for 24-25 November 2018 (from NWS Omaha/Valley 2018).

0.4 inches (1 cm) of each other at the final snowfall accumulation value. Within the 30 hour observed window; however, the average departure of forecasted snowfall accumulation compared to the final snowfall accumulation by the NDOT-MDSS is 0.3 inches (0.8 cm) and 0.4 inches (1 cm) for W80 and P80 respectively. This small of an average variation across the forecast period indicates that the NDOT-MDSS is indeed handling snowfall accumulation well, albeit slightly over-forecasting the final amounts. It can also be inferred that the NDOT-MDSS forecasts more accurately for snowfall accumulation for W80 over P80. Similar patterns are be observed between HW34 (Figure 4.13) and the two interstate road sections where a pronounced spike prior to the snowfall onset is seen. The attendant variability in the snowfall forecast takes on similar characteristics and exhibits an average over-forecasted value of 0.3 inches (0.8 cm). The two southernmost routes at HW33 and HW77 show comparable trends although, upon further examination, HW33 produces a much more pronounced spike in accumulation prior to snowfall onset and accrues an average over-forecast value of 0.1 inches (0.3 cm) while HW77 is the only route to have a negative under-forecast value of 0.3 inches (0.8 cm). The NDOT-MDSS again demonstrates rather sound forecastability at the longer-range forecast runs and finally produces variability within 1.0 inch (2.5 cm) of the actual snowfall accumulation throughout the duration of the snowfall.

The NDOT-MDSS forecasted event length prior to and during the event illustrates a less than satisfactory story compared to the actual event length of between 7 and 12 hours depending on the route. The event length is not obtained until the snowfall had ended for the interstate road sections (Figure 4.14). The forecasted event length is within

two to five hours of the actual event length up until the end of the event. The highway routes (Figure 4.15) exhibit a much higher degree of accuracy across the forecast runs with variations between two to three hours in comparison to the observed event length. The differential graphs for event end time (forecasted end time - observed end time) aid in identifying whether the variation produced by the forecast is a product of the NDOT-MDSS incorrectly forecasting the start or end time (Figure 4.17). The difference between forecasted and observed event length shows that the NDOT-MDSS over-forecasted across all of the routes and that for the northern routes (W80, P80, HW34) all show that the NDOT-MDSS over-forecasted the end time for this event. The HW33 route oscillates around zero across much of the forecast period while the HW77 route moves between a one hour over-forecast and a correct forecast throughout. Both routes correctly forecast the end time six hours prior to the snowfall ending. From this, it can be easily seen that where the NDOT-MDSS has the greatest issues forecasting event length correspond with the NDOT-MDSS over-forecasting the end time for this November event. Even though the margin of variation is minimal, the event length is important in drafting maintenance protocols for any given event. Knowledge of how long maintenance crews may need to maintain the roadways and when snowfall is going to begin is critical in designating times for snowplows to begin maintenance and also how much chemical would need to be put down across the duration of the event.

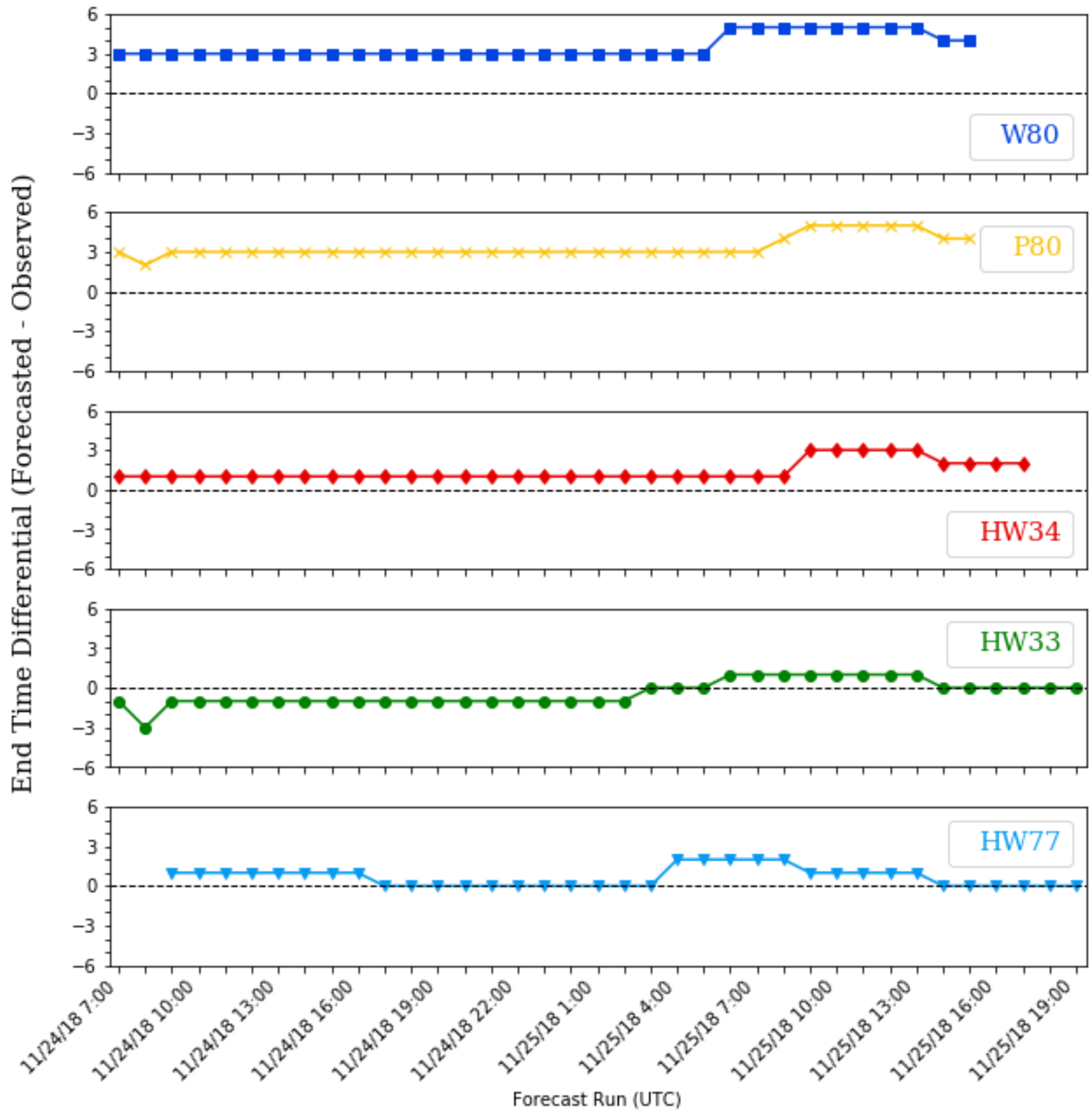

Figure 4.17: 24 – 25 November 2018 Snowfall end time difference graphs for the five observed routes from the NDOT-MDSS.

4.2 Case Study II: 21-25 February 2019

4.2a) Synoptic Analysis

The upper air analyses for 1200 UTC 22 February 2019 show a vertically stacked atmosphere with a deep trough observed over the Pacific Southwest. The polar jet stream had dipped south along with this well-defined trough. Southwesterly flow (Figures 4.18a, 4.19a) is observed across the upper (300 and 500 hPa) and lower (700 and 850 hPa) levels as well, which had begun to stretch the column through its ascent up the Rockies. This southwest-to-northeast oriented jet is accompanied by a weak divergent signal aloft (Figure 4.18a) in southeastern Colorado. Elsewhere in the lower levels, a slightly positive moisture signal is observed with more southerly winds in place (Figures 4.20a, 4.21a). The weak divergent signal at 300 hPa corresponds well with the weak low pressure region also in place at the surface (Figure 4.22a). Light easterly winds and moderate moisture are in place across the Central Plains as high pressure begins to vacate the region.

Observations taken at the 0000 UTC 23 February 2019 show a slight eastward progression of the system into the Four Corners region. This eastward movement results in an even stronger signal of divergence aloft (Figures 4.18b, 4.19b) along the Front Range in eastern Colorado, which hints at the likely formation of a more pronounced low pressure system at the surface. The two very distinct regions of divergence aloft on either side of the Rockies also illustrate the conservation of potential vorticity as the inferred region of convergence aloft is over the Rockies. This region of convergence aloft induces

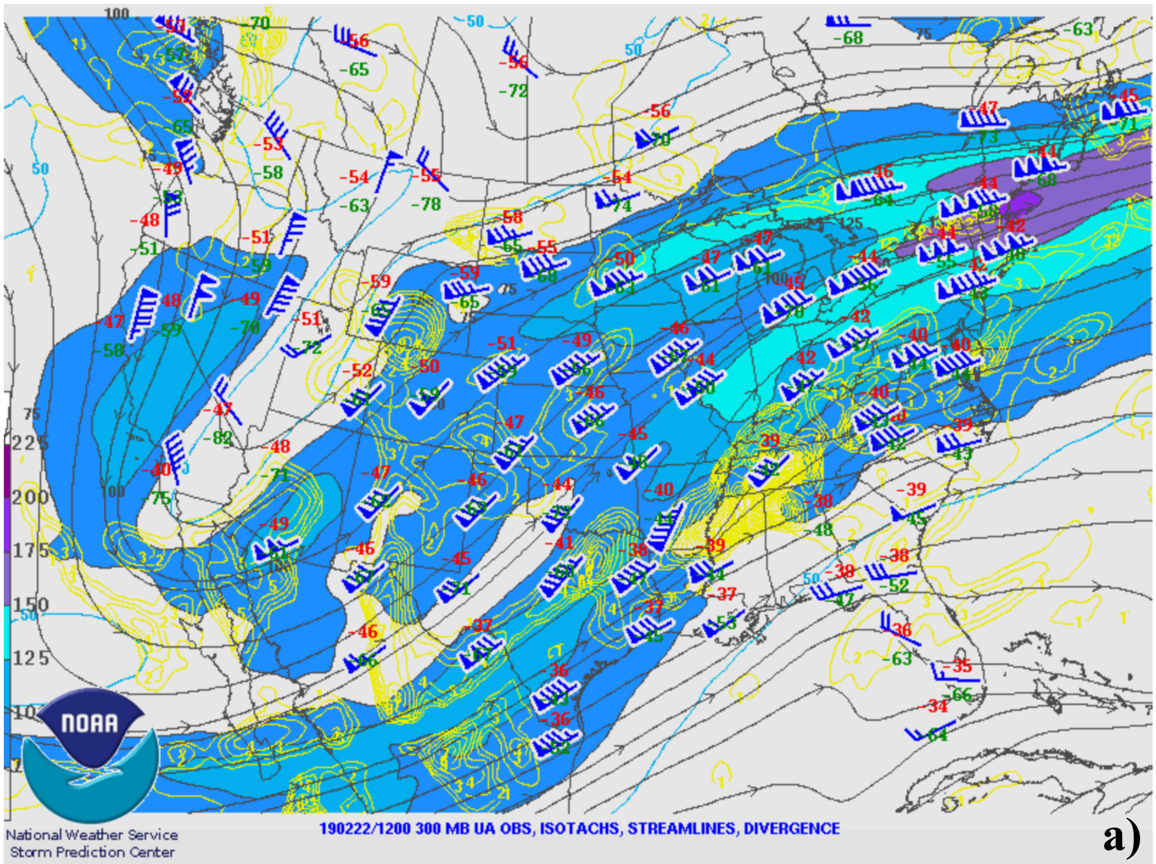

Figure 4.18a: 300 hPa analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

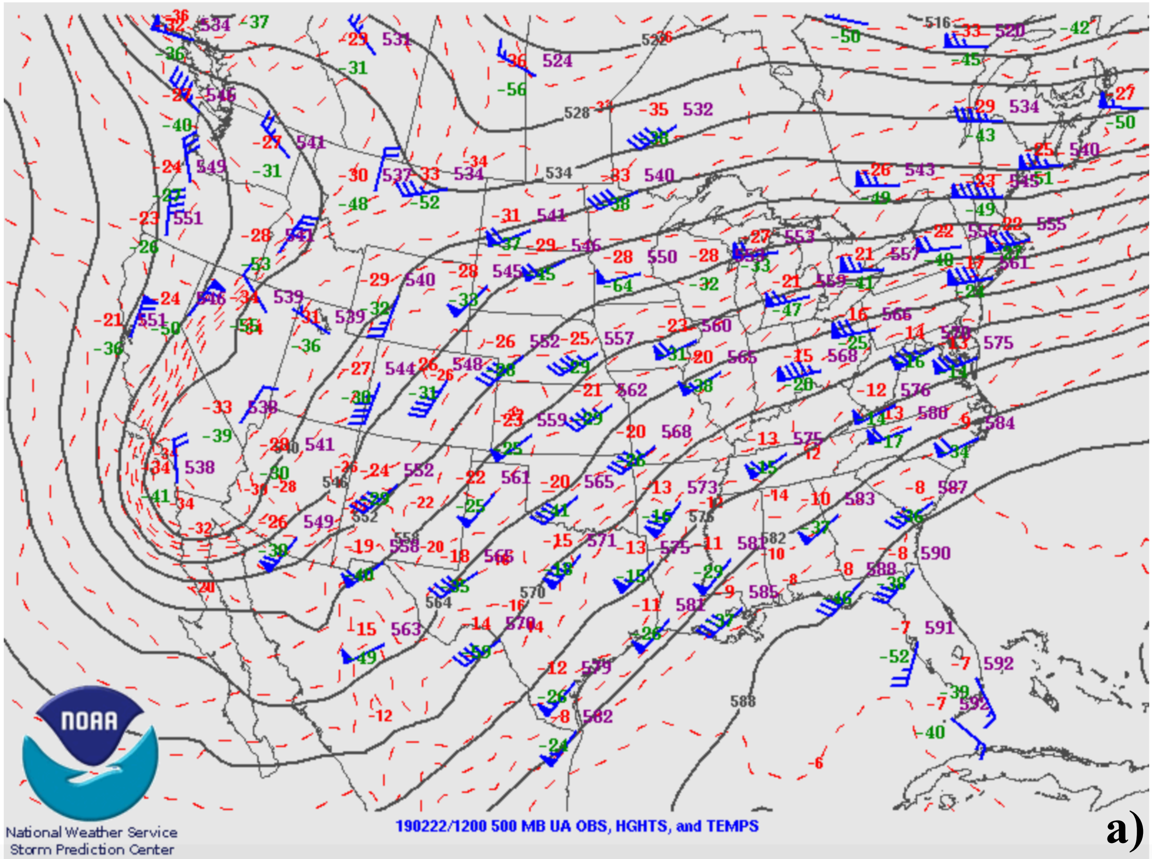

Figure 4.19a: 500 hPa analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

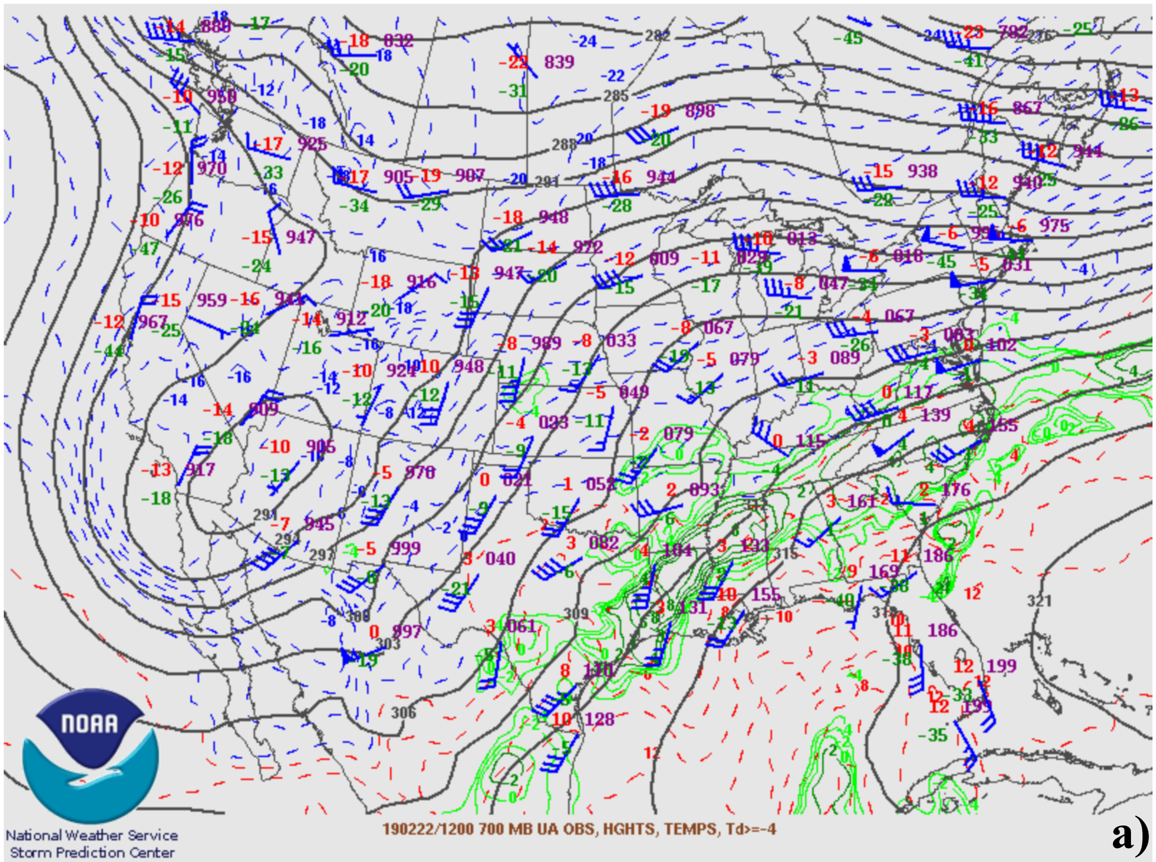

Figure 4.20a: 700 hPa analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

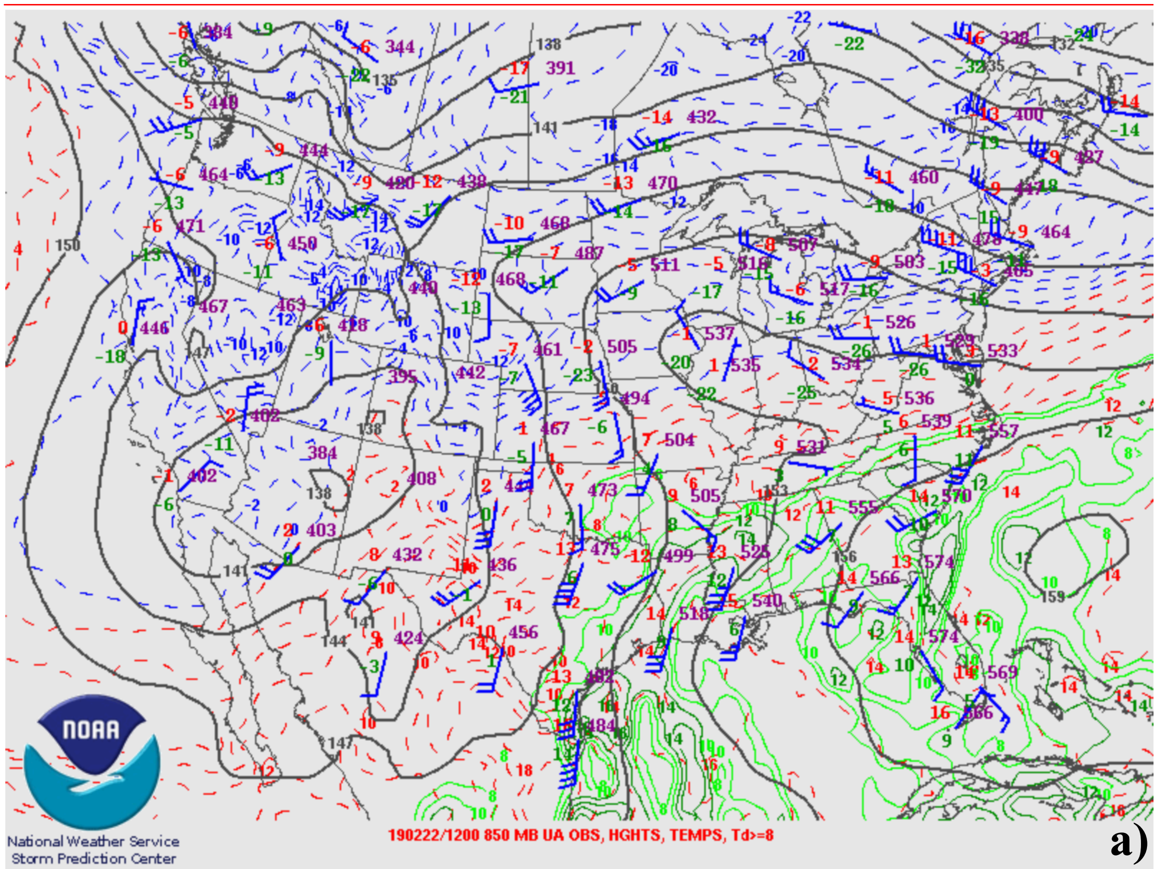

Figure 4.21a: 850 hPa analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

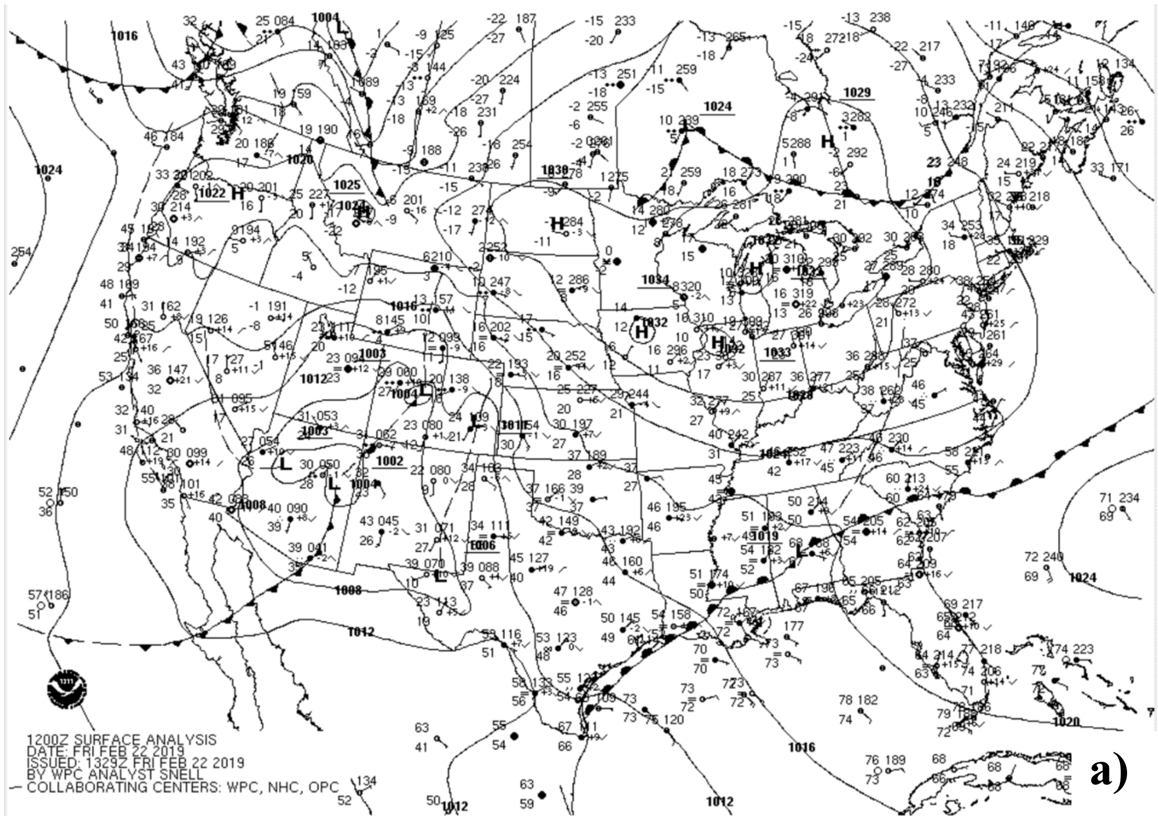

Figure 4.22a: Surface analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

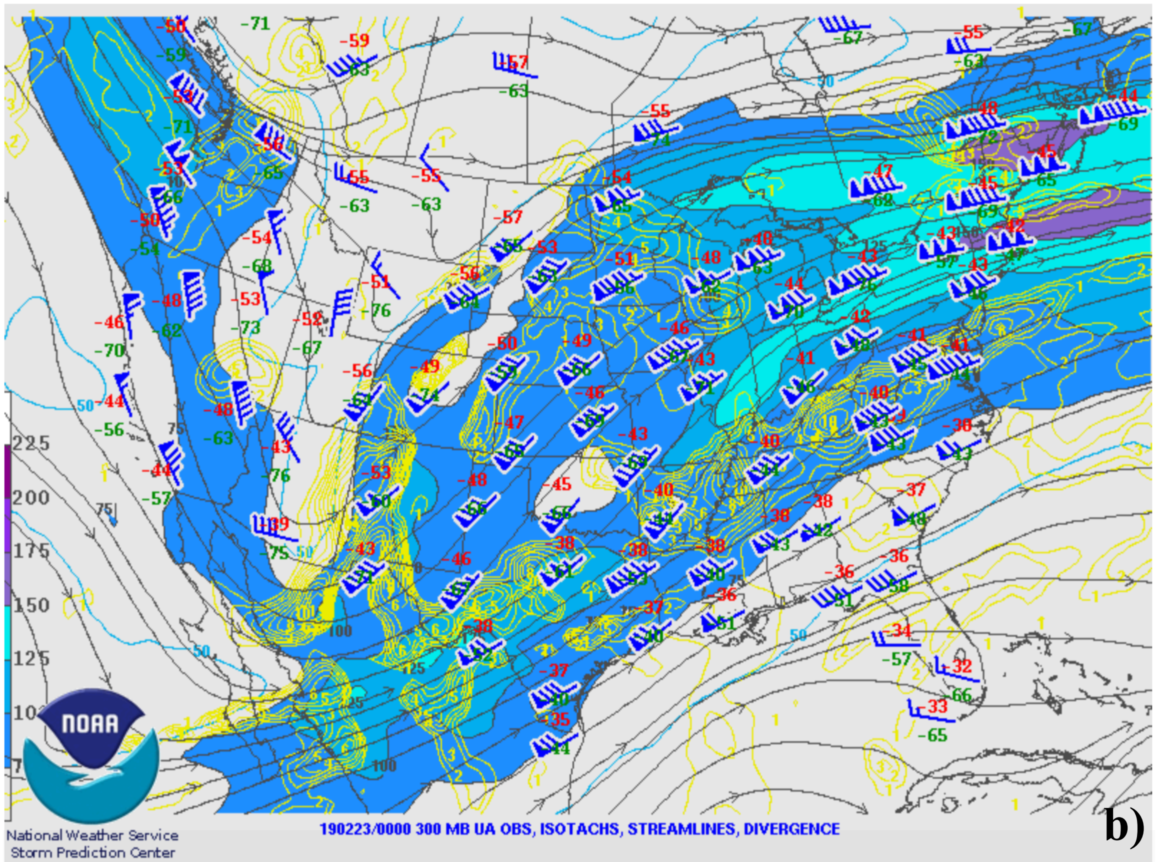

Figure 4.18b: 300 hPa analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

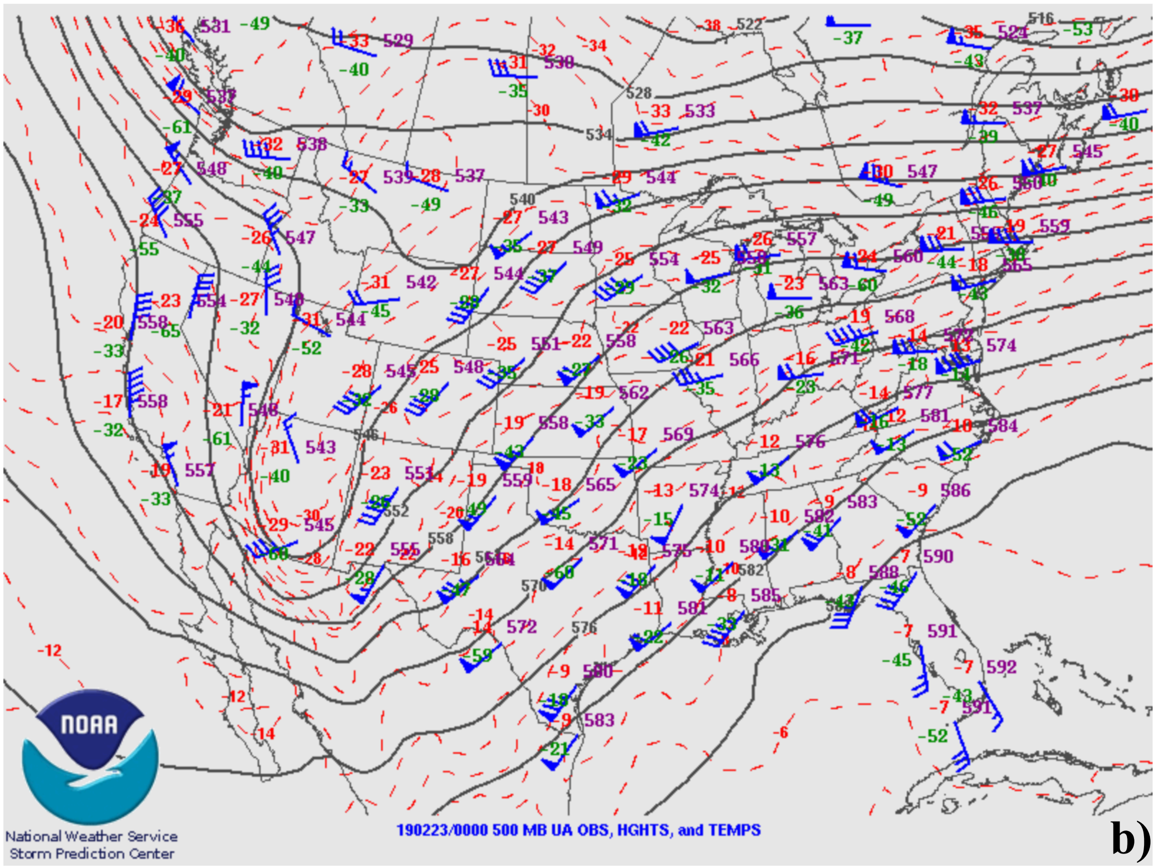

Figure 4.19b: 500 hPa analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

westerly downslope flow on the lee side of the Rockies, which in turn causes pressure falls from the adiabatic warming. At the lower levels, the trough reaches the Rockies and imparts strengthening southerly winds across the Central Plains. The slight moisture signal at 700 hPa (Figure 4.20b) increases in areal extent while nearly saturated air is already observed at 850 hPa (Figure 4.21b). At the surface, a nearly closed-contour low pressure system is being observed over southeastern Colorado with warm and cold frontal boundaries (Figure 4.22b). Easterly winds still dominate much of the region on the eastern side of the low pressure system. Meanwhile, ample moisture content is in place over much of western Nebraska. Moisture across eastern Nebraska has become a bit more limited, with dewpoint depression values increasing between 4 to 11 ^{o}F (-15.6 to -11.7 ^{o}C) across the area when compared to the prior analysis period. Analysis of the 1000-500 hPa partial thickness layer (Figure 4.23a) depicts a clear, albeit broad, temperature gradient across the Plains. At this time, the Lincoln, NE area is on the southern side of the 5400 m contour, which agrees well with observations of non-frozen precipitation in the area.

The deep trough observed earlier has become more embedded in the general flow pattern (Figures 4.18c, 4.19c) by 1200 UTC 23 February 2019. A region of strong divergence aloft at 300 hPa (Figure 4.18c) is observed from eastern Colorado into western Kansas and southwestern Nebraska. This again coincides with the low pressure system observed at the surface and the strength of the divergence aloft is directly tethered to the steadily decreasing pressure at the surface. Again, eastern Nebraska is observed to

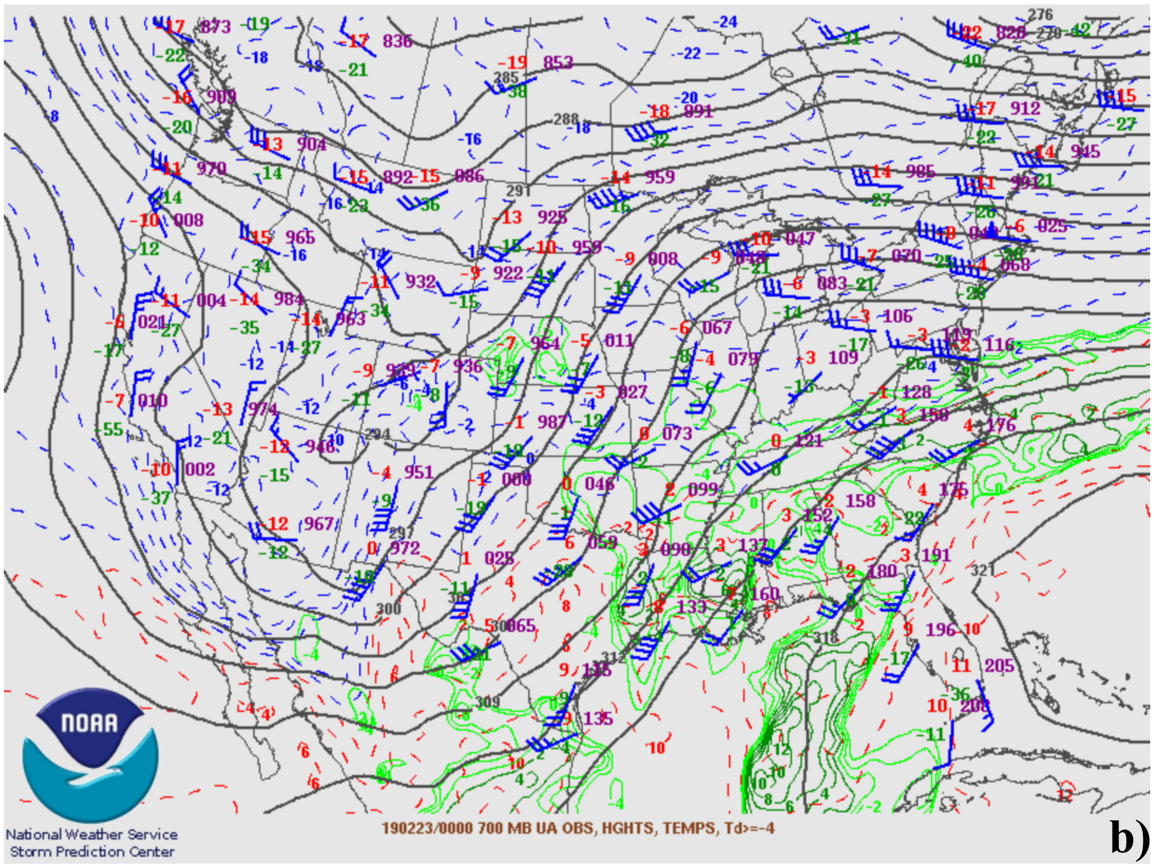

Figure 4.20b: 700 hPa analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

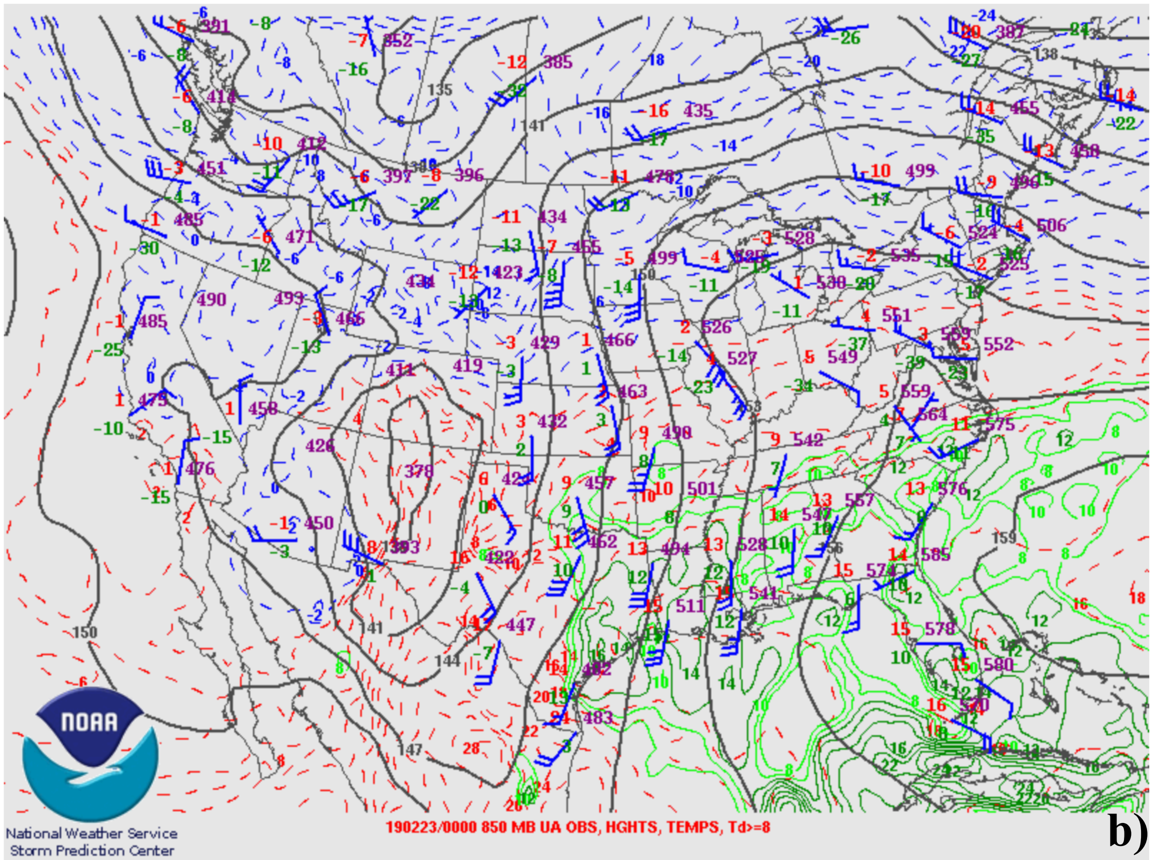

Figure 4.21b: 850 hPa analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

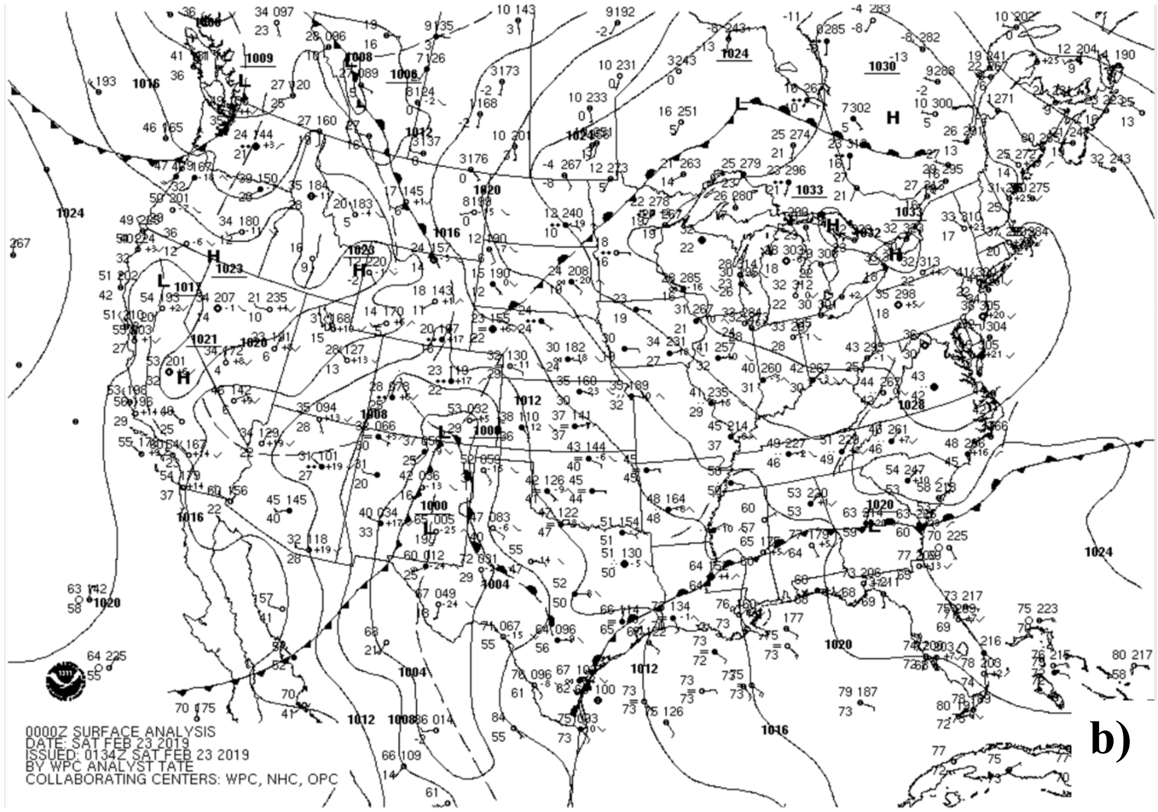

Figure 4.22b: Surface analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

a)

b)

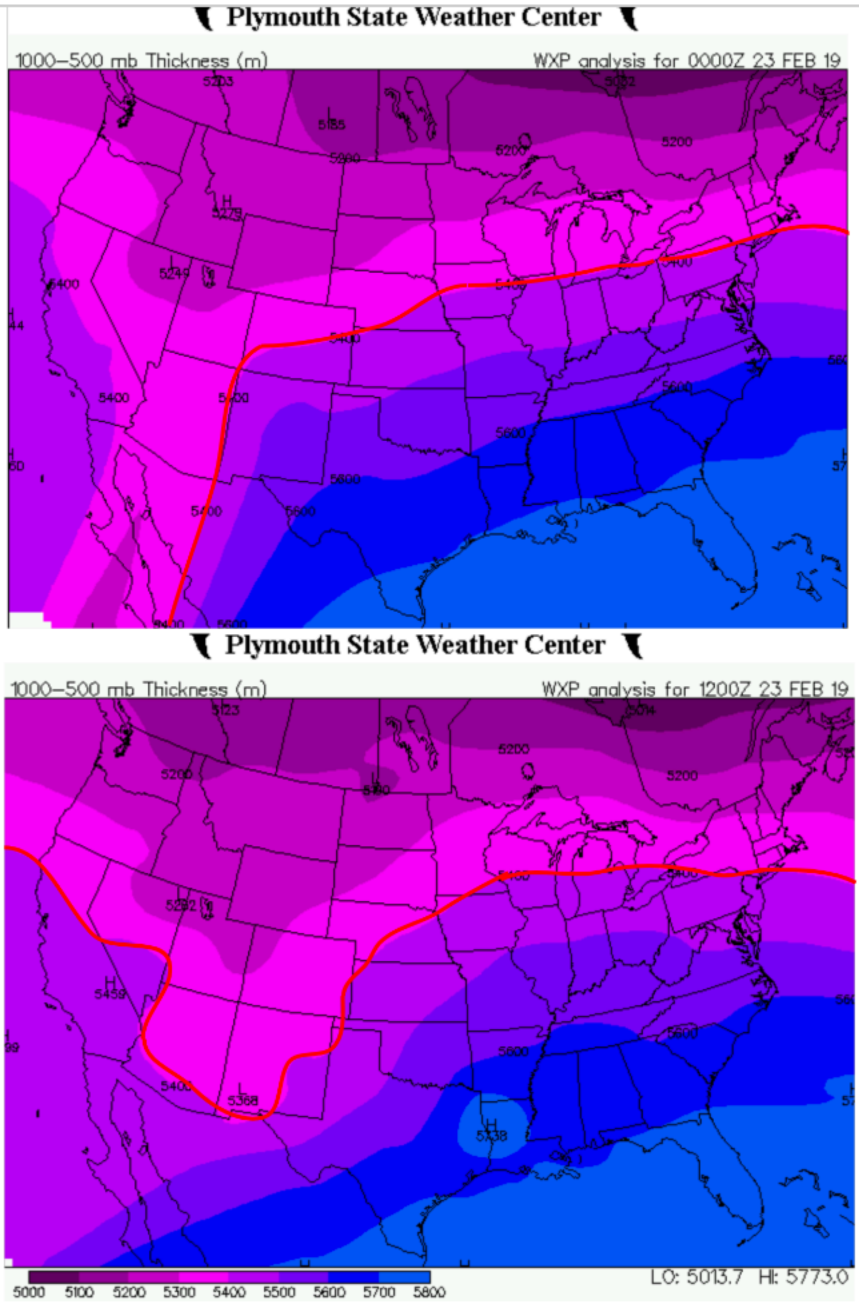

Figure 4.23: 1000-500 hPa partial thickness analysis with 5400 m critical thickness level outline (red) at: a) 0000 UTC 23 February 2019 and b) 1200 UTC 23 February 2019 (from Plymouth State 2020)

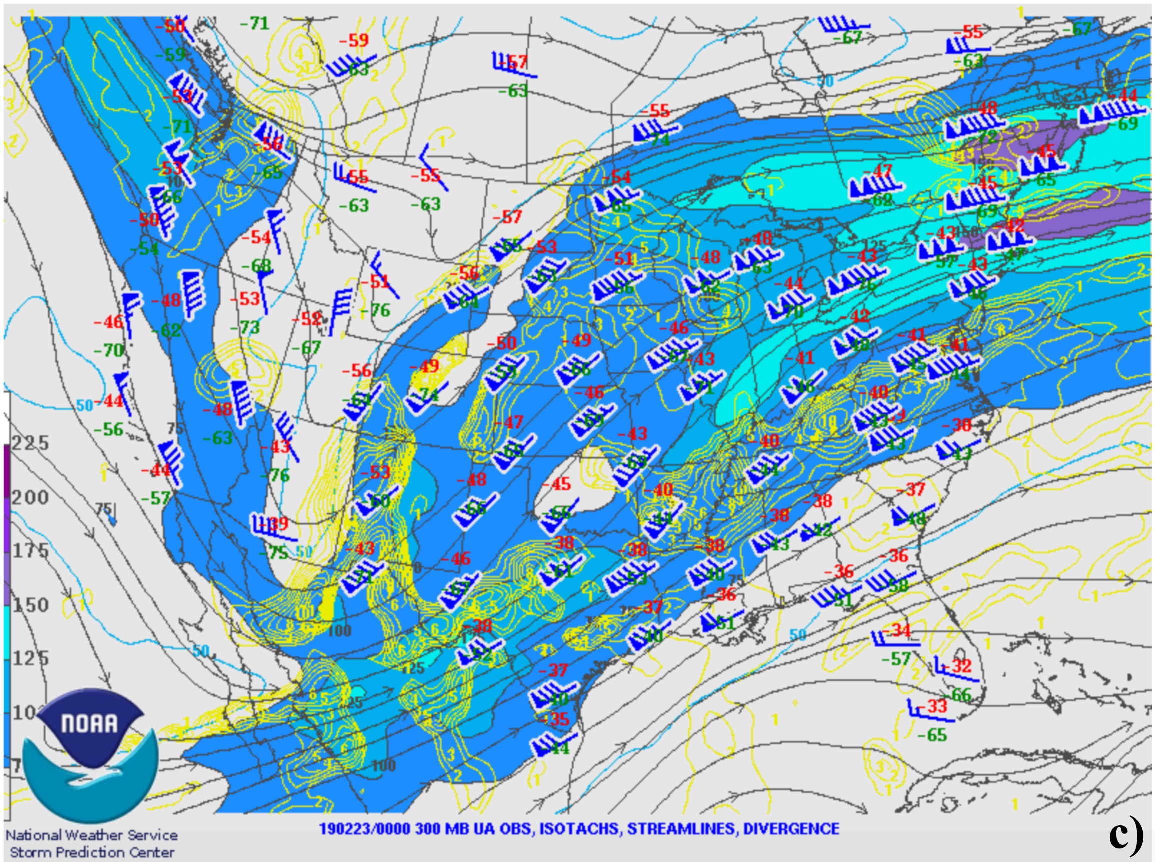

Figure 4.18c: 300 hPa analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

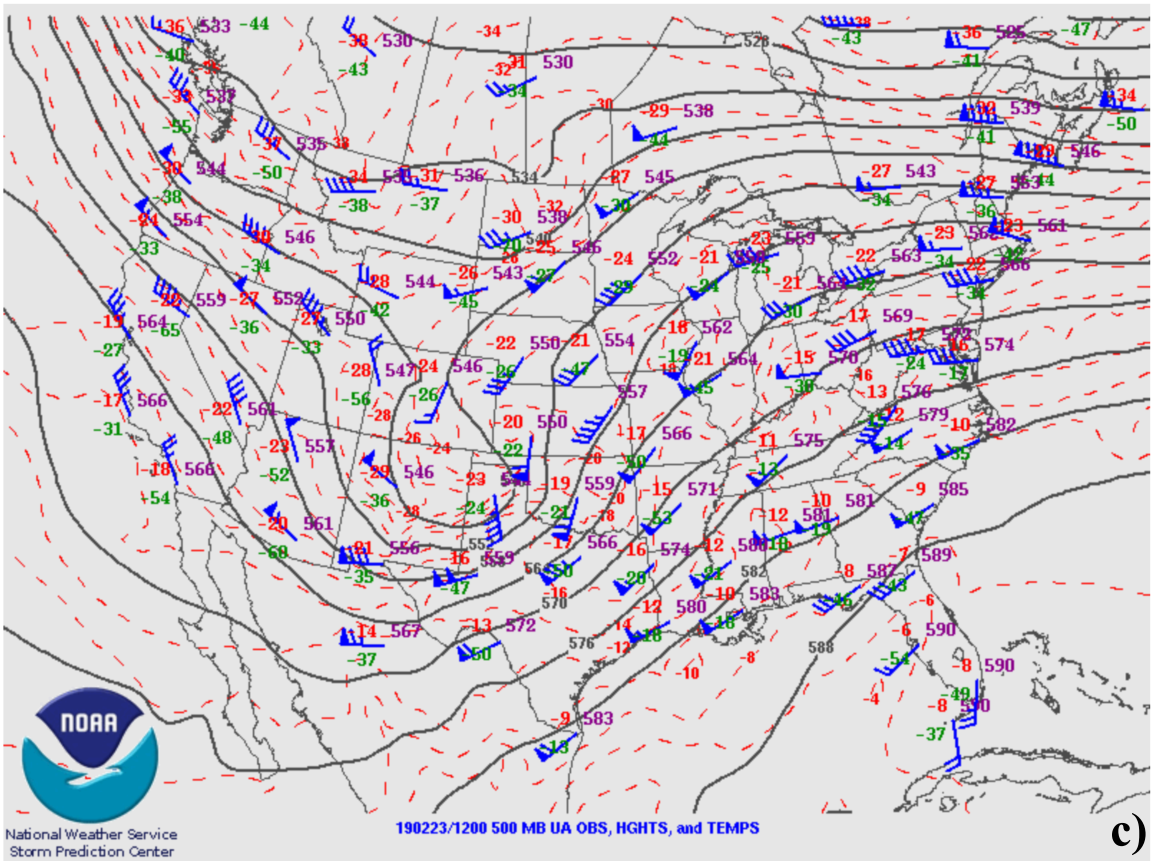

Figure 4.19c: 500 hPa analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

be in the vicinity of the left exit region of the jet stream, which helps to enhance the vertical lift of the system. The lower levels show a closed height system at both levels with conflicting wind directions. At 700 hPa (Figure 4.20c), south-southwesterly winds are observed, while northerly winds were beginning to impact Nebraska at the 850 hPa level (Figure 4.21c). A sharp decrease in available moisture is evident at 700 hPa, while the moisture at 850 hPa stayed constant. This is most likely why light rain/mist, instead of heavier precipitation, is observed across eastern Nebraska during the morning. At the surface, the low pressure system is finally affecting eastern Nebraska as winds have started to shift to a north-northeasterly direction (Figure 4.22c). Moisture content across the Central Plains at the surface had rebounded to values at or near saturation, also aiding in the presence of light rain/mist being observed. The 5400 m contour (Figure 4.23b) is retreating northwestwardly on the morning of 23 February 2019, as non-frozen precipitation continued across the region.

As the system progressed into the day on 23 February 2019, precipitation intensity also increased. Most of the morning is typified by light rain until around 1700 UTC when a quick transition between precipitation types occurred. In the lower levels, moisture had begun to wrap around the system and into the region. The clear moisture difference that is evident from the moisture disparity between the surface and lower levels is eroding, and at the 0000 UTC 24 February 2019 observation, the column up to 500 hPa is either at or near saturation. During the late morning of 23 February 2019, the light rain transitions to sleet, then ice pellets, then finally snow all within an hour with snow being the observed precipitation type at 1800 UTC 23 February 2019

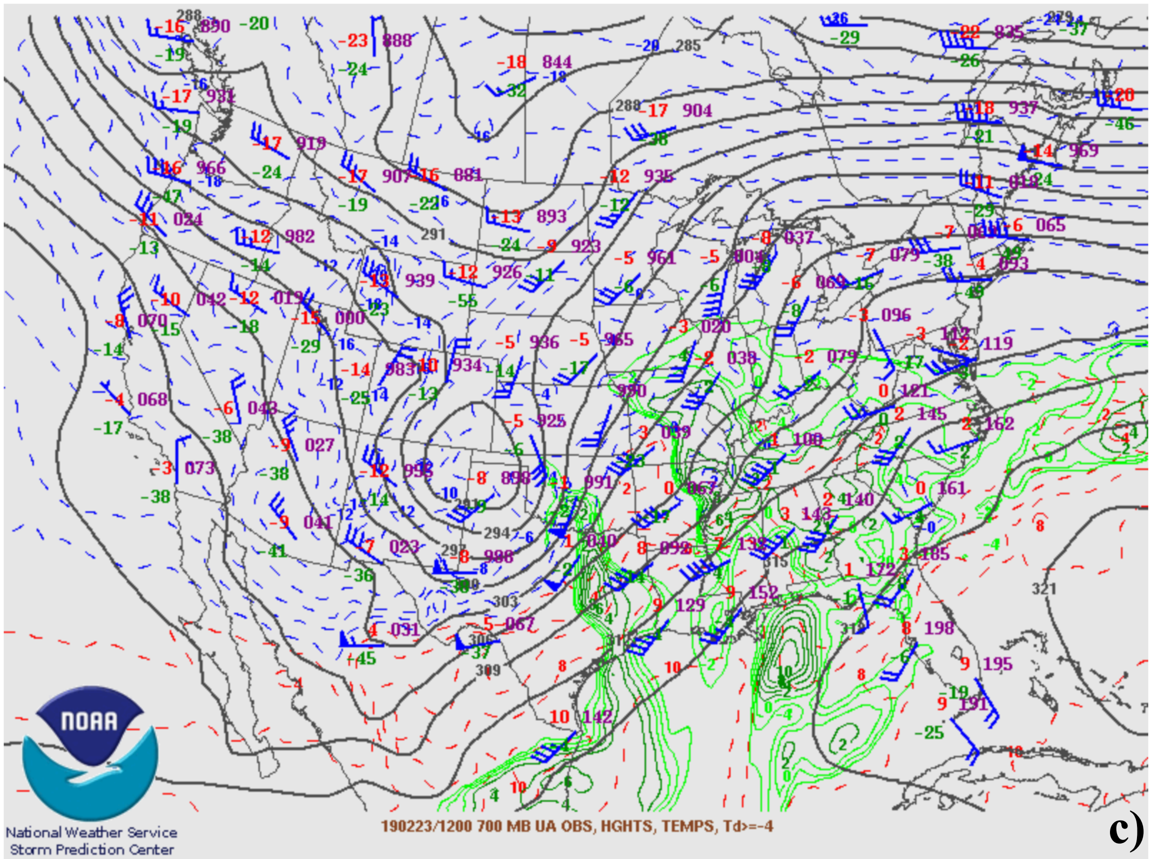

Figure 4.20c: 700 hPa analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

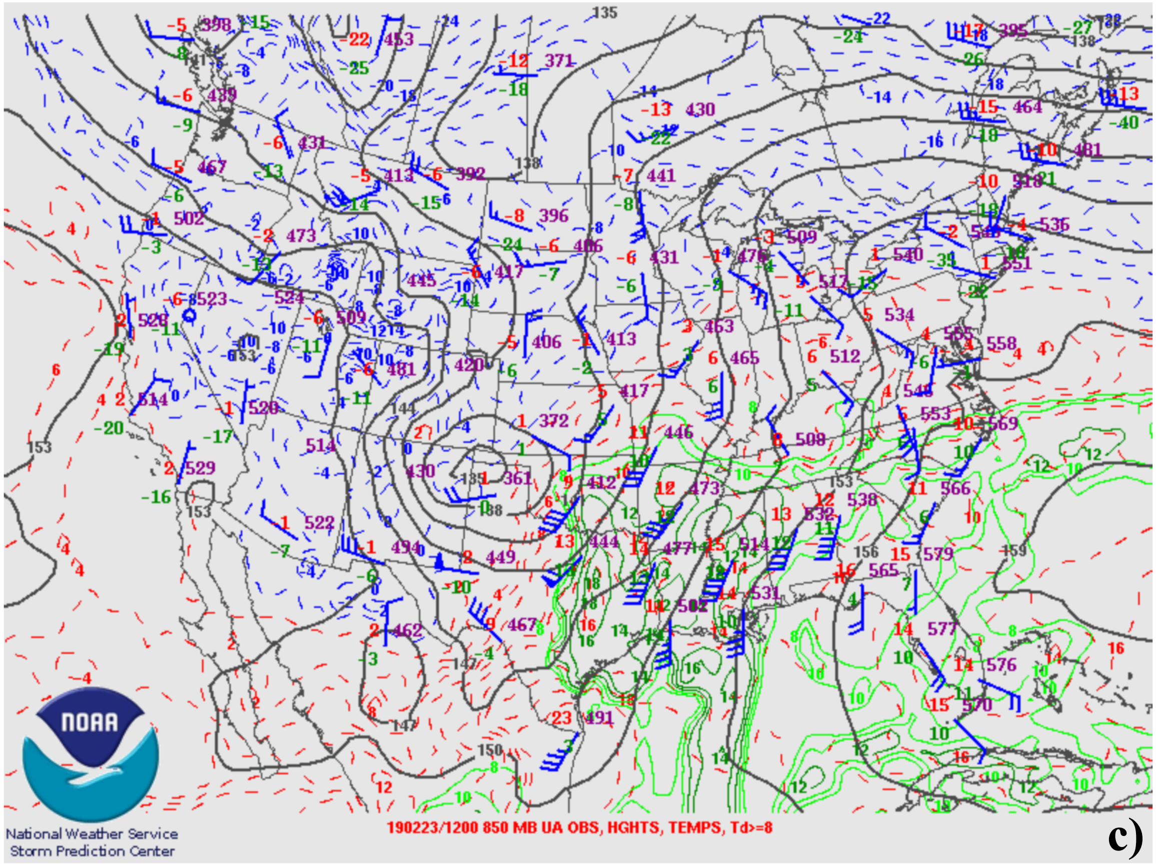

Figure 4.21c: 850 hPa analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

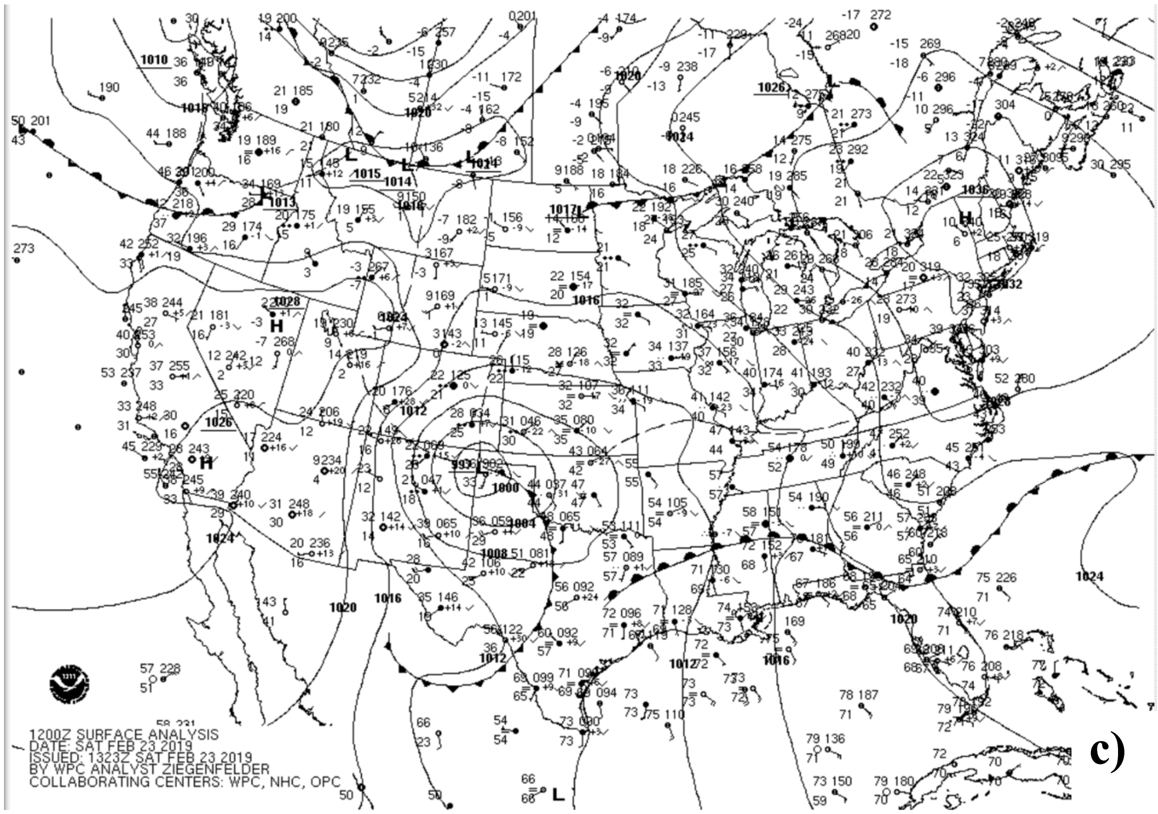

Figure 4.22c: Surface analysis at: a) 1200 UTC 22 February 2019 b) 0000 UTC 23 February 2019 c) 1200 UTC 23 February 2019 (from SPC 2019).

(SPC 2019). The presence of sleet during the transition to snow may have led to some of the observed forecasting issues. The low pressure system then progresses on a northeasterly trajectory and by 0600 UTC 24 February 2019 is over northern Illinois and southern Wisconsin. At this time, snowfall ceased over Lincoln and a strong northwesterly wind had begun to overtake much of the Central Plains.

A region of low pressure at the surface (Figure 4.22) forms in southeastern Colorado and then moves slowly off in a southeasterly direction and is observed over the Oklahoma and Texas panhandles by 12 UTC 23 February 2019. In comparison, the surface low pressure region for the November event (Figure 4.5) also originated in southeastern Colorado, yet 12 hours later the low pressure center was observed over southeastern Kansas. By the last time step, 12 UTC 23 February and 12 UTC 25 November respectively, much of eastern Nebraska is at saturation at the surface with temperatures right around freezing for both events. The February event is around 2 – 3 ^{o}F (1.1 – 1.7 ^{o}C) warmer, with slightly weaker winds at the surface compared to the November event. Aloft, the two systems look similar. A deep trough is embedded within the upper level flow during both the February (Figure 4.18) and November (Figure 4.1) events. The only noticeable differences are that during the November event, the trough had progressed farther east with a slightly stronger jet streak region compared to the February event. Although, a more concentrated region of upper level divergence is observed for the February event. These analogs correlate well with the surface as the November storm progressed off to the east much more quickly than the February storm,

which most likely contributed to the shorter event lengths that were recorded for the northern routes during the November event.

4.2b) MDSS Analysis:

The NDOT-MDSS analysis for the February case will follow suit of the NDOT-MDSS analysis for the November 2018 event and are conducted between 17 UTC 23 February 2019 and 05 UTC 24 February 2019. Snowfall analyses are constrained between 17 UTC 22 February 2019 and end times varying from 04 - 05 UTC 24 February 2019 for the observed routes.

Weather observations from the interstate road section for the February event are actually in stark contrast to those of the November event (Figure 4.24). The NDOT-MDSS consistently over-forecasted the air temperature values across all of the forecast runs. The forecast for the P80 outperforms the forecast for W80, with the largest deficit of 3 ^{o}F (1.7 ^{o}C) for P80 and 12 ^{o}F (6.7 ^{o}C) for W80. The forecast temperatures for the W80 route have more considerable variations for the different time periods than the other routes and 12 hours prior is arguably more accurate than the 9-hour forecast. Consistency correlation with the 16 mi (25.8 km) distance between HW34 and HW33 can also be noted through the temperature forecasts. Reasonable variation within 2 ^{o}F (1.1 ^{o}C) is observed across the first four forecast hours with the NDOT-MDSS failing to capture the magnitude of the temperature decrease at 21 UTC 23 February 2019. The largest disparity is observed to occur at the last hour of the forecast run for HW77 with an

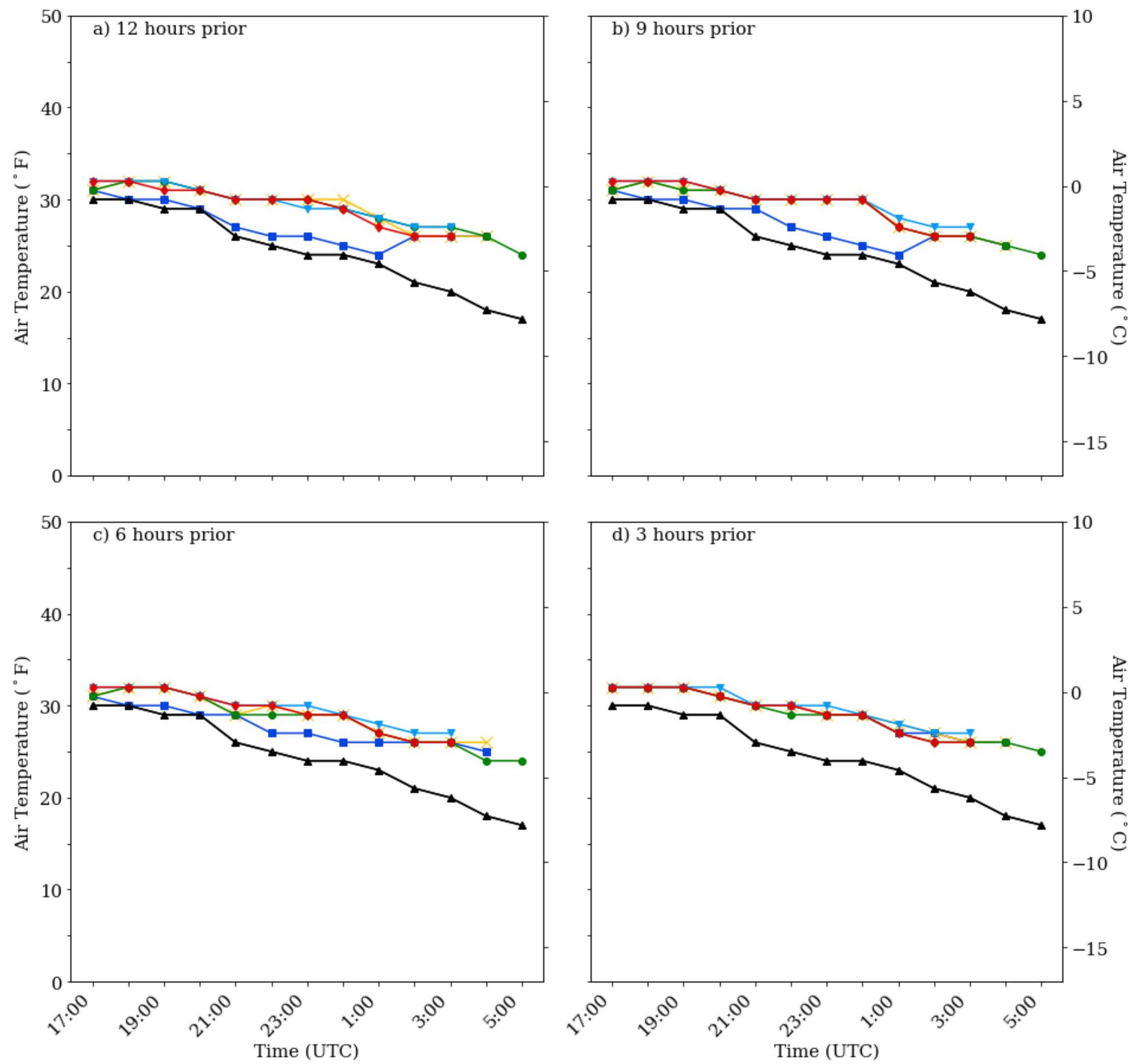

Figure 4.24: 23 – 24 February 2019 hourly temperature forecasted by MDSS at (a) 0500 UTC forecast run (12 hours prior to snowfall start), (b) 0800 UTC forecast run (9 hours prior to snowfall start), (c) 1100 UTC forecast run (6 hours prior to snowfall start), and (d) 1400 UTC forecast run (3 hours prior to snowfall start) for W80 (yellow), P80 (blue), HW34 (red), HW33 (green), and HW77 (light blue) compared to ASOS observed (black). Date and time run from the start of snowfall to the end of snowfall.

overage of 10 ^{o}F (5.6 ^{o}C). In general, air temperature forecasts for all the routes follow a similar progression, with temperature forecasts for all hours being better in the earlier part of the storm compared to later in the event. The air temperature differences (Figure 4.25) show how the NDOT-MDSS over-forecasted across nearly all of the forecast runs. This could be another example of the NDOT-MDSS having difficulties projecting the exact track of the low pressure system and therefore predicting eastern Nebraska to stay within a region of warmer air for longer.

In general, dewpoint temperature forecasts for all the routes perform better at the beginning of snowfall onset and decrease in accuracy towards the end of the event (Figure 4.26). The W80 route again has the most substantial variations across all forecast times compared to the other routes. However, the most distinctive characteristic is the under-forecast for both sections when compared to ASOS observations. This trend does fit as the lower temperatures at W80 comparatively to P80 would naturally indicate lower dewpoint temperatures. The largest deficit at P80 is 5 ^{o}F (2.8 ^{o}C), while the largest deficit at W80 is 14 ^{o}F (7.8 ^{o}C). The largest deficit for dewpoint temperature is 10 ^{o}F (5.6 ^{o}C) recorded at the last hour of the 12 hour prior forecast run for both HW33 and HW77. This could be interpreted as the NDOT-MDSS forecasting much drier conditions and therefore lessened snowfall accumulation except, as will be documented later, this is not the case. Of the four forecast runs of the NDOT-MDSS (3, 6, 9, and 12 hours prior to snowfall) that are investigated, the 12 hour prior forecast is the most accurate, which indicates that the NDOT-MDSS has a better handle upon forecasts at longer range (Figure 4.27).

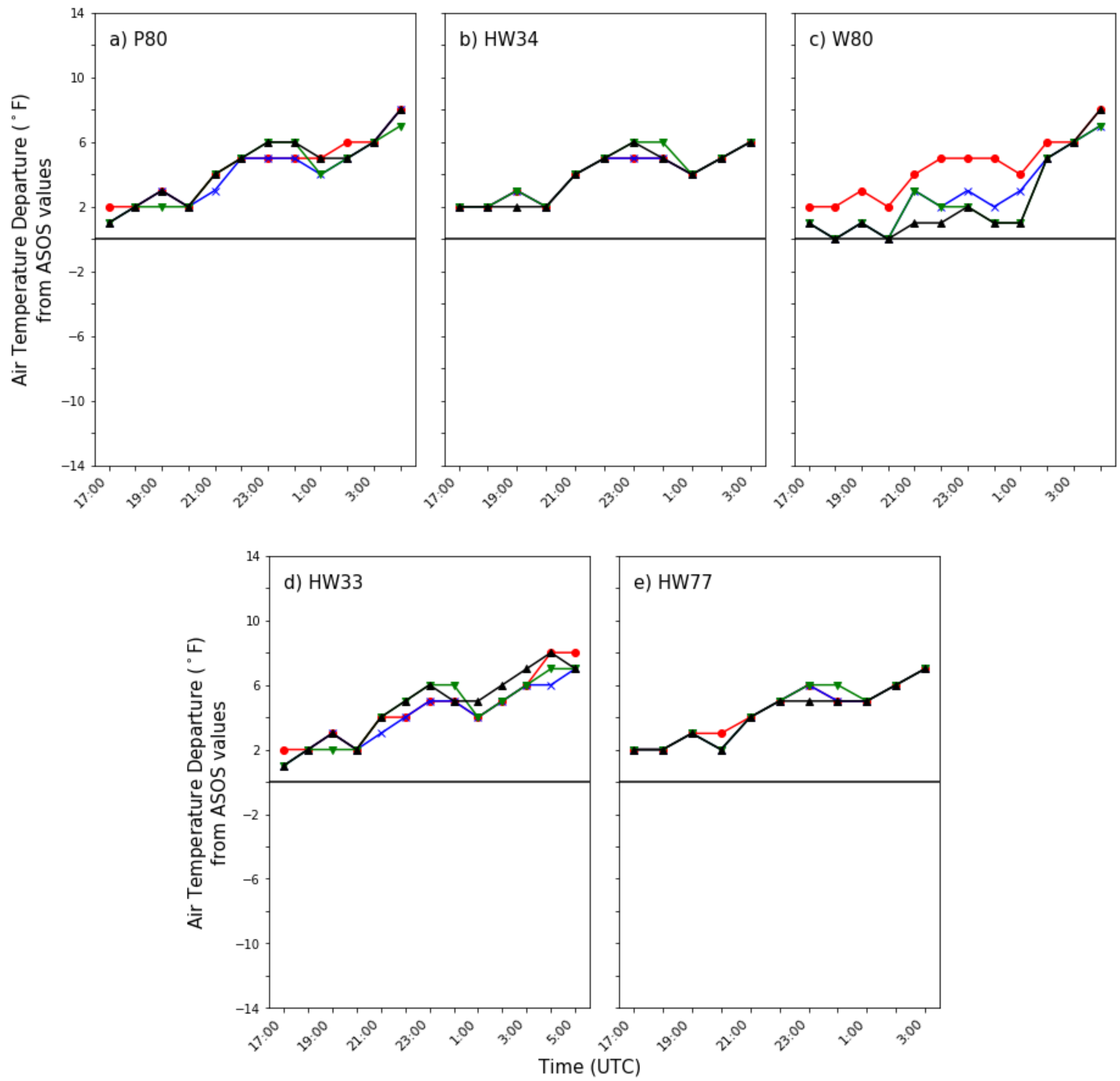

Figure 4.25: Difference graphs of the NDOT-MDSS forecasted temperature departure for 23 – 24 February 2019 from the observed ASOS values at (a) P80, (b) HW34, (c) W80, (d) HW33, and (e) HW77 for 3 hours (red) for 3 hours (red), 6 hours (blue), 9 hours (green), 12 hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

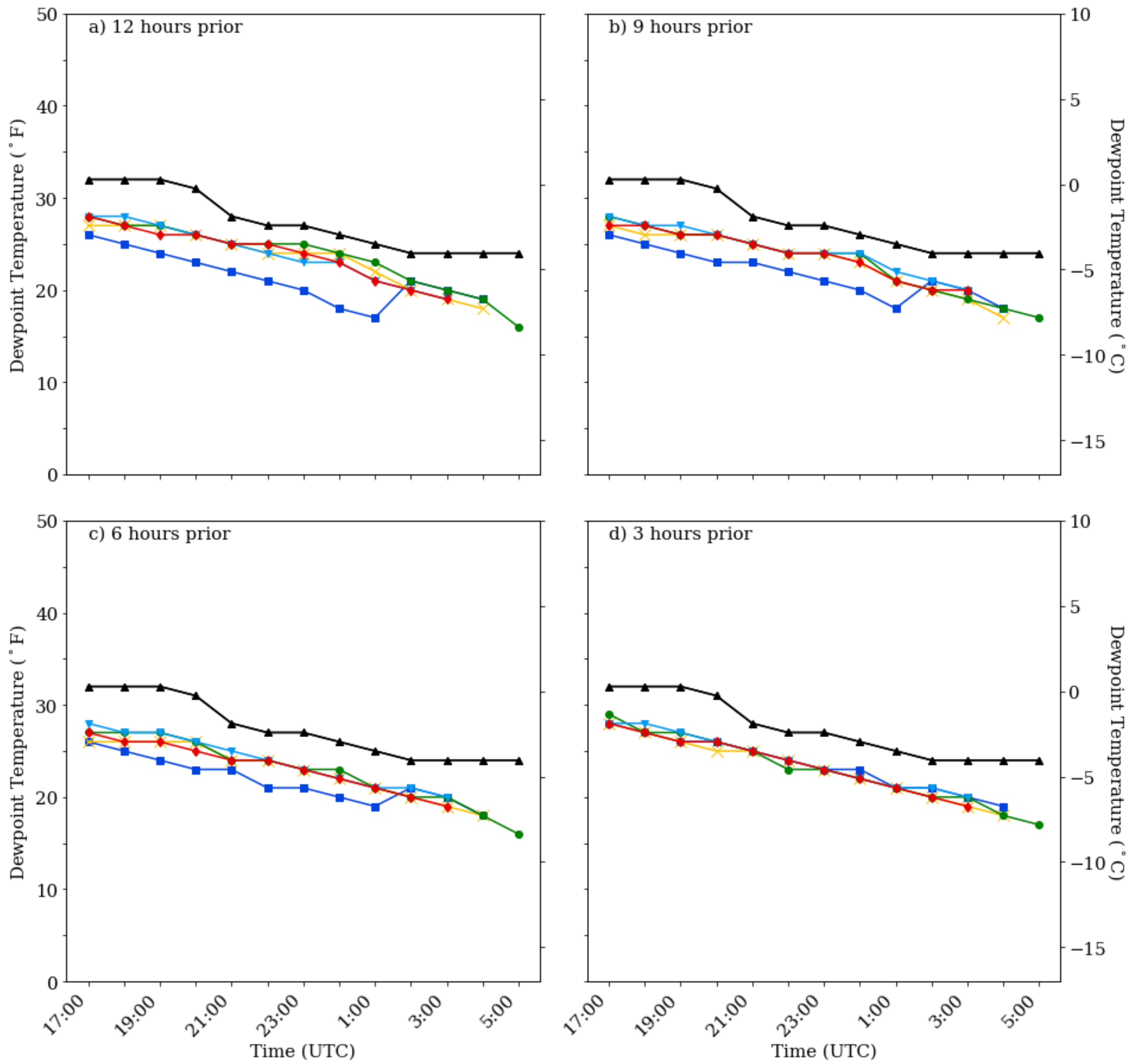

Figure 4.26: 23 – 24 February 2019 hourly dewpoint temperature forecasted by MDSS at (a) 0500 UTC forecast run (12 hours prior to snowfall start), (b) 0800 UTC forecast run (9 hours prior to snowfall start), (c) 1100 UTC forecast run (6 hours prior to snowfall start), and (d) 1400 UTC forecast run (3 hours prior to snowfall start) for W80 (yellow), P80 (blue), HW34 (red), HW33 (green), and HW77 (light blue) compared to ASOS observed (black). Date and time run from the start of snowfall to the end of snowfall.

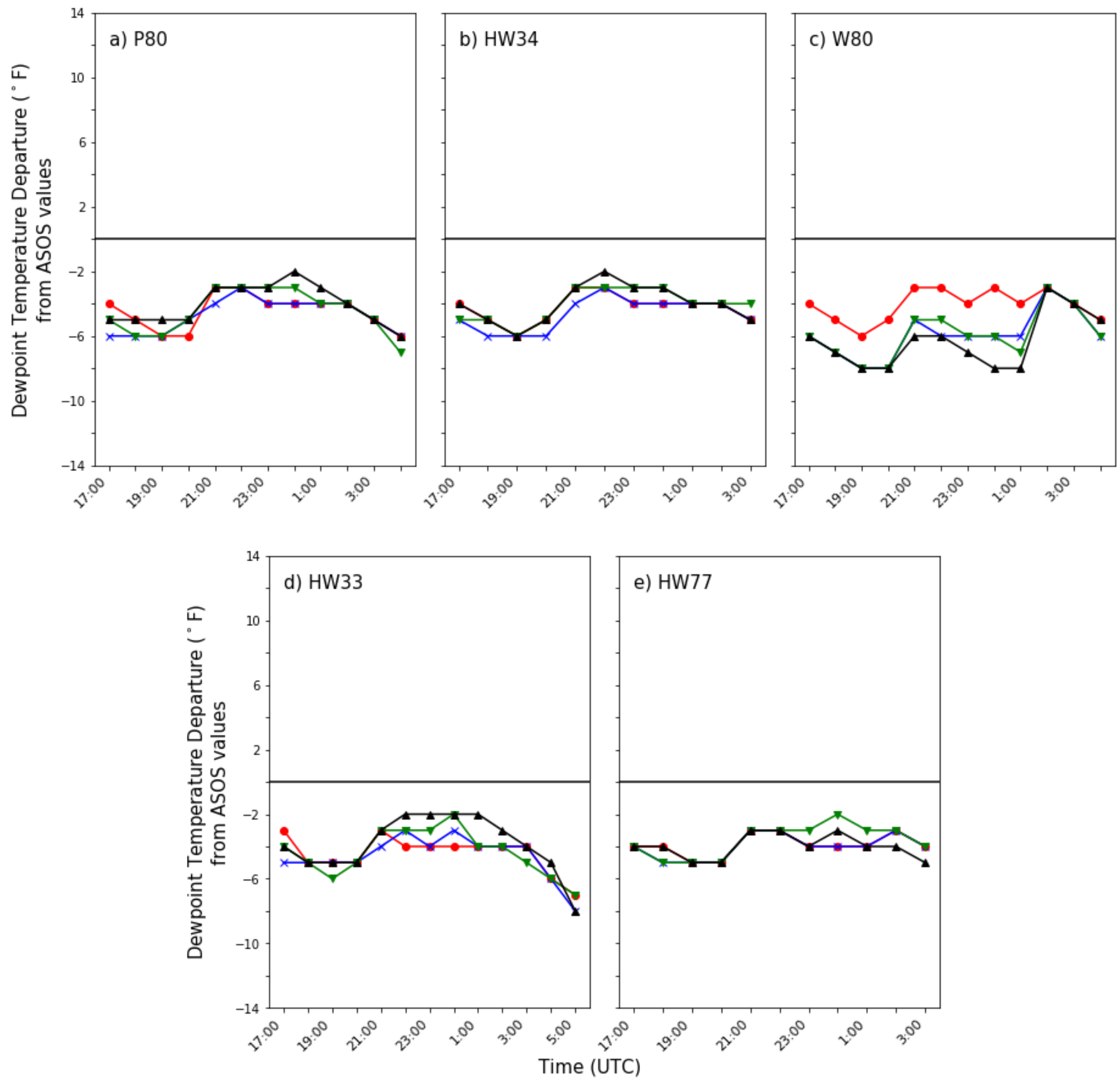

Figure 4.27: Difference graphs of the NDOT-MDSS forecasted dewpoint temperature departure 23 – 24 February 2019 from the observed ASOS values at (a) P80, (b) HW34, (c) W80, (d) HW33, and (e) HW77 for 3 hours (red) for 3 hours (red), 6 hours (blue), 9 hours (green), 12 hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

The November case study generally under-forecasted wind speed for all of the routes, while for the February event (Figure 4.28), the NDOT-MDSS nearly correctly predicted wind speeds for all of the routes early in the event. Later in the event, the differences in forecasted wind speed compared to observed wind speed are much larger. Maximum observed overages of 8.0 kt (4.1 m s^{-1}) at P80 and W80 are noted with occasional deficits at the time of the ASOS wind speed maxima. The wind speed forecasts all tended to under-predict initially and then over-predict with increasing variation towards the end of the event (Figure 4.29). A pronounced spike in snowfall accumulation also occurs prior to and during the initial snowfall event (Figure 4.30). These variations could be a result of the NDOT-MDSS over-forecasting the intensity of the storm. While the NDOT-MDSS does tend to over-predict actual values of wind speed, the important takeaway is that the NDOT-MDSS forecasted the trend of wind speed evolution over time moderately well. At the beginning of the event, the wind speeds are forecasted to be increasing with time until a peak and then decreasing incrementally after all of the runs forecast the peak. The main issue with the patterns is that the peak forecasted wind speeds are lagged by 3 hours compared to the ASOS observations. Ideally, NDOT would be able to locate this wind speed trend within the NDOT-MDSS forecast and inform the plow truck drivers of the proper maintenance precautions with regards to an uptick in wind speed.

The difference graphs (Figure 4.25, 4.27, 4.29) are useful in diagnosing how well the forecast evolved over time when compared against the ASOS observed values. When studying the differential graphs for W80, it is seen that there is consistency across all of

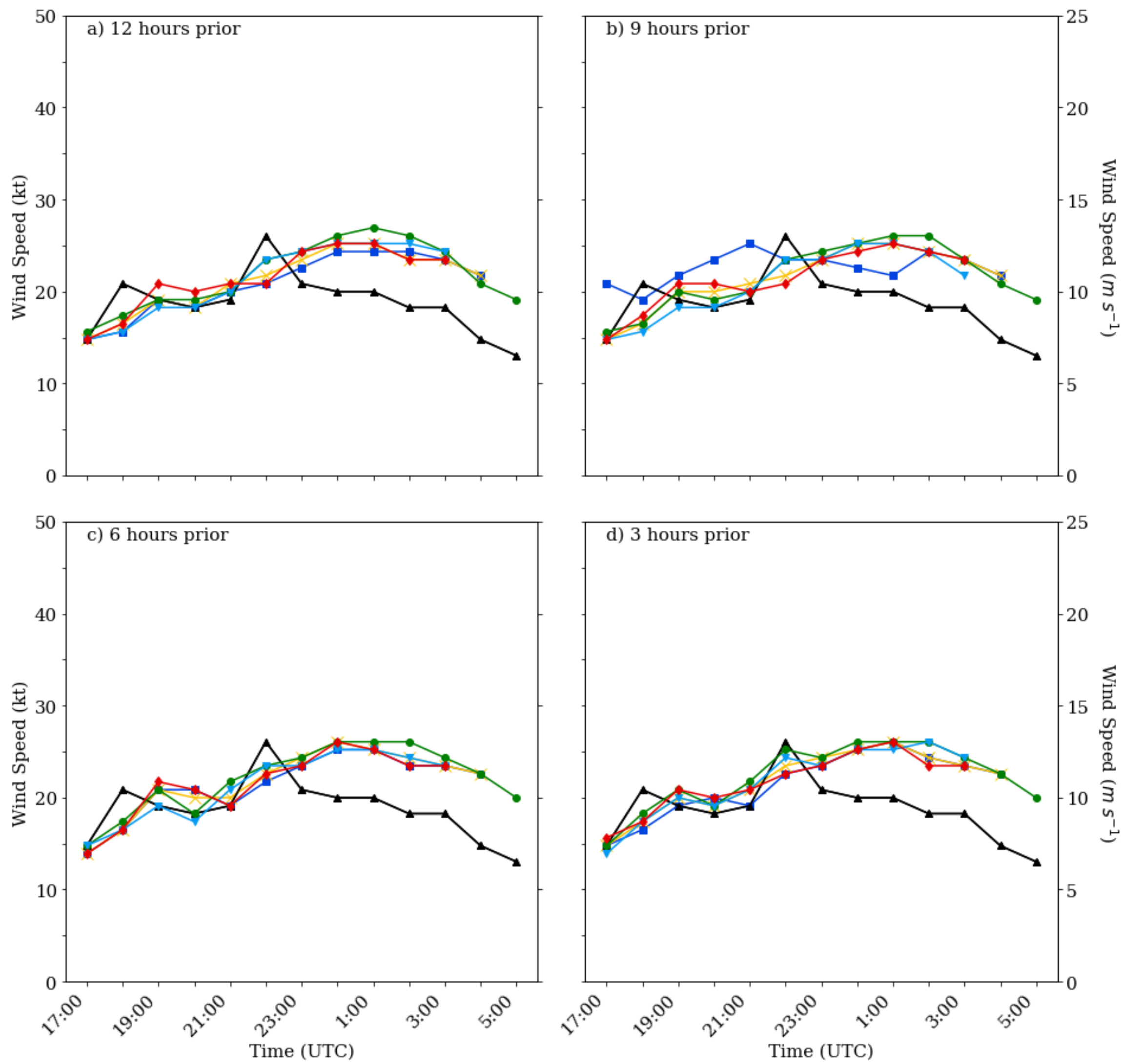

Figure 4.28: 23 – 24 February 2019 hourly wind speed forecasted by MDSS at (a) 0500 UTC forecast run (12 hours prior to snowfall start), (b) 0800 UTC forecast run (9 hours prior to snowfall start), (c) 1100 UTC forecast run (6 hours prior to snowfall start), and (d) 1400 UTC forecast run (3 hours prior to snowfall start) for W80 (yellow), P80 (blue), HW34 (red), HW33 (green), and HW77 (light blue) compared to ASOS observed (black). Date and time run from the start of snowfall to the end of snowfall.

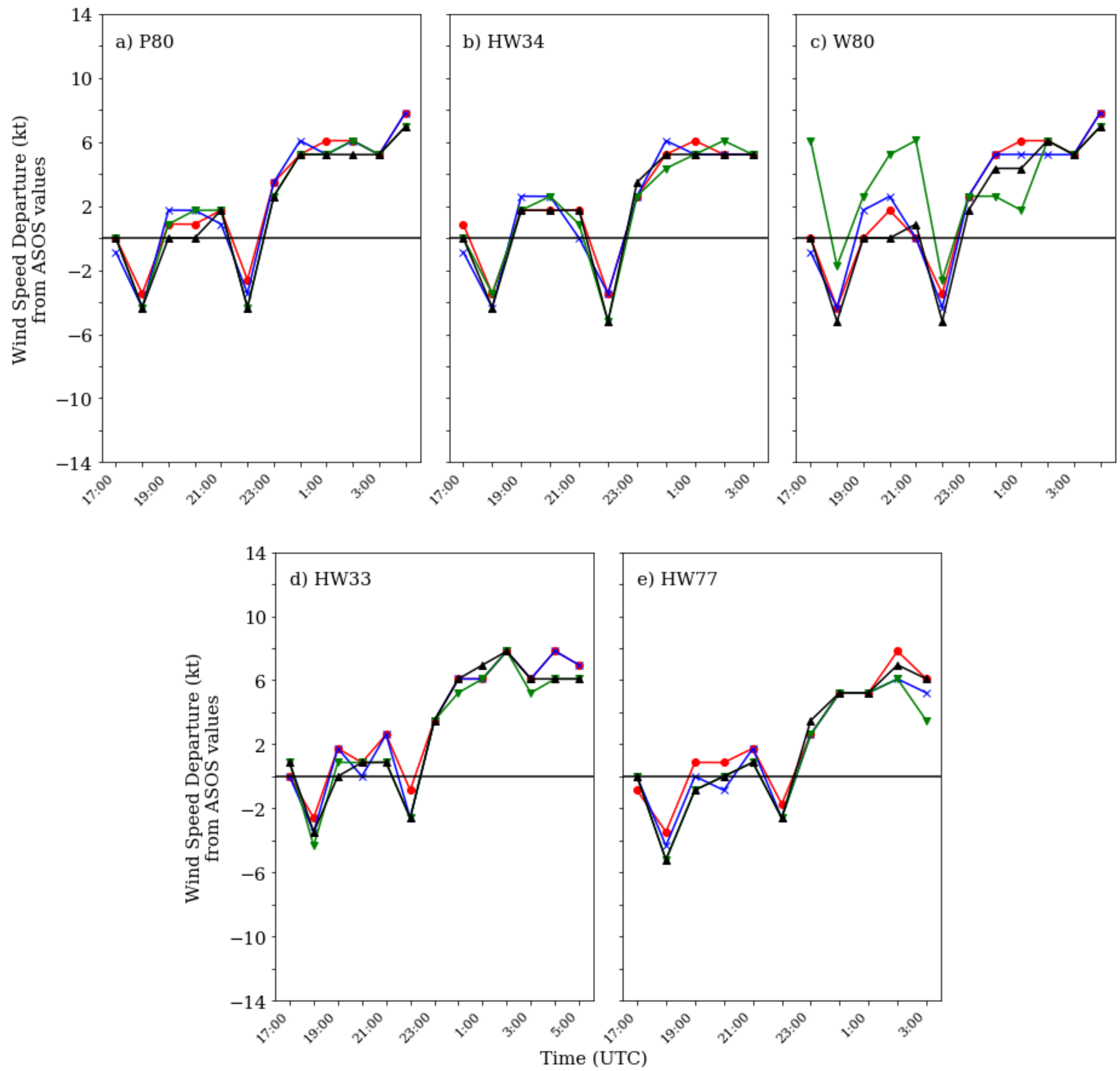

Figure 4.29: Difference graphs of the NDOT-MDSS forecasted wind speed departure 23 – 24 February 2019 from the observed ASOS values at (a) P80, (b) HW34, (c) W80, (d) HW33, and (e) HW77 for 3 hours (red) for 3 hours (red), 6 hours (blue), 9 hours (green), 12 hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

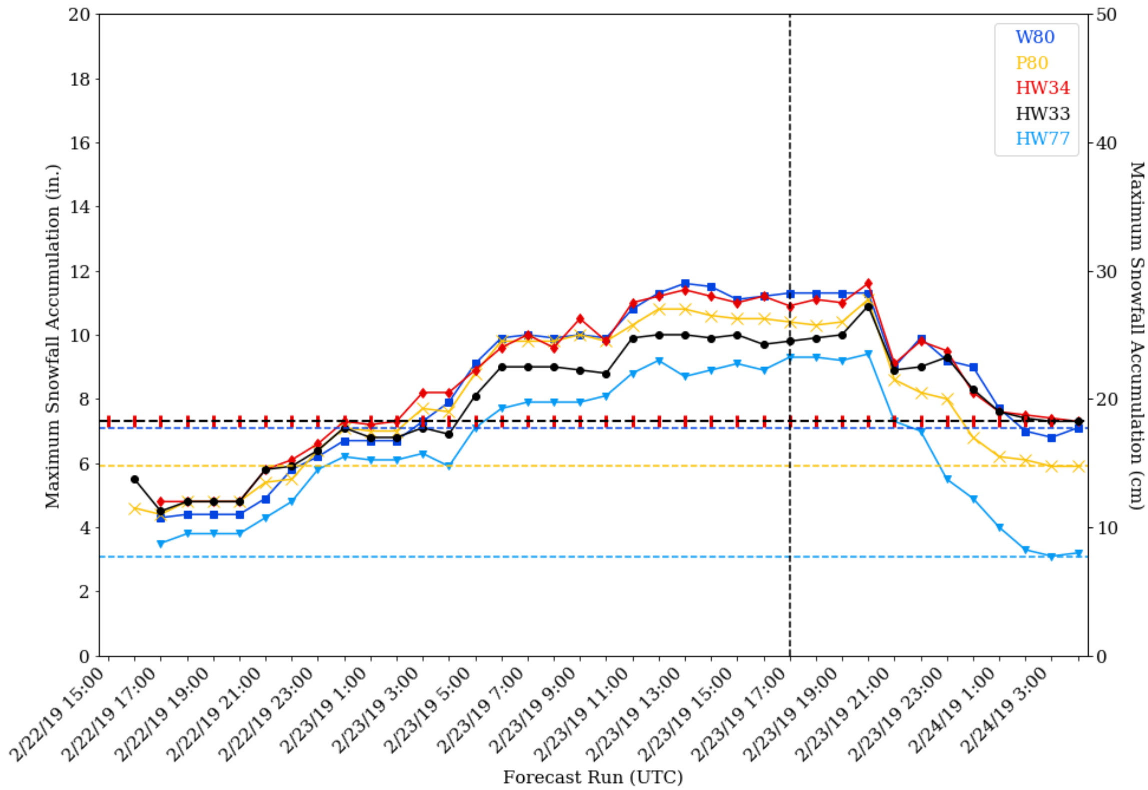

Figure 4.30: Maximum MDSS forecasted snowfall accumulation for the individually observed routes per forecast run. The vertical dotted line denotes snowfall start time. The color-coded horizontal lines denote the final snowfall accumulation totals recorded at the snowfall end time for their corresponding routes.

the runs, with the largest margin of variation at only two units across all of the forecast runs. As stated previously, the temperature forecast is within 3 ^{o}F (1.6 ^{o}C) away from ASOS at any given time within the different forecast runs. Dewpoint and wind speed both have moderately high departures from ASOS yet again exhibit the same consistent trend across all forecast runs. The difference graphs for P80 display the same forecast trend consistency with much less accuracy at air temperature than the W80 forecast. Across the three forecast parameters, the differential graphs are remarkably consistent for each of the highway routes observed. While the NDOT-MDSS is consistent, the lack of accuracy in relation to the ASOS values is observed. The most important takeaways from the time series difference graphs for these routes are the magnitude of forecasting variation for temperature and dewpoint and the confidence with which the NDOT-MDSS continually produces similar forecasts even as the time advances closer to the snowfall start time.

The over-forecasted air temperatures, in conjunction with the under-forecasted dewpoint temperatures, in theory, would lend to under-forecasting snowfall. A lack of moisture at the surface would inhibit the available moisture for the whole system and could even work to evaporate hydrometeors as they descend towards the surface. In contradiction to this hypothesis, though, the NDOT-MDSS over-forecasts snowfall (Figure 4.30) from 03 UTC 23 February 2019 to 01 UTC 24 February 2019 at W80 and from 23 UTC 22 February 2019 to 02 UTC 24 February 2019 at P80. An upper air forecast from the NDOT-MDSS would aid in diagnosing this issue and possibly resolve why the NDOT-MDSS ended up over-forecasting snowfall accumulations; however, the

NDOT-MDSS does not provide these analogs in their forecast suite. The most accurate forecast for snowfall accumulation by the NDOT-MDSS is 17 and 18 hours prior to snowfall onset at W80 and P80, respectively.

While the NDOT-MDSS does ultimately adapt through the snowfall event to end up at the correct value for the route, the most accurate forecasts from the system (within 1.0 inch (2.54 cm)) are produced more than 10 hours prior to snowfall start. An initial spike in accumulation maxima at snowfall onset is observed for all three of the highway routes (Figure 4.30). When all of the observed routes together are compared against each other, it is evident that the NDOT-MDSS has outlined a clearly defined pattern that evolved over time. The northernmost routes (W80, HW34, P80) have the highest accumulations and the southernmost routes (HW33 & HW77) were lower prior to snowfall onset. The final snowfall accumulation amounts display the same distribution and also include the variance from the east-west gradients of snowfall as P80 received nearly an inch less than W80. Peculiarly enough, there is a difference of 1.4 inches (3.6 cm) of snowfall accumulation between P80 at 5.9 inches (15.0 cm) and HW34 at 7.3 inches (18.5 cm), which are separated by 4.5 mi (7.2 km). This large difference is particularly of note because the difference in snowfall accumulation between the two routes for the November event is only 0.1 inches (0.3 cm). There is no noticeable gradient (Figure 4.31) in the observed data that encompasses the two routes. This could be related to the issue of averaging over route length, as the HW34 route is roughly half the length of the P80 route.

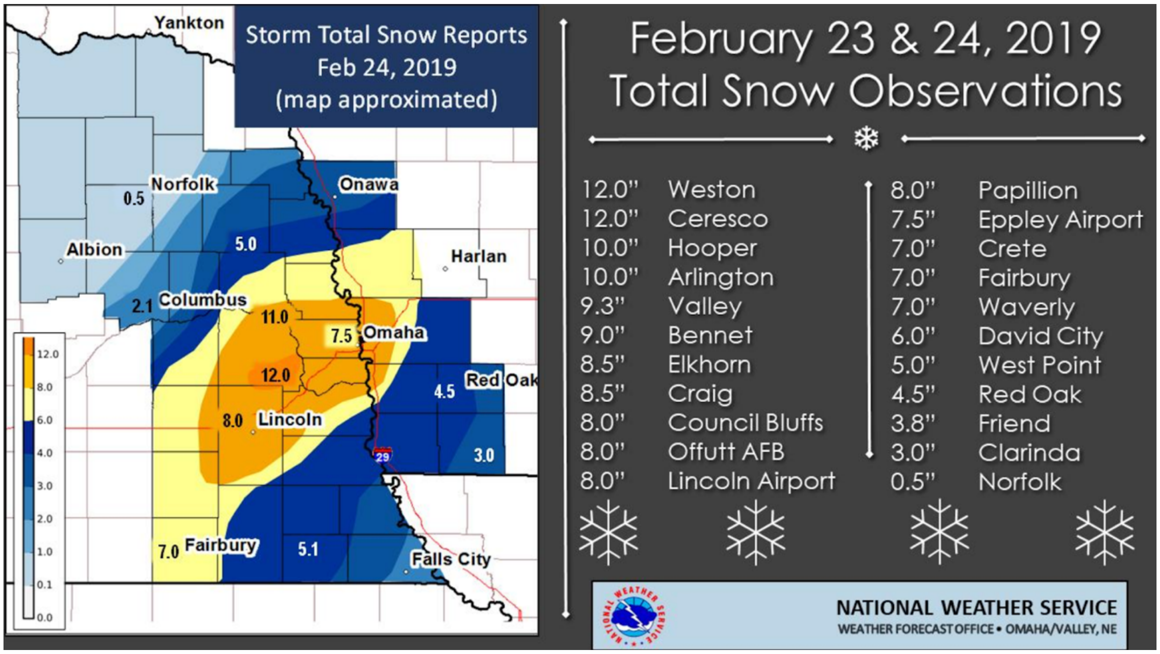

Figure 4.31: Total snowfall accumulation map across the NWS Omaha CWA for 23-24 February 2019 (from NWS Omaha/Valley 2019).

Event length variations differed between the February event and the November event. Event length (Figure 4.32, 4.33) is consistently under-forecasted for each of the routes per forecast run leading up to the start of snowfall. The interstate routes have a similar margin of variation to the November event (Figures 4.14, 4.15), spanning two to four hours after the NDOT-MDSS had begun to forecast the full event length. Variations for the highway routes span one to three hours for HW34 and HW77, while HW33 exhibits a variation of two to four hours, which is much more akin to the interstate routes. The primary discrepancies in variations among the routes are that the HW34 and HW77 routes both recorded event lengths two hours shorter than the other three routes. A comparison of the end times (Figure 4.34) for the February event demonstrated that P80 and HW34 are accurate over the forecast period. That being said, P80 and HW34 still mostly under-forecast the end times, albeit by two hours maximum. The differences for HW33 and HW77 show consistent and more substantial under-forecasting across the forecast period. The outlier from the group for the February event is the W80 route, which oscillates between one hour earlier and one hour later during the forecast period and finally correctly forecasts the end time during its last six forecast runs. The result of under-forecasting the event length for this event is also notable because, comparatively, Colorado low systems will have a longer event length. It is worth noting that while this February case negatively correlates with the November event in regard to event length and end time, there is still minimal consistency across the individual routes. One conclusion from the data on both of the events is that there is better accuracy along the routes that are closer to the higher snowfall totals. This is a positive sign as it is typically

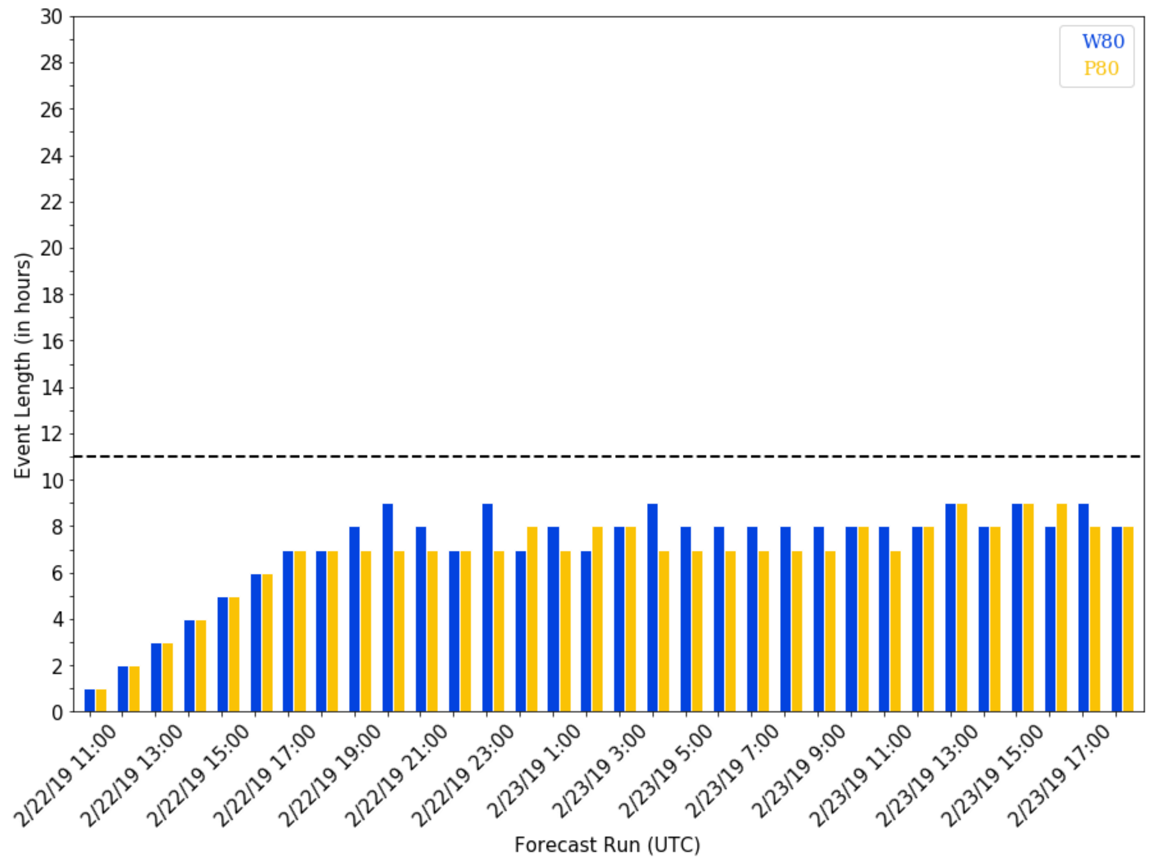

Figure 4.32: MDSS forecasted event length for the W80 (yellow) and P80 (blue) per forecast run. The horizontal dashed line denotes the final recorded event length for the corresponding routes.

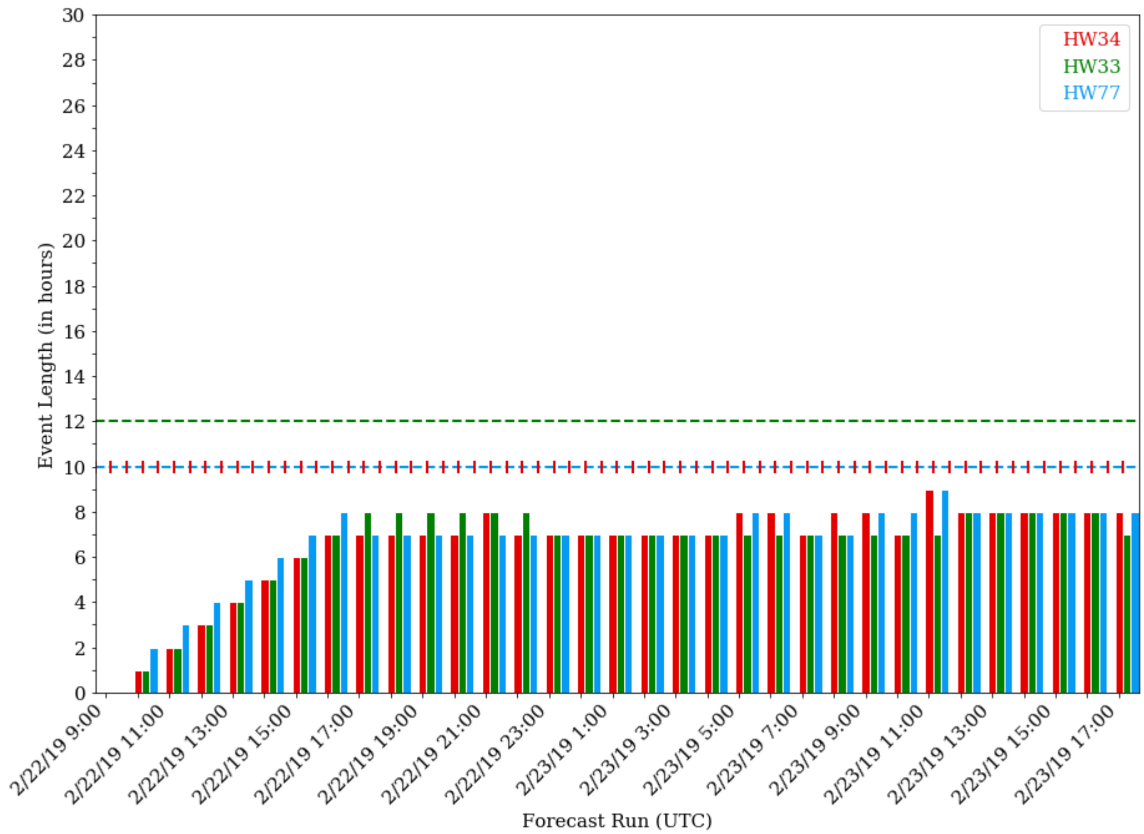

Figure 4.33: MDSS forecasted event length for HW34 (red), HW33 (black), and HW77 (light blue) per forecast run. The color-coded horizontal lines and vertical ticks denote the final recorded event length for the corresponding routes.

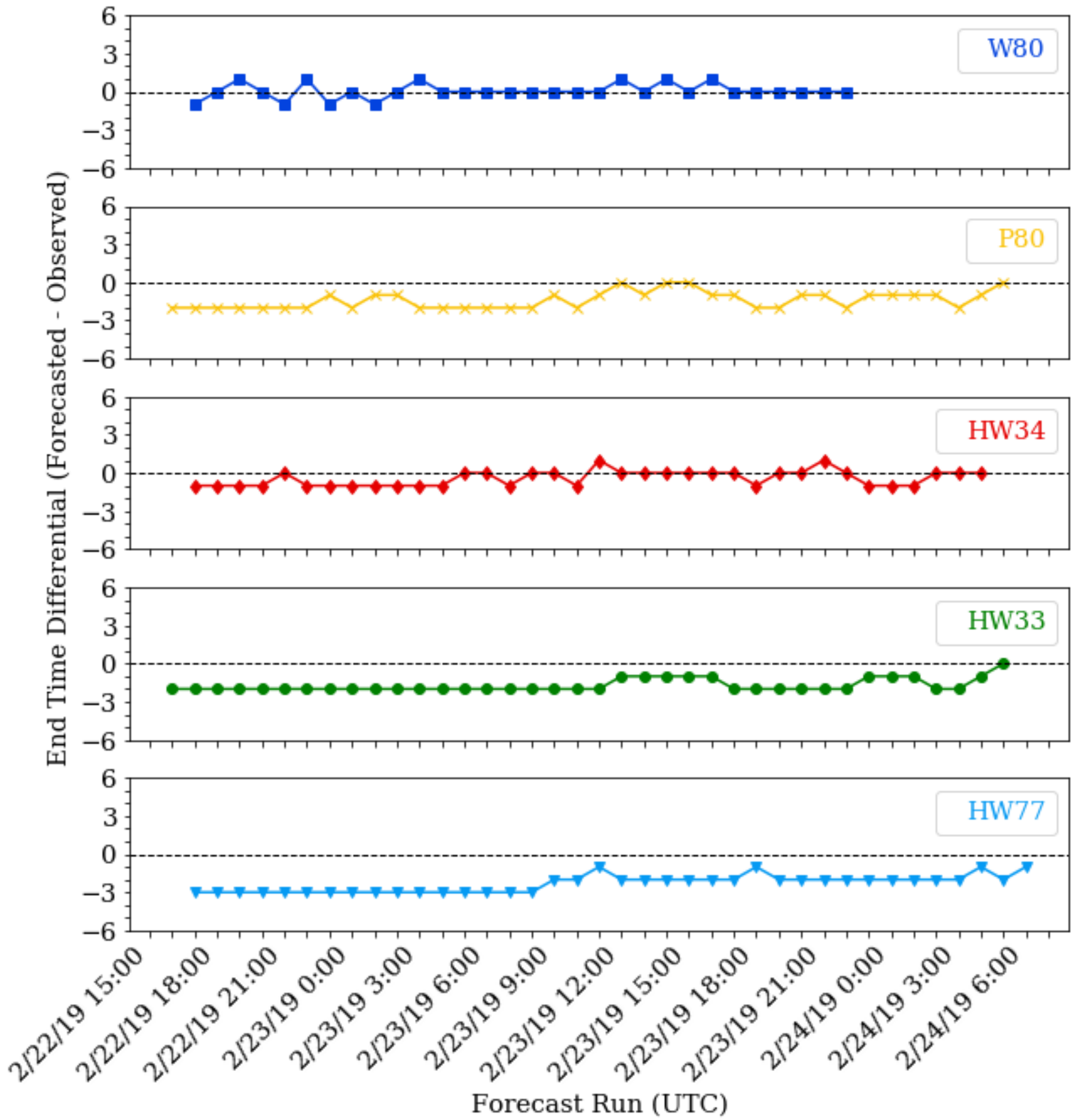

Figure 4.34: 22 – 24 February 2019 snowfall end time difference graphs for the five observed routes from the NDOT-MDSS.

easier to develop a forecast for a region within the bullseye of highest snowfall accumulation than it is to forecast for the snowfall totals and event length at areas on the edges of where the storm is primarily impacting.

4.3 Snowfall Forecast Analysis:

Snowfall accumulation forecasts are further compared against the NWS zone forecasts for Lancaster County and ASOS observed snowfall for the Lincoln airport as well as the GFS, 12 km NAM, 4 km NAM, RAP, and their model average for KLNK at a 12:1 SLR value for the November event and a 14:1 SLR value for the February event. The representative SLR values are calculated from the ASOS observations of daily snowfall total divided by the daily liquid precipitation. These snowfall analyses for November (Figure 4.35) are conducted between 08 UTC 24 November 2018 and 08 UTC 25 November 2018, which includes forecasts at least 24 hours prior to the snowfall onset. Snowfall analyses for the February event (Figure 4.36) are conducted between 09 UTC 22 February 2019 and 17 UTC 23 February 2019 and follow the same methodology that is used in determining the time frame for the November event.

Overall, snowfall accumulation for the November event (Figure 4.35) is forecasted well across the routes. The ASOS observed snowfall accumulation for the event is 3.6 inches (9.1 cm) and is used as the final snowfall accumulation. The first finding is the difference in the NDOT-MDSS final recorded snowfall for each of the road segments compared to the ASOS snowfall total. From Section 4.2, the snowfall analyses (Figure 4.13) all show final snowfall accumulations of at least 1.0 inch (2.5 cm) higher

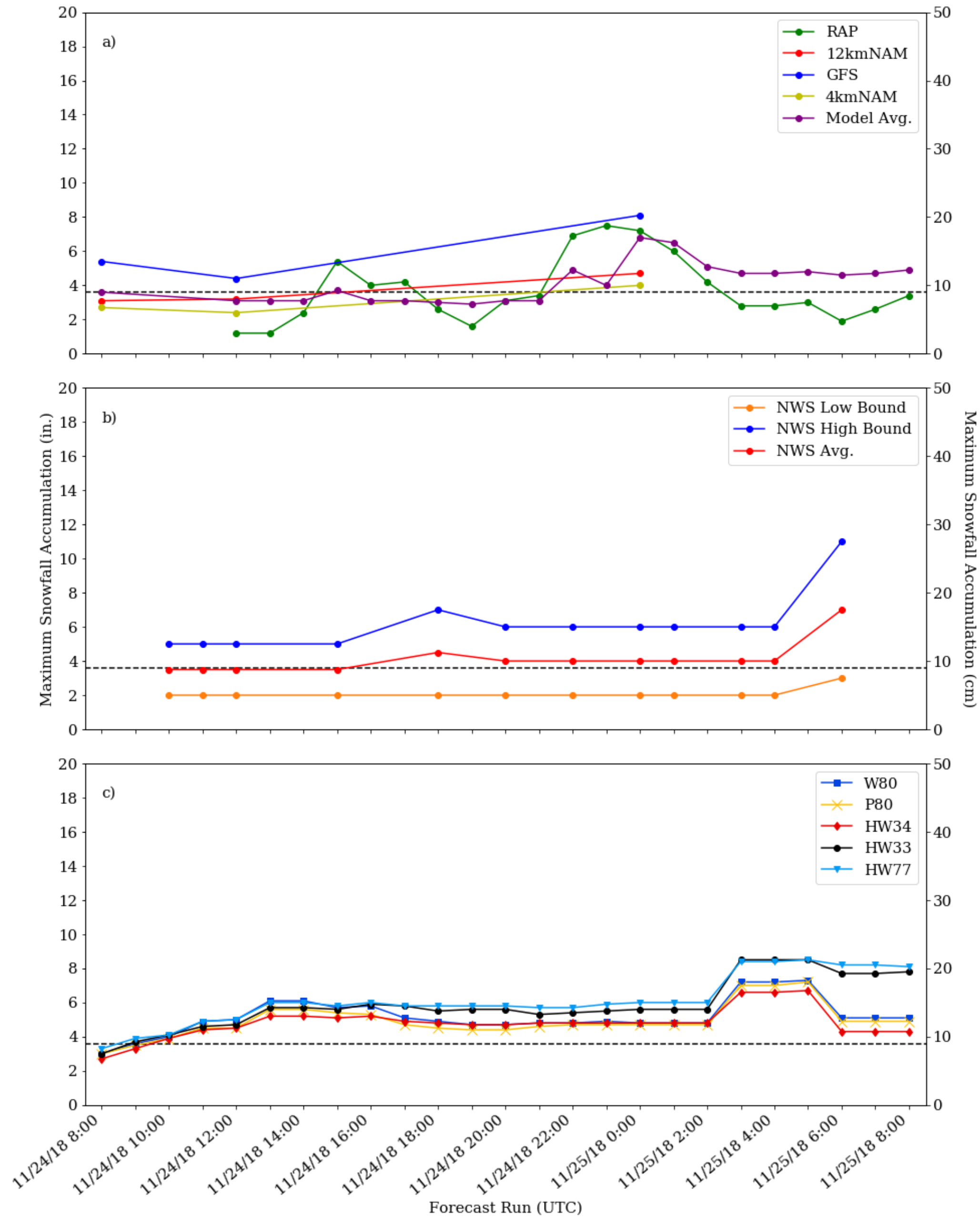

Figure 4.35: November case study forecasted snowfall accumulation composite for: a) weather models (RAP, 12 km NAM, GFS, 4 km NAM), b) National Weather Service zone forecast product, c) the NDOT-MDSS.

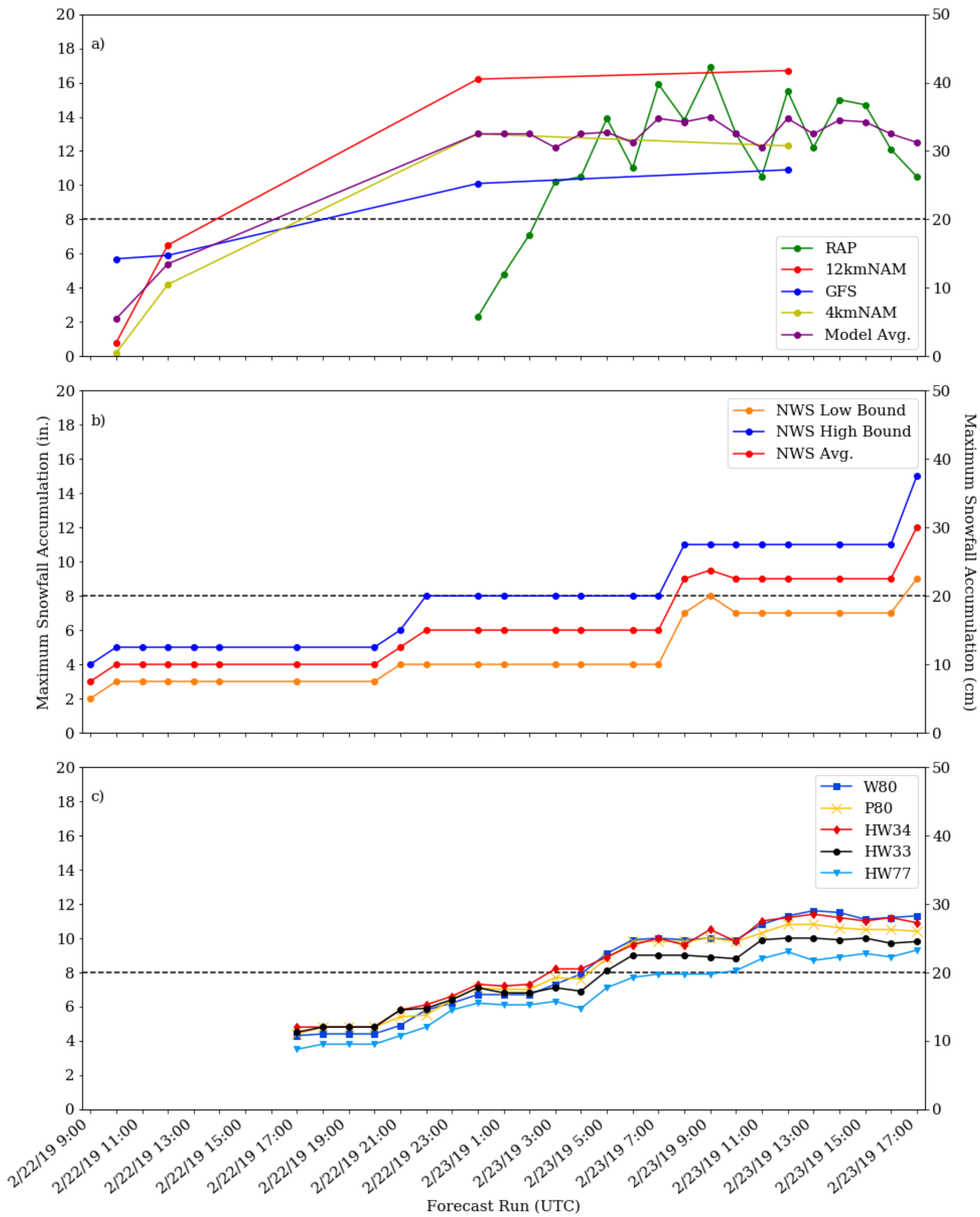

Figure 4.36: February case study forecasted snowfall accumulation composite for: a) weather models (RAP, 12 km NAM, GFS, 4 km NAM), b) National Weather Service zone forecast product, c) the NDOT-MDSS.

than the ASOS snowfall accumulation. Some of this difference can be attributed to the location of the routes relative to the ASOS station, especially for HW33 and HW77, which are both south of Lincoln. While the northernmost routes which are closer in proximity to the ASOS station are closer to the ASOS snowfall accumulation, the totals exceeded the ASOS value by 1.1 inches (2.8 cm) at HW34, 1.2 inches (3.0 cm) at P80, and 1.6 inches (4.0 cm) at W80.

Model output for the November event is a bit erratic, with a lot of variation about the ASOS observed snowfall accumulation value. The GFS model (Figure 4.35a) is over-forecasting total snowfall accumulation for the event. Both of the NAM models also perform well up until the 12 UTC 25 November 2018 runs, where both models began to under-forecast. The model average performed well yet was also sensitive to large changes in the individual model forecasts. For instance, when the GFS and RAP both spike around the 00 UTC 25 November 2018 run, the model average also skews to its highest point above the ASOS value. When compared against the zone forecast for Lancaster County, the models fall well within the range of snowfall accumulations forecasted by the NWS (Figure 4.35b). One issue with using the zone forecast by county from the NWS is that the snowfall totals are sensitive to the highest or lowest snowfall accumulation that can be seen throughout the county. That being said, the NWS forecast performed as well as one can hope for with the average between the upper and lower bounds falling right around the ASOS observed value for most of the forecast runs. While there is a noticeable spike around the 06 UTC forecast from the NWS, the same spike in snowfall totals is forecasted by the NDOT-MDSS (Figure 4.35c). As illustrated by the NWS

observed snowfall plot (Figure 4.16), the axis of highest snowfall totals fell to the southeast of Lincoln and Lancaster County. The model spike in snowfall accumulation can most likely be attributed to all the models attempting to accurately place the region of highest snowfall accumulation that would affect southeastern Nebraska.

The models perform much better for the November event when compared against the February event (Figure 4.36a). The ASOS observed snowfall accumulation total for the February event is 8 inches (20.3 cm) and the models all under-forecasted initially by at least 5 inches (12.7 cm) or over-forecasted later in the later forecast runs by at least 2 inches (5.1 cm). Both the 12 km and 4 km NAM, as well as the RAP all overproduced snowfall after their first three respective forecast runs. An interesting note about the models is how little weight the RAP is given during its first few forecast runs. Even as the RAP is outputting strong under-forecasts, the model average does not respond to the early variations being produced. In contrast to the other models and to its November performance, the GFS produces the lower bound of snowfall totals that better resembles the ASOS station observation for the February event.

The NWS zone forecasts (Figure 4.36b) again performed well when compared to the final ASOS snowfall total. An initial ramp-up in snowfall totals is observed in the earlier forecast runs and by early morning on 23 February 2019, the NWS forecast is within an inch of what would eventually fall at the Lincoln airport. The most noteworthy aspect of the NWS forecast is the spike in forecast snowfall accumulation right as snowfall is beginning in Lincoln at 17 UTC. The spike is not observed in any of the

models nor the NDOT-MDSS, which begs the question of what the NWS is seeing at the time to warrant the increase in forecasted snowfall accumulation.

The NDOT-MDSS forecasted snowfall accumulation prior to snowfall onset (Figure 4.36c) does not show the spike in snowfall accumulation prior to snowfall onset yet its progression up to snowfall start is similar to the overall pattern exhibited by the NWS forecast. This does not show the exact weight that the NDOT-MDSS gives NWS forecasts in its own forecasts; however, it does emphasize that the NDOT-MDSS might take NWS forecasts into consideration. The NDOT-MDSS final snowfall accumulation totals for the February event also show a distinct disconnect from the ASOS observed snowfall accumulation, which is similar to what took place during the November event. As snowfall occurs across the area, the forecasted snowfall accumulation totals spike and then drop off rapidly not long after (Figure 4.30). The forecasts prior to snowfall onset are less accurate than those produced after the storm had begun producing accumulation. The two exceptions of note are the snowfall accumulation totals for HW77 and P80. It is hypothesized that the averaging over the route may have contributed to the noticeably lower totals for HW77. When compared to the observed snowfall accumulation map produced by NWS Omaha/Valley (Figure 4.31), the numbers do not line up. Even the southernmost extent of HW77 would still be in the region of at least 5 inches (12.7 cm), according to the map. The variation observed at the P80 route is even more mysterious. P80 is the route that is located nearest to the ASOS observation station at the Lincoln airport and is not along any gradient of snowfall accumulation according to the NWS map. While the ASOS value is reported at 8 inches (20.3 cm), the value observed at P80

at the end of the event was 5.9 inches (15 cm). Of note also, the forecasted values for HW77 and HW33 are closer to the ASOS values than the northernmost routes that are closer in proximity to the ASOS station. While the general pattern mirrors what other forecast entities are outputting for the event, the NDOT-MDSS still over-forecasted total snowfall accumulation compared to the ASOS values.

Analysis of the snowfall forecasts from the NDOT-MDSS has shown that the system provides a reasonable forecast prior to snowfall events. The most accurate snowfall accumulation forecasts by the NDOT-MDSS for both of the events occur at least 12 hours prior to snowfall onset. Forecasted snowfall for the November event (Figure 4.35) is most accurate at greater than 20 hours prior to snowfall start while the snowfall forecast for the February event (Figure 4.36) is most accurate at greater than 12 hours prior to snowfall onset. In contrast, the environmental parameters are forecasted more accurately at greater than six hours prior to snowfall for the November event (Figure 4.7 - 4.12) and greater than 10 hours prior to snowfall for the February event (Figure 4.24 - 4.29). The differing forecast accuracy between environmental parameters and snowfall accumulation is unusual. One would assume that during the November event, for instance, since the snowfall accumulation forecast is most accurate further out from the snowfall onset that the accuracy of the environmental parameter forecasts would also be more accurate further out when compared to the February event. This is not the case and no definite conclusions as to why can be drawn at this time.

Along with radar observations, the NDOT-MDSS uses visibility to produce an estimate for snowfall accumulation along the routes. Visibility is then analyzed in

conjunction with the snowfall accumulation to investigate whether the routes that saw higher amounts of snowfall or higher snowfall rates coincided with visibility recorded by the NDOT-MDSS. A quick look at the recorded visibility values determined that this was not the case. During the February event (Table 4.13), the visibility values across all of the routes are identical at the same hours. This should produce identical snowfall accumulation totals across all of the routes if the NDOT-MDSS does indeed use only visibility to calculate snowfall. The November event (Table 4.14) displayed similar characteristics, although there is a distinction between the northernmost routes (W80, P80, HW34), where snow began earlier than the southernmost routes (HW33 and HW77), where snow began later. This distinction falls in line with the gradient of snowfall for the November event. Even more so, HW77 shows an acute drop in visibility that would be representative of the higher snowfall totals and more intense snowfall that fell to the southeast of the Lincoln area. In both the November 2018 and February 2019 cases, the NDOT-MDSS visibility matches up well with the ASOS observed visibility. In the November case, where the visibility values are much more representative of the environment, the northern routes, which are much closer in proximity to the ASOS station, correspond well.

Table 4.13: ASOS (KLNK) vs. NDOT-MDSS visibility (in sm) from the 21-25 February 2019 event

Forecast Hour (UTC)	ASOS	W80	P80	HW34	HW77	HW33
2/23/19 17:00	2.0	10	5	10	5	5
2/23/19 18:00	0.8	5	5	5	5	5
2/23/19 19:00	1.8	2.62	2.62	2.62	2.62	2.62
2/23/19 20:00	0.5	0.25	0.25	0.25	0.25	0.25
2/23/19 21:00	0.2	0.25	0.25	0.25	0.25	0.25
2/23/19 22:00	0.2	0.25	0.25	0.25	0.25	0.25
2/23/19 23:00	0.5	0.25	0.25	0.25	0.25	0.25
2/24/19 0:00	0.2	0.25	0.25	0.25	0.25	0.25
2/24/19 1:00	0.5	0.25	0.25	0.25	0.25	0.25
2/24/19 2:00	0.8	0.25	0.25	0.25	0.25	0.25
2/24/19 3:00	1.0	0.25	0.25	0.25	0.25	0.25
2/24/19 4:00	3.0	0.5	0.5	0.5	0.5	0.5
2/24/19 5:00	3.0	0.75	0.75	0.75	0.75	0.75
2/24/19 6:00	4.0	0.75	0.75	0.75	0.75	0.75
2/24/19 7:00	4.0	1	1	1	1	1
2/24/19 8:00	4.0	1	1	1	1	1
2/24/19 9:00	4.0	2	2	2	2	2
2/24/19 10:00	4.0	2	2	2	2	2
2/24/19 11:00	4.0	2	2	2	2	2
2/24/19 12:00	10	2	2	2	2	2

Table 4.14: ASOS (KLNK) vs. NDOT-MDSS visibility (in sm) from the 25 November 2018 event

Forecast Hour (UTC)	ASOS	W80	P80	HW34	HW77	HW33
11/25/18 7:00	4.0	5	5	5		
11/25/18 8:00	6.0	0.5	0.5	0.5	5	5
11/25/18 9:00	2.0	0.25	0.25	0.25	0.25	0.5
11/25/18 10:00	2.0	0.5	0.5	0.5	0.25	0.25
11/25/18 11:00	1.2	0.5	0.5	0.5	0.25	0.5
11/25/18 12:00	0.5	0.5	0.5	0.5	0.25	0.37
11/25/18 13:00	0.8	0.5	0.5	0.5	0.25	0.25
11/25/18 14:00	0.5	1	1	1	0.25	0.5
11/25/18 15:00	0.8	1	1	1	0.5	0.5
11/25/18 16:00	10	1	1	1	0.5	1
11/25/18 17:00	10	1	1	1	1	1
11/25/18 18:00	10	1	1	1	1	1
11/25/18 19:00	10	1	1	1	1	1
11/25/18 20:00	10	1	2	2	1	1
11/25/18 21:00	10	2	2	2	2	2

Chapter 5: Conclusions

This study investigated the forecastability of an MDSS system by analyzing two case studies from the 2018-2019 winter season. The two case studies, 23-24 November 2018 and 21-25 February 2019, were chosen because both were Colorado low systems that prominently affected the eastern half of Nebraska. The analysis was conducted to observe how well the NDOT-MDSS forecasted environmental parameters and snowfall accumulation when compared to other forecast quantities. All of the analyses were presented in an effort to better understand the capabilities and limitations that come with MDSS systems.

Synoptically, both of the systems yielded very similar weather situations. The surface low pressure systems moved from the vicinity of southeastern Colorado east-northeastward across the Central Plains. The November event had a slightly more southerly trajectory and was a drier event with high winds and blizzard conditions. The February event was preceded by freezing rain and sleet, which had begun the evening prior and then transitioned to blizzard conditions during the following day. Both of the systems caused road closures due to low visibility and slick road conditions and were denoted as "pathfinder events".

While the NDOT-MDSS has been a valuable asset, it certainly does not exist without apparent limitations. From a purely comparative standpoint, the NDOT-MDSS output reasonable forecasts for both of the storm systems studied. When the forecasts are compared against ASOS observations at the Lincoln airport, the individual routes had differing amounts of variation across the environmental parameters and snowfall

accumulation for both events. While there are instances of a drop-off in accuracy with the routes farther away from the ASOS observing location, P80 and HW34 should have realistically had the least amount of variation due to their close proximity to the ASOS station, although, this was not always the case. There were no clear analogs as to why this variation was present.

A notable feature of the black box that was integrated into this system was the fact that road section length carries weight with regards to meteorological variables. This meant that meteorological variables, forecasted and observed, were averaged along the length of the selected route and admittedly, this averaging technique would have to be a near necessity for the system to be able to forecast for a multitude of individual routes. However, if a section of road along the gradient of the rain-snow line had observed snowfall on the northern periphery with liquid precipitation on the southern extent, snowfall total accumulations would then be adversely affected for the route because it would have to add accumulations of 0 inches (0 cm) of snowfall to the running average due to the placement of the road. There was also no information given as to how exactly the system weights section length compared to forecasts and observations.

Once this obstacle was understood, the next issue considered was that the past or "observed" data could be changed after the fact. The initial maintenance forecast issued by the MDSS was observed to run independently. However, the MDSS updated future forecasts are based upon what the system hoped would be real-time procedures being used by the plow truck driver for the selected route. There is leniency when it comes to reporting conditions within the MDSS as any variable can be retroactively changed or

updated within 24 hours after the observation time (e.g., the Saturday 8 AM conditions may be changed at any time prior to 8 AM Sunday). While there could be a litany of reasons why maintenance procedures may or may not be recorded immediately, the MDSS is held back by the fact that it cannot update itself properly if actual maintenance procedures are not input into the system in a timely manner. Another limitation with the MDSS stems from how the system records snowfall accumulation. During a teleconference call with the managers of the system, it was made known that the MDSS records snowfall accumulation by visibility observations from land-based observation stations. A much better method for estimating real-time snowfall accumulation has been noted to be dual-polarization radar and while visibility can give an estimate, there is very little meteorological skill behind this method.

The final major limitation was that no matter how long the storm system may have spanned, we were limited to the saved storm data. This created issues if storms were occurring back to back and when there was difficulty forecasting storm severity and impacts ahead of time. In both of these cases, the amount of data that could be analyzed using the saved storm data was limited to the foresight given to the NDOT to qualify the impending storm as a saved storm. The MDSS allows the NDOT personnel to look back 72 hours to begin recording saved storm data. If the storm occurs recently enough after a prior storm or is not observed quickly enough or before personnel leave for the weekend, some of the initial data from the beginning of the storm may not be recorded. While this was not an absolute detriment to data analysis, the limitation to saved storm data did limit the total forecasted data that could be examined before the storm started.

It was evident that there were interesting corresponding patterns between variables for the different routes across the two case study events. The forecasts for each of the routes are found to be consistent based upon each storm. For instance, the air temperature was over-forecasted across all of the routes during the February event and under-forecasted for the November event. While the November event under-forecasted the air temperature parameter, it had a much higher accuracy and lower margin of variation when compared to the forecasted air temperature for the February event. This higher accuracy was the overall theme when comparing the meteorological variables of the two case study events.

It would be reasonable to infer that because the November event had higher accuracy across the three forecasted meteorological variables that the forecasted snowfall accumulation would also follow suit. The issue of higher accuracy further from the event start time still occurred during both of the case study events. This was possibly the most important finding from the study. Understandably, there might be more potential for inaccuracy with the February event as the freezing rain and sleet preceded the event, which would create a forecast of less snowfall. Naturally, there are going to be issues with regards to the placement and movement of the rain-snow line and how it evolves throughout an event's duration for both numerical models and human forecasters. Sleet tends to result in lower snowfall amounts. So, under the circumstances, the NDOT-MDSS forecasted for the snowfall accumulation relatively well. As for the November event, while there were certainly fewer environmental factors, such as the

transition from rain to sleet to snow augmenting the forecast, considerable inaccuracies were still present.

The best forecasts for environmental parameters were produced by the NDOT-MDSS greater than six hours prior to snowfall start time for the November events and greater than 10 hours prior to snowfall start time for the February events. Snowfall accumulation forecasts were more variable by the NDOT-MDSS. Forecasted snowfall for the November event was more accurate at greater than 20 hours prior to snowfall start, while the snowfall forecast for the February event was most accurate at greater than 12 hours prior to snowfall onset. This is imperative knowledge that would be invaluable in assessing the maintenance protocols necessary concerning an individual winter system. Preparations may vary from storm to storm and maintenance yard to maintenance yard. A good rule of thumb to follow that was stated to the research team by NDOT personnel has been taking into account the forecast within 3 hours prior to forecasted snowfall onset. While there is value in merely utilizing the most recent forecasts to advise decision-making, these new findings indicate that in conjunction, it may be more prudent to weight the forecasts from between six to twelve hours prior to snowfall for environmental parameters and greater than 12 hours prior to snowfall onset even more than the most recent forecast runs of MDSS.

This study was limited to the analysis of two Colorado low systems, which affected eastern Nebraska during the 2018-2019 winter season. While the results were notable, there is still a need to broaden the study of the NDOT-MDSS in order to draw more robust conclusions. Future investigations into this MDSS should analyze different

synoptic systems and their meteorological complications to observe how the NDOT-MDSS compares to other forecasts and observations in those situations. As with any forecasting entity, it is important to remember that a numerical forecast is only as good as the variables input and the person interpreting the output data.

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