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**16. Abstract**

Improving winter maintenance is a goal of most transportation agencies including the Nebraska Department of Transportation (NDOT). One approach is to develop a decision support system to aid in the winter maintenance recommendations. Iteris has developed a maintenance decision support system (MDSS) and has teamed up with NDOT to provide winter weather guidance for operations. This report investigates how well the MDSS functions for several routes across Nebraska for different storm systems. The analysis was performed from saved events within MDSS and compared to meteorological observations during different storm events, mainly Colorado or Alberta Clipper type storms that moved through and affected different regions of Nebraska. Winter severity index for the State of Nebraska (NEWINS) values were calculated for the years of study and NDOT maintenance districts around the state where the individual route segments are found. The NEWINS values were then analyzed and compared to the MDSS conditions. The NEWINS values compared favorably with the MDSS conditions, highlighting the impacts of the storms. The weather conditions produced and reported within MDSS equated well to the observational data with minor variations due mainly to differences in the distance between the route segment studied and the observation point location. There were some forecasting variations between what was observed and what was being forecasted within MDSS. Some of the variation was probably meteorological in nature; however, some were within MDSS resulting in inaccuracies in the forecasts. In most cases when there were variations in the forecast, the MDSS forecast was predicting snowfall over a longer period of time which also resulted in some cases with more forecasted snowfall than what was observed within MDSS. During the analyses, there were a few non-meteorological finds of importance. The major finding was the route segment length had a large influence on the parameters obtained for that segment within MDSS compared to segments of smaller lengths making comparison between routes a little sensitive.

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# Correlation Analysis of MDSS and NEWINS

**SPR-P1(19) M081**

**Mark R. Anderson**
**Department of Earth and Atmospheric Sciences**
**University of Nebraska-Lincoln**

**Curtis L. Walker**
**National Center for Atmospheric Research, Boulder, Colorado**

**Nancy Barnhardt, Nathan Rick, and Cameron Wunderlin**
**Department of Earth and Atmospheric Sciences**
**University of Nebraska-Lincoln**

**April 2020**

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Table of Contents

## 1.0 Introduction

This research conducted a detailed analysis of the weather conditions within the Maintenance Decision Support System (MDSS) a product of Iteris Pooled Fund Maintenance Decision Support System used by the Nebraska Department of Transportation (NDOT). The analysis was performed by investigating individual winter weather storms that moved across different regions of Nebraska and could be evaluated by choosing selected routes within the NDOT Districts. The project set out to investigate three major objectives. The first objective was to determine how well the MDSS system produced information regarding the meteorological conditions for different winter weather events. Were there any differences in the MDSS interpretation of the winter events depending on the type of winter storm occurring over the state? For the most part, these winter storms can be broken into Colorado or Alberta Clipper type low pressure systems. The Colorado type lows are usually associated with southwesterly to northeasterly moving events and have an ample supply of moisture for precipitation. Snowfall amounts are usually heavier with these types of events. The Alberta Clipper type events are usually a northwesterly to southeasterly moving storm which is usually moisture depleted. For the event studied, the Alberta Clipper type system moved more from the west to east in the movements across Nebraska. Usually Alberta Clipper types systems produce less snowfall compared to the Colorado low type systems, therefore the emphasis in this project was to investigate Colorado low type systems.

Some of the main concerns within this objective was how well did MDSS represent the weather conditions? For example, how well is the freezing line represented in the data? Colorado low type systems usually will produce varying precipitation types across the state of Nebraska. Does the precipitation type represented in the MDSS data represent what was taking place? One could also ask, is the MDSS representing other important weather conditions during an event? Analyses were also preformed to determine the accuracy of temperature, dewpoint temperature, and wind speeds, all very important parameters for NDOT. The parameters from MDSS were compared to National Weather Service (NWS) observations.

The second objective was to calculate Nebraska Winter Severity Index (NEWINS) values for the case study events. This was completed to be able to classify the importance of each case study event, and to determine the representative nature of the NEWINS values to the MDSS snowfall accumulations. Each case study event will then be compared to the District NEWINS values. NEWINS values are first determined by NDOT District, then combined for an annual value. Annual state NEWINS values will also be discussed.

The last objective was to investigate actual forecasts made by MDSS for individual route segments during a storm event and how the MDSS forecasts related to the observed weather conditions that took place during the event. Were there differences in MDSS forecasts? For example, do intersecting or nearby north/south vs east/west route segments have the same results when the meteorological conditions are consistent over the region? Did other neighboring route segments also have similar conditions within MDSS? How well did the forecasts made within MDSS concur with other forecast techniques?

To resolve the objectives, multiple case studies were formulated to investigate the MDSS observations and forecasts. The first set of case studies looked at two Colorado low type major snowstorms that moved across the central and northern parts of the state, comparing MDSS values to weather observations obtained from the National Weather Service (NWS). The analysis was completed to indicate similarities and differences between the MDSS and NWS observations. These two case studies resulted in partial explanations of the three objectives. However, the analysis also highlighted other issues within MDSS that needed further investigation. The second set of case studies looked at individual routes in District 1 to see if there were different forecasts made within MDSS for nearby route segments. All route segments would be compared to a single NWS location. The goal of the second set of case studies was to determine if different routes had different forecasts or observations within MDSS when meteorological conditions would be considered consistent for the segments, satisfying the last objective. Different winter storm types and conditions also were investigated in this set of case studies to further investigate all objectives, such as, did storm type influence the MDSS forecasts? The last case study investigated spatially distributed route segments within a single NDOT District, District 7, further aiding the objective results. The goal of this case study was to look at routes across District 7 and determine relationships between the MDSS forecasts and observations. How representative were the snowfall observations across the district?

In all three sets of case studies, winter weather conditions were obtained from the saved storms archive within MDSS. Individual MDSS parameters used for the evaluation are explained in the Methods and Data section. Additionally, meteorological observations were obtained for comparisons from archives from the National Center for Environmental Information (NCEI) for locations nearest to route segments assigned within MDSS. These observations are also explained in the Methods and Data section. NEWINS values were also determined for each event and comparisons are made in the Results section. The three sets of case studies were representative winter events, which aided in the investigation of the three objectives and the results of this study.

## 2.0 Literature Review

### 2.1 Maintenance Decision Support System

Throughout the 1990’s the U.S. 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 (Mahoney and Myers 2003). An MDSS is a system that uses current and forecasted weather data along with road surface modeling to recommend treatment options for materials or actions needed to treat specific roads. One of the main areas of focus during the development of MDSS was to increase the benefits or the savings for maintenance operations during winter weather events by reducing chemical usage (Mahoney and Myers 2003). Up to 33% of state highway budgets are used in winter road maintenance during snow and ice events even though these events occur very rarely throughout the year (Hanbali 1994). With new technology and more accurate weather forecasts, maintenance crews can become more proactive than reactive when it comes to applying chemicals to treat the roads. Treating roads earlier may help weaken the bond that snow or ice forms with the roadway. With the bond being weaker, there is less of a need to use chemicals to clear the roadways which leads to lower maintenance costs and less human power hours needed during an event (Shi 2009). MDSS recommends various solid and liquid road treatments during winter events.

Five research labs were part of the development of the FHWA MDSS: Army Cold Regions Research and Engineering Laboratory (CRREL), National Center for Atmospheric Research (NCAR), Massachusetts Institute of Technology-Lincoln Laboratory (MIT/LL), National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory (NSSL), and NOAA Forecast Systems Laboratory (FSL) (Andrle et al. 2003). This MDSS was set up as a modular system with different individual parts. The reasoning behind the modular design was so that if improvements needed to be made, individual parts could be improved without changing the entire system (Mahoney and Myers 2003). Mahoney and Myers (2003) also noted that there were a few different components that were implemented into MDSS. One of the main modular components is the Road Weather Forecast System (RWFS) This component of MDSS uses data from various sources such as the National Center for Environmental Prediction (NCEP) mesoscale models, Road Weather Information System (RWIS), and automated surface observing system (ASOS). The RWFS takes in the weather data from the various NCEP models and ASOS stations to give current conditions and forecasts.

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

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

A functional prototype was presented to the FHWA in 2002 (Petty and Mahoney 2008). The Iowa Department of Transportation (IDOT) was one of the states chosen to implement an MDSS when it was still a prototype (Andrle et al. 2003). Evaluations of the different parts of MDSS took place including the weather forecasting tools, the different treatment recommendations that were given, and the potential benefits and limitations of the system. Fifteen test routes were selected in the Ames and Des Moines, IA vicinities. The evaluations occurred between 3 February and 7 April 2003. During this time period, there were three heavy snow events, five light snow events and one mixed precipitation event. There were various weather data sources, real-time and archived, which were used to verify MDSS weather data during these nine events. The recommendations given by IDOT after the evaluations were completed, showed that the accuracy of the weather forecasts, especially the timing of the event, needed improvement and the MDSS display and data collection portion were both difficult to use.

The 2003-2004 field demonstration campaign introduced a multitude of upgrades including a time-lagged ensemble of the mesoscale 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 observation determined by the report noted that, IDOT 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 $3.5M 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 next test site was moved to central CO for the winter of 2004-2005 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. MDSS changed the quantitative precipitation forecast (QPF) forecast weights from 60% for the NAM, 30% for the RUC, 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 .002 in $hr^{-1}$ (0.05 mm/hr) and a 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).

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. MDSS did not predict these types of events well because the system requires highly specific precipitation forecasts (Pisano et al 2005). Often these events had high impacts that were poorly forecasted 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 stated described the inadequacy of RWIS sensors to observe freezing or frozen precipitation accumulation and the lack of accurate observations of precipitation from ASOS stations also. These poor representations of observed precipitation data often inhibited the MDSS's ability to provide sound verification of events (Pisano et al. 2005). Additional iterations were developed in later releases as advances were made technologically and operationally. Reports were constructed by various Departments of Transportation (DOT) 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; Drobot 2012).

Furthermore, an internal report of the background processes within 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 & alerts, and monitoring and maintaining alerts behind the actual system that culminate in the final user friendly interface. An inhouse satellite broadcast network (NOAAPORT) system was constructed by Meridian as well as general data acquisition from state DOTs and mesonets. A 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. Furthermore, Block et al. (2003) stated that the numerical weather data were displayed using the gridded analysis and display system (GrADS) developed by the Center for Ocean-Land-Atmosphere Studies (COLA).

Naturally, once the numerical weather data are gridded, a gridded forecast can be created. As with any forecast, the forecaster may take certain liberties such as objective 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 SNTHERM which was developed by the CRREL in Hanover, NH (Jordan 1991). Simply stated, SNTHERM is a physically based ground condition model that is defined by surface fluxes (Frankenstein 2012). However, in 2007 the SNTHERM model discontinued active development and opened up 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 (Frankenstein and Koenig 2004) , and model of the environment and temperature of roads (METRo), a Canadian developed 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 actually 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 RWIS stations throughout a designated area are collected and ran through various publicly available weather models such as the North American mesoscale model (NAM), global forecast system (GFS), and model output statistics (MOS). 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. MDSS has been no stranger to this process and the outside evaluations of the system (Ye et al. 2009; McClellan et al. 2009) outlined improvements that should be further investigated to 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 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 compiled after. The Chapman et al. (2008) report implemented MDSS in and around the city of Denver, CO for the Colorado Field Demonstration, which spanned the winter of 2007-2008. The Denver case was compared against 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.

Part of the NCAR review (Chapman et al. 2008) was to document how well the new implementations aided in the forecasts at the new testbed in Colorado. There were 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 article recommended that the model should possibly be revised to decrease dependence upon NAM forecasts if the inaccurate trend continues.

Ultimately, the MDSS was created as a supplement for maintenance crews to combine pertinent road weather data with road maintenance recommendations flawlessly 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. 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 MDSS in general.

**2.2 Storm systems**

Nebraska is primarily impacted by 2 different types of low pressure systems. These low pressure systems can be described as Colorado Low and Alberta Clipper type systems. Both are 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 of the lee side of the Rocky Mountains, especially in eastern Colorado and points southward. A Colorado Low trajectory will generally progress on an east then northeastward trajectory after its formation in the lee of the Rockies (Figure 2.1). An Alberta Clipper type 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 locations southward to Colorado. An Alberta Clipper will move eastward or dip down on a southeasterly trajectory, "clipping" states in the northern and central Plains as well as the Midwest, and then quickly progressing along a northeastward trajectory (Figure 2.2). Alberta Clipper type systems are generally regarded as smaller scale systems. Due to the more northerly formation, they exhibit a lack of available moisture which usually results in relatively low precipitation amounts over a narrow path. Mainly Alberta Clippers are cyclones that are often associated with light-to-moderate precipitation (Hutchinson 1995). Moderate precipitation generally occurs in areas up to a few hundred kilometers north of the system's track while lighter precipitation generally falls to the south of the track. An Alberta Clipper type system is also a faster moving low due to the upper level meteorological conditions above the low pressure system. Often the most significant sensible weather element associated with Alberta clippers is strong wind (Thomas and Martin 2007). Often the passage of a Clipper results in a dramatic increase in winds over a broad area. The strong winds that follow the passage of a Clipper, coupled with preexisting or freshly fallen snow, can result in considerable blowing and drifting of snow and the creation of ground blizzard conditions (Stewart et al. 1995; Schwartz and Schmidlin 2002). Initial differences between the two

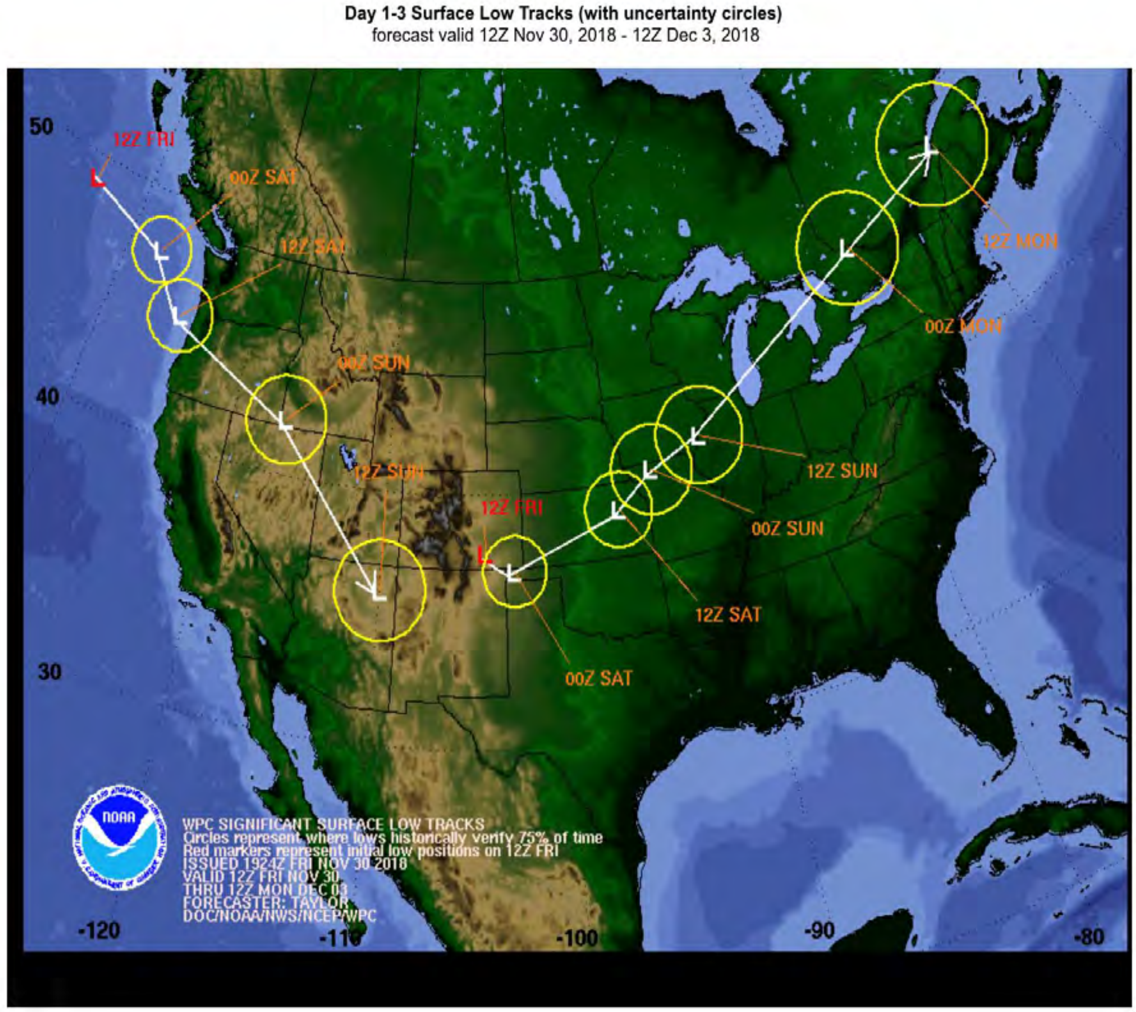


Figure 2.1: General formation area and trajectory of a Colorado Low system (from WPCWW 2019)

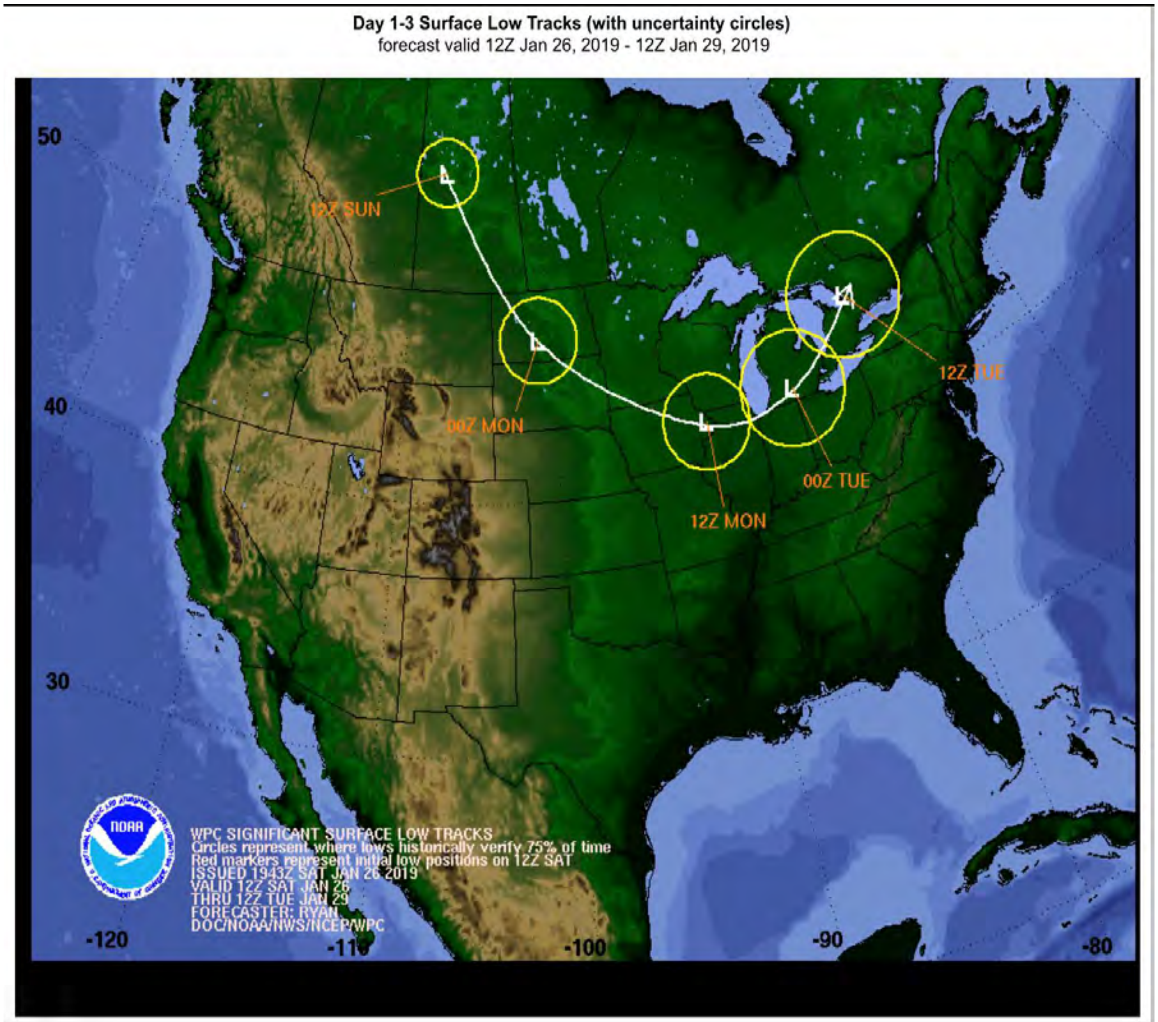


Figure 2.2: General formation area and trajectory of an Alberta Clipper system (from WPCWW 2019)

systems are directly related to their starting locations, trajectory, and their attendant moisture content as they traverse the continent. In addition, they typically have different upper air conditions. The Colorado type low is supported aloft by a longwave trough system, producing strong southwesterly flow in the upper levels and strong support for a strong surface low. The Alberta Clipper type system is usually supported by a short wave feature in the upper levels which does not support a stronger low.

Typically, a Colorado low when compared to an Alberta Clipper will produce a heavier, denser snowfall that has higher accumulations. The main reasons for this are due to the availability of and access to Gulf of Mexico moisture and stronger upper air support. More moisture allows for higher liquid content snowfalls. 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 scale moisture sources caused by lakes, which are typically frozen, along its trajectory path during the winter. This contrast in moisture will naturally bring about a differential in total snowfall potential. Weaker upper level support will also produce less vertical lift, reducing snowfall production.  Blowing and drifting can occur with both systems since winds are created from the pressure falls associated with each storm system. However, the drifting usually occurs during the event during a Colorado Low's snowfall period. After the snowfall stops, there is less drifting due to higher liquid content of the snow, making snow more difficult to blow in the wind.

During an Alberta Clipper type low, blowing and drifting associated with the systems high winds will occur during and after the snowfall period, since the snow is typically drier and then more susceptible to blowing and drifting once it has landed on the ground surface. The movement 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 in this way. A Colorado Low can expect to drop anywhere between 1 - 12 inches of snow depending on your location and proximity to the center of the low pressure system, with larger snowfall amounts falling on the eastern and northern side of the low pressure system if temperature conditions are favorable. An Alberta Clipper will usually yield lower snowfall accumulations of 1 - 5 inches due to the lack of available moisture and faster storm movement. Instances of heavier (lighter) snowfall for both types of systems can also be observed in conjunction with the presence (lack) of a deformation zone, producing more snowfall in the northwestern portion of the storm.

One of the forecasting difficulties for a Colorado Low compared to the Alberta clipper type systems 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 can and do advect warmer temperatures into the storm system creating a rain-snow line. Forecasting this transition can be difficult. In addition, the greatest snowfalls are usually found close to the rain-snow line. The greater snowfalls are created by warmer temperatures holding more moisture than colder temperatures. Therefore, the greater snowfalls are usually just to the west and north of the rain-snow line. The forecasted duration of precipitation from Colorado Low type systems tend to move more slowly than their Alberta Clipper counterparts also allowing the warmer air to advect further to the north during a Colorado low.

Around 1875, the National Weather Service stated that a moderately useful analog for snowfall prediction that could be used was the 10:1 ratio; meaning that 10 inches of snowfall would come from one inch of liquid water (Henry 1917). As time passed, investigations 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 conducted in order to create a climatology of snow liquid water contents (SLRs) that take into account geographic and microphysical processes (Baxter et al. 2005). Statistically, the average SLR distribution is 13:1 for the three Nebraska NWS offices (North Platte, Hastings, Omaha/Valley) within the state. Variability within the mean SLR values for Nebraska shows that early October and November (Figure 2.3) as well as late March and April (Figure 2.4) snowfalls generally will have SLRs 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 2.5), increases to a range between 13:1 and 18:1 (Figure 2.6). These distributions are logical, since colder, drier air intrudes during the heart of 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. Lower SLRs can also be found within a Colorado low type storm system independent of time or season.

Weather prediction in itself 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 were 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 at or below 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,

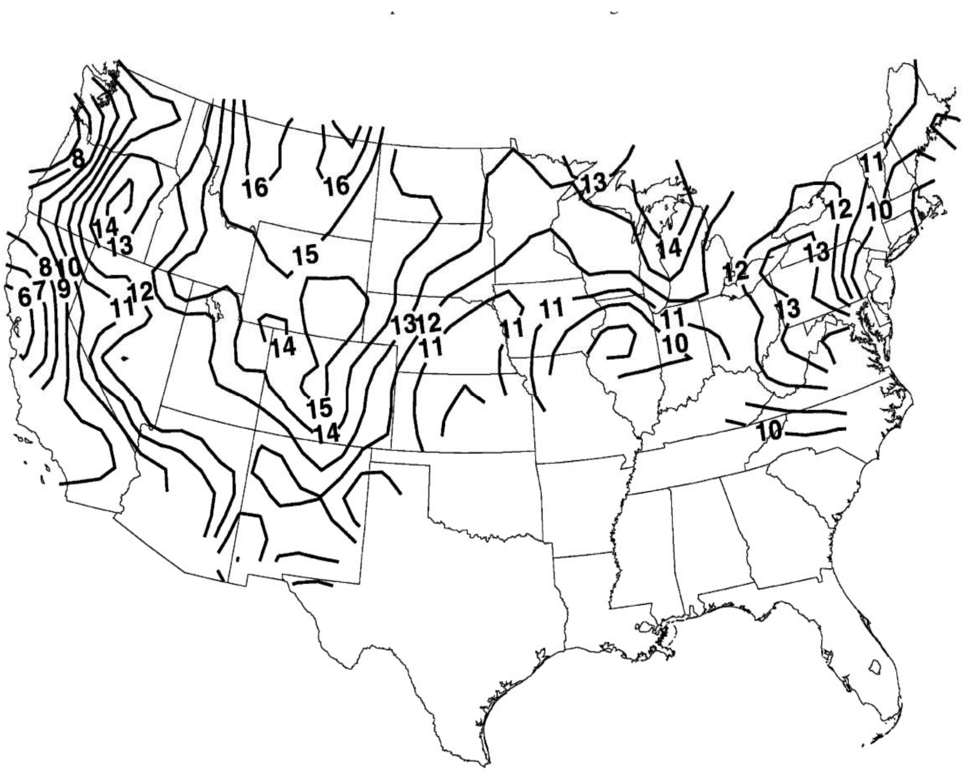


Figure 2.3: Mean SLR (1971-2000) values for October and November (from Baxter et. al, 2004).

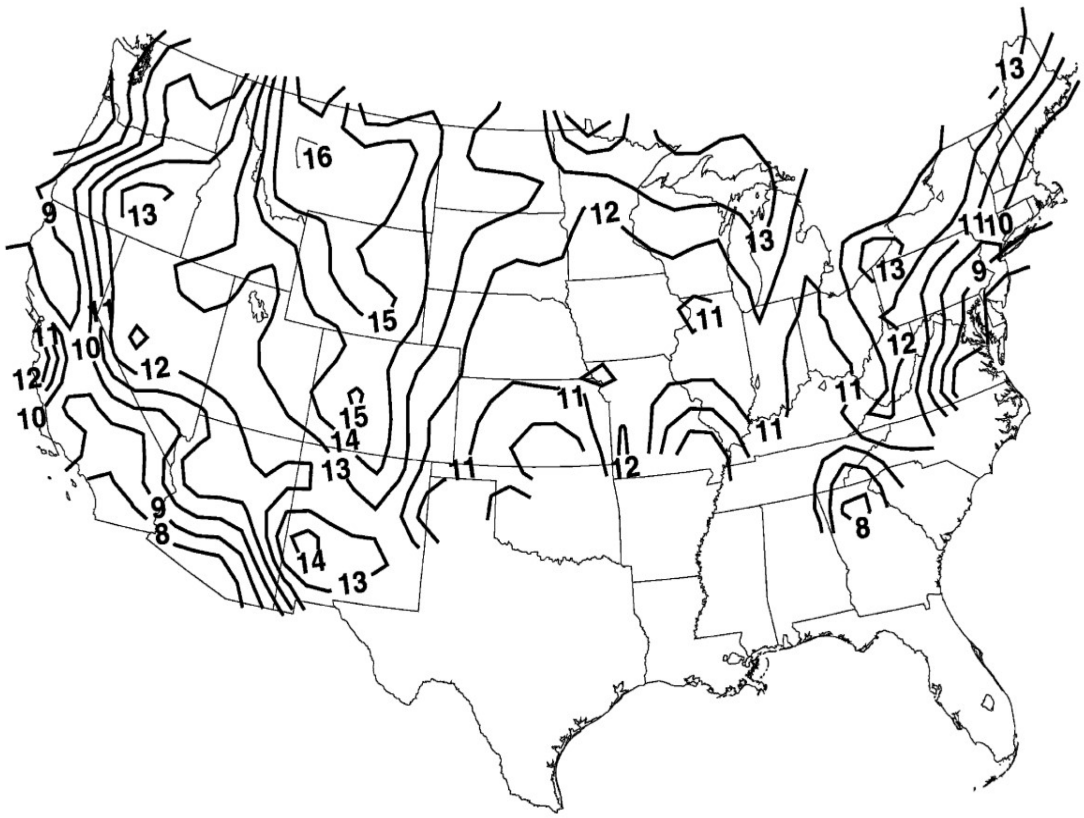


Figure 2.4: Mean SLR (1971-2000) values for March and April (from Baxter et. al, 2004).

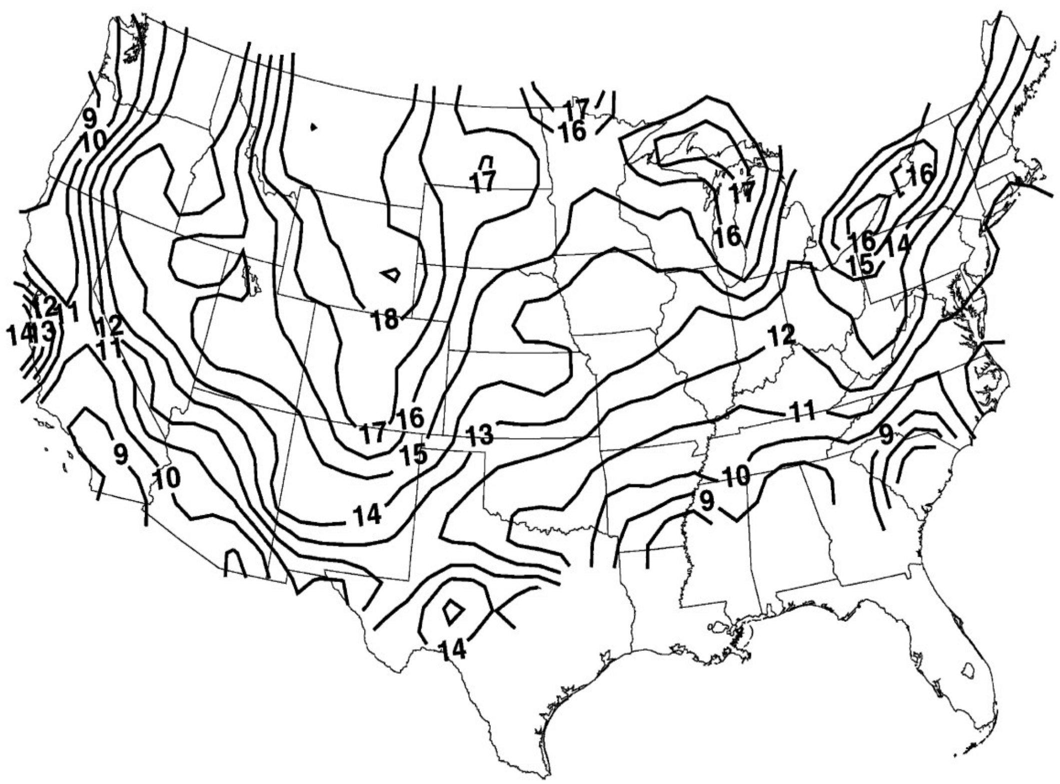


Figure 2.5: Mean SLR (1971-2000) values for December, January, and February (from Baxter et. al, 2004).

and riming can all work to alter snowflake size and inherently, snowfall intensity and depth. These factors also play into the SLR values found during individual snowstorms.

## 3.0 Methods and Data

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

The MDSS data for all archived storms were extracted from the web interface of MDSS. Since the MDSS archive is a proprietary entity, control of the data within the archive is not set by the authors and may limit analyses with these case studies. Meteorological observations: temperatures, wind speeds and directions, visibilities and snowfall observations were obtained from archives at the National Center for Environmental Information (NCEI). In addition, snowfall data were obtained from local NWS forecast offices covering the Nebraska region (Figure 3.1) for comparison. Upper air data were also analyzed to gain a more thorough understanding of the atmospheric conditions, besides the surface information presented in MDSS. The upper level data 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). However, discussions of the upper air conditions are not presented in this report, detailed analysis can be found in Barnhardt 2019, Rick 2020, and Wunderlin 2020. NWS zone forecasts

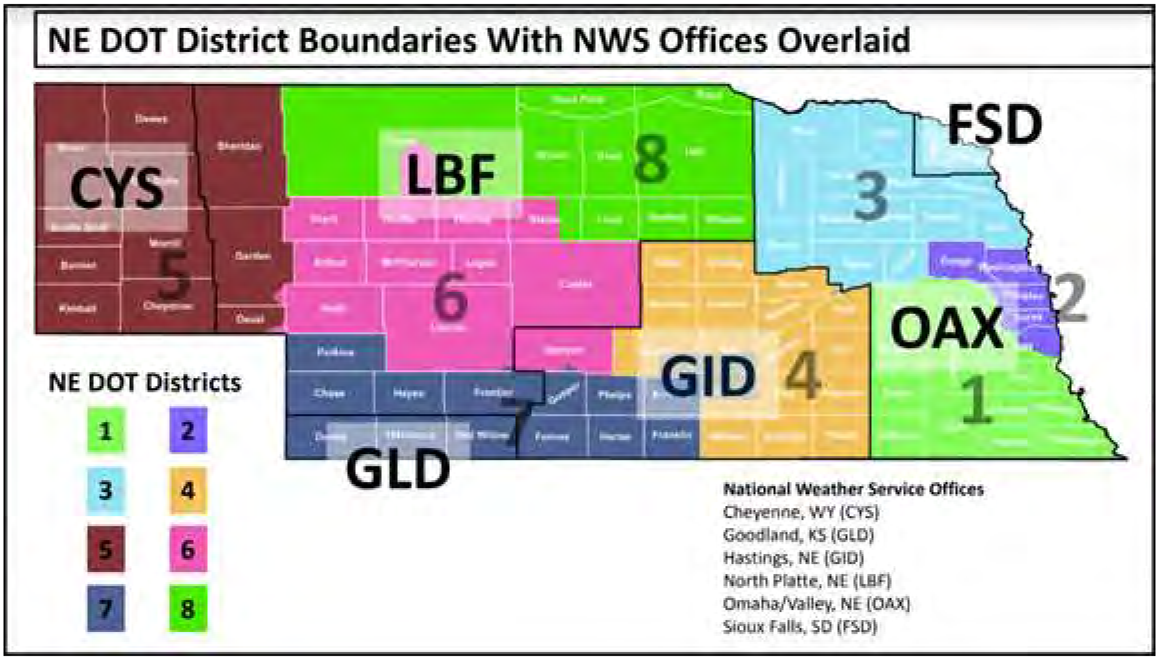


Figure 3.1: County Warning Areas for NWS Weather Forecast Offices serving Nebraska overlaid onto the 8 NDOT maintenance divisions (Adapted from NDOT 2019).

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

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

and area forecast discussions (AFDs) for each event were also gathered and used for comparison with the information obtained from the MDSS.

For further evaluation of the MDSS, NEWINS values were calculated for the winter seasons of 2016-2017, 2017-2018, and 2018-2019 using the techniques from Walker et al. (2019). The NEWINS values for these years are combined with the values from Walker et al. (2019) and are presented in Figure 3.2. The NEWINS results indicate that the 2018-2019 winter season was the worst season so far studied, surpassing the winter of 2008-2010, emphasizing the extreme conditions of the 2018-2019 season. The individual NEWINS values for each NDOT District were calculated as part of the state values and are reported for each storm event.

Storms were chosen for the case study analysis based on the type of storm event and the impacts of the event. In total, there were five Colorado low type systems; 21-23 January 2018, 13-15 April 2018, 24-25 November 2018, 19-20 February 2019, and 22-24 February 2019, and one Alberta Clipper type system; 15-16 February 2019. These storms were chosen because winter weather conditions occurred across the specific study region and had major impacts on travel, including many road closures. These storms are very representative of the types of winter storms which affect NDOT maintenance operations throughout a typical winter weather season.

For determining the event length, snow start time was identified in the MDSS as when the hourly snow rate had increased and by the next hour there was also a change in snow accumulation. The end time was observed as the hour when snow rate fell to 0.00 in $hr^{-1}$ 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.

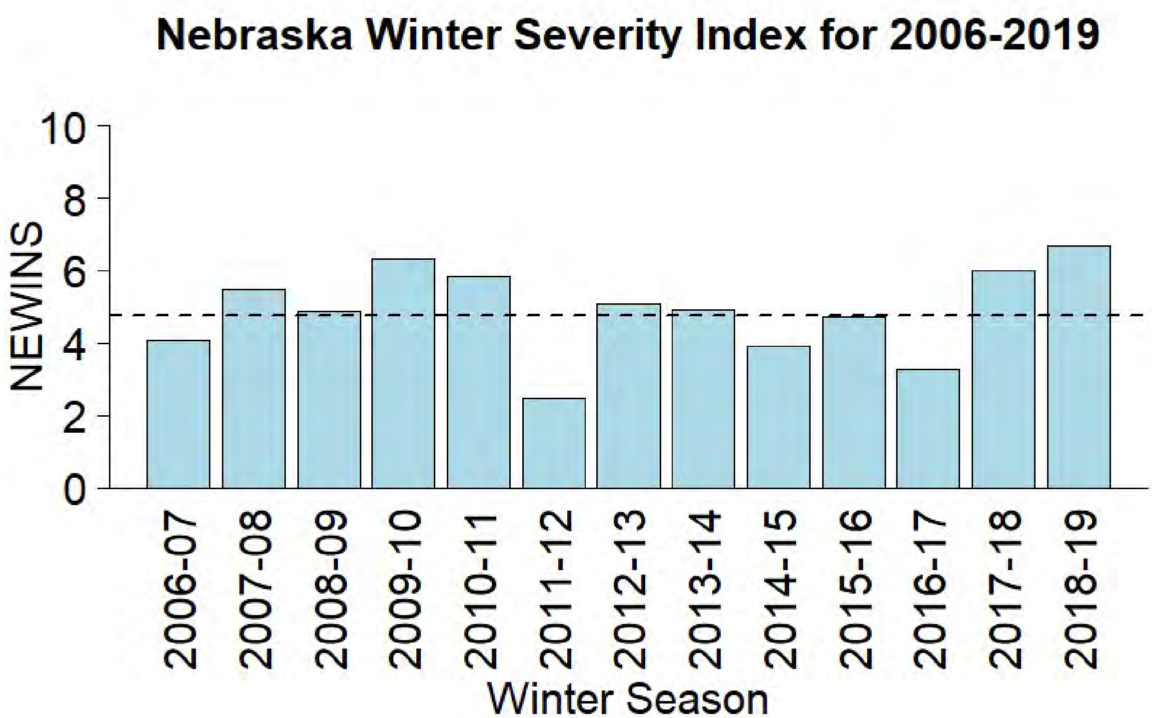


Figure 3.2: NEWINS winter-season values with decadal average (black dashed line)

### 3.1 Storms moving across central and northern Nebraska

The storms are very similar in terms of strength and snowfall. Eight routes (Table 3.2, Figure 3.3) were chosen in total representing Districts 3, 6, and 8 based on the impacts of the storms. These routes are identified by a numerical number. The MDSS data for both archived storms were extracted from the web interface of MDSS (2018). Since the MDSS archive is a proprietary entity, control of the data within the archive is not set by the author and may limit analyses with the case studies. Three-hourly increments were chosen for each storm, starting from the beginning of the saved storm within the MDSS system, which is up to 24 hours prior to the onset of the storm, to the end of the precipitation for that route. Images of the analysis of the conditions for every route provided by MDSS were also taken at three-hourly increments to show how the storm progressed as well as how well the system identified heavy precipitation and the location of the rain-snow line. The placement of the rain-snow line within the MDSS will be compared to known critical thicknesses of different layers in the atmosphere. In addition, the surface freezing level from ASOS observations will be used to determine variations within MDSS.

### 3.2 Storms moving across the Lincoln region

The four case studies for the Lincoln, NE region representing District 1 characterized the impacts from the different storm types. All MDSS observations and forecasts, as well as observations obtained elsewhere were analyzed differing intervals. The first and second events were Colorado low type events, with cold temperatures so the rain vs snow line was not an issue and all precipitation fell as snow. The third event was a Colorado low type system; however, in this case, the rain-snow line was an issue and there was a strong gradient of snowfall across Lancaster County and the selected routes. The last event was more of an Alberta Clipper type system with mainly lower accumulations of snowfall.

Table 3.2: Selected Test Routes from the MDSS

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

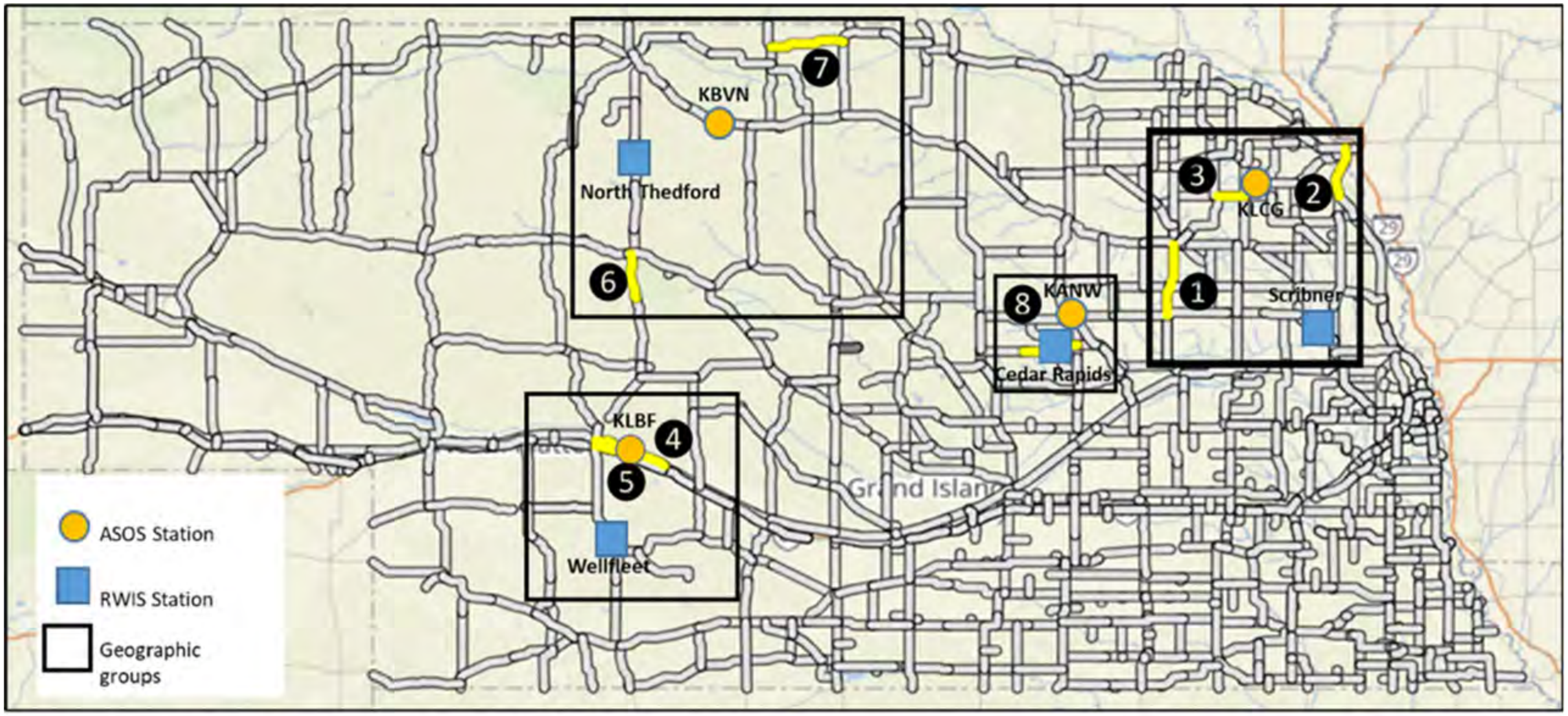


Figure 3.3: Locations of ASOS and RWIS stations used for comparison against the MDSS routes (yellow, route # in black)

Even in this case, snowfall was not a major event though there were still road impacts. The routes selected around Lincoln, NE are the same for all four events (Figure 3.4). 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 Urban Commuter levels of service (Table 3.1). The remaining three routes consisted of 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) which 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 level of service.

### 3.3 WMRI Analysis

A module known as the Winter Maintenance Response Index (WMRI) is also included within the MDSS system. The WMRI was developed as another analog to assess the severity and impacts of winter weather on maintenance cost and resources (FHWA 2015). Two different sources of weather data, "analyzed" and "modeled", can be analyzed with the WMRI tool. Analyzed data are described as data from surface based observations, weather radars, satellites, and other resources that are run through various processes to output a best-estimate of what the module believes would have occurred at the route. The modeled data are compiled via the shortest-term weather forecasts produced from the MDSS. Comparisons of the MDSS saved storm data and WMRI datasets were conducted to observe how well the WMRI analyzed data fit against the MDSS saved storm observations.

The WMRI is reviewed and analyzed in comparison to the MDSS data. Data within the MDSS system is subject to change up to 24 hours after it is recorded. The MDSS data were

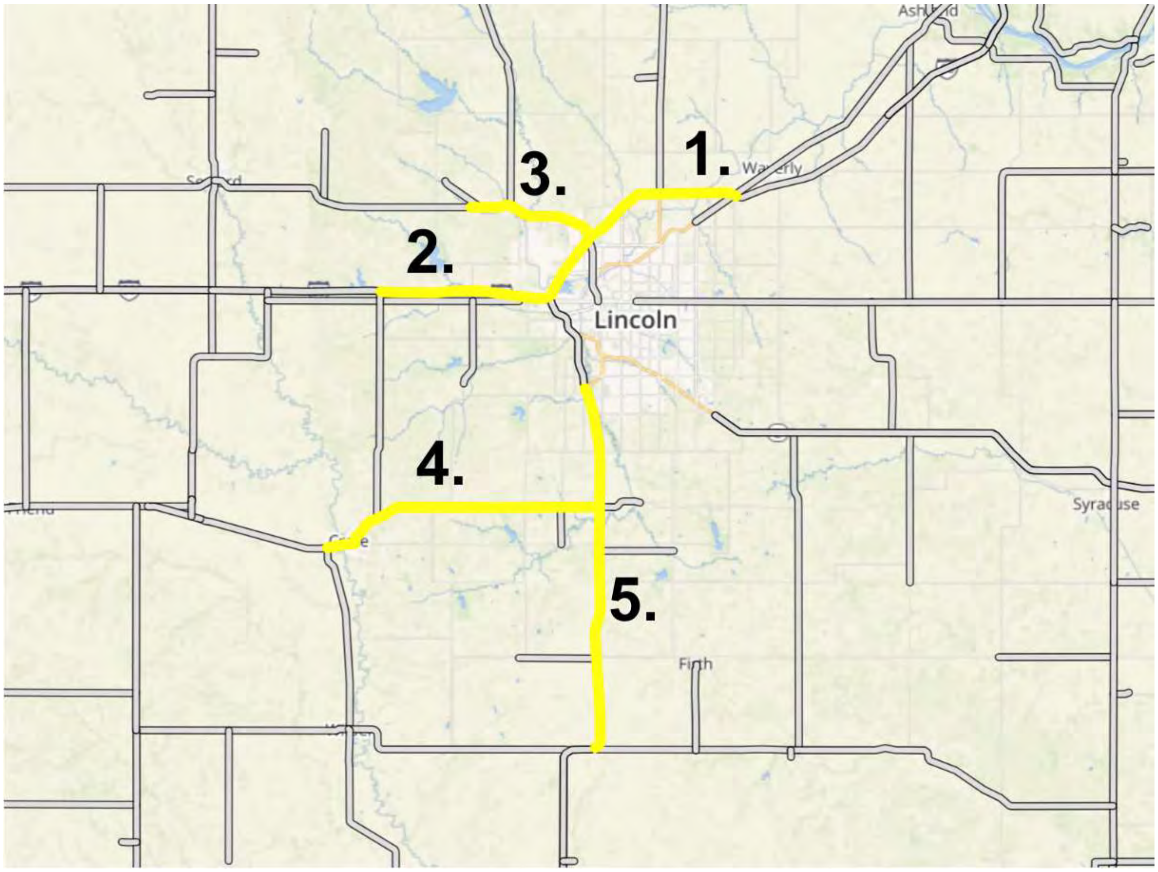


Figure 3.4: The five selected routes (1.) W80, (2.) P80, (3.) HW34, (4.) HW33, (5.) HW77 for observation within the MDSS system from district 1 for the case study events (from MDSS)

compiled for the time period of 24 hours after the MDSS snowfall start time. This was done intentionally to ensure that recorded data in the past would not be altered by outside means and cause variations in the data that are being analyzed. Therefore, the MDSS data would be indicative of “observed” data recorded by the MDSS. After this distinction, the MDSS dataset is then fit to be compared against the “analyzed” WMRI data. For this analysis, hourly snowfall accumulation was compared between the MDSS and WMRI and the ASOS observed daily snowfall totals.

To compare the WMRI to the MDSS accumulations for the February case studies, the five routes in District 1 (Figure 3.4) and five routes within District 7 (Figure 3.5) will be used. The routes selected in District 7 are: Highway 61 from Imperial to Grant (HW61), Highway 183 from Holdrege to the Platte River (HW183), Highway 34 from Benkelman to the Colorado state line, denoted as the western segment of Highway 34 (HW34w), Highway 34 from McCook to 3 mi west of Culbertson, denoted as the central segment of Highway 34 (HW34c), and Highway 34 from Arapahoe to the Highway 46 junction, denoted as the eastern segment of Highway 34 (HW34e). These routes are spread out across the entirety of District 7, which was done to contrast the lower spatial variability in routes from District 1. All of the District 7 routes were also chosen because they are in close proximity to ASOS, RWIS, or traffic cams for verification purposes. Examination of the District 7 routes was conducted for each of the February 2019 events (15-16, 19-20, and 23-24 February 2019).


Figure 3.5: The five selected routes (1.) HW61, (2.) HW183, (3.) HW34w, (4.) HW34c, (5.) HW34e for observation within the MDSS system from district 7 for both case study events (14-15, 19-20, and 21-25 February 2019) (from MDSS)

## 4.0 Results

The results section is divided into three parts. The first part looks at two representative Colorado low systems that moved across central and northern Nebraska during the 2017-2018 winter season mainly investigating how MDSS represented the meteorological conditions during the events. The second part investigates several different storm types that moved across District 1 for the 2018-2019 winter season, especially February 2019, highlighting the MDSS weather conditions around Lincoln. During February, several different storms tracked across the region and were analyzed. The last part reviewed several of the same saved storms from part two that also tracked across District 7 to investigate how well MDSS forecasts represented the weather within a single NDOT District.

### 4.1 Storms across central and northern Nebraska

#### 4.1.a 21-23 January 2018 event

The effects of the first storm in Nebraska started at 1800 LST 21 January in the far western parts of the state. This can also be seen in the NEWINS data (Table 4.1) where District 5 has a NEWINS value of 2 on 21 January and no other district is reporting snowfall. The Colorado low had not fully matured, so areas in the western part of the state did not receive as much snow as the central and eastern parts of Nebraska. As the low moved into Kansas from southeastern Colorado, the low strengthened and areas in Nebraska to the northwest of the low received upwards of 10-12 inches of snow (Figure 4.1). Drifting caused road closures on both state and county roads throughout central Nebraska. This is also observed in the 22 January NEWINS values (Table 4.1), where NEWINS observed snowfall in every district, with District 6 and 7 reporting NEWINS values of 6. A category 6 within NEWINS would represent road closures. To the east of the heavy snowfall, the precipitation was mainly rain and freezing rain, before switching over to snow across the eastern half of the state. NEWINS values also show the snowfall only being observed in the Eastern part of the state during the last day of the event. Throughout the event,

Table 4.1 NEWINS values for the different NDOT Districts during the case study events. Blanks represent no NEWINS value calculated, since no snowfall was observed in the District.

| Date | NDOT District | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| | | | | | | | | |
| 21 January 2018 | | | | | 2 | | | |
| 22 January 2018 | 1 | 1 | 4 | 4 | 4 | 6 | 6 | 5 |
| 23 January 2018 | 2 | 4 | 5 | 3 | | | | |
| | | | | | | | | |
| 13 April 2018 | | | | | 3 | | | |
| 14 April 2018 | 2 | 2 | 3 | 2 | 3 | 4 | 4 | 5 |
| 15 April 2018 | 2 | 2 | 2 | 2 | | 3 | 1 | |
| 16 April 2018 | | 2 | | | | | | |
| | | | | | | | | |
| 24 November 2018 | | | | | 1 | | | |
| 25 November 2018 | 4 | 2 | 2 | 3 | 4 | 3 | 4 | 2 |
| 26 November 2018 | 5 | | 3 | | | | | |
| | | | | | | | | |
| 15 February 2019 | | 1 | | 2 | 2 | 2 | 2 | 2 |
| 16 February 2019 | 3 | 2 | 3 | 3 | | 2 | 3 | 2 |
| | | | | | | | | |
| 18 February 2019 | | 1 | 1 | | | | | 2 |
| 19 February 2019 | | | | 2 | 2 | 2 | 1 | |
| 20 February 2019 | 4 | 4 | 5 | 4 | 2 | 3 | 4 | 4 |
| | | | | | | | | |
| 22 February 2019 | 1 | | | 1 | 2 | 1 | 1 | 3 |
| 23 February 2019 | | | 1 | 1 | 3 | 1 | 1 | 2 |
| 24 February 2019 | 4 | 6 | 1 | 4 | | 1 | 2 | |
| | | | | | | | | |

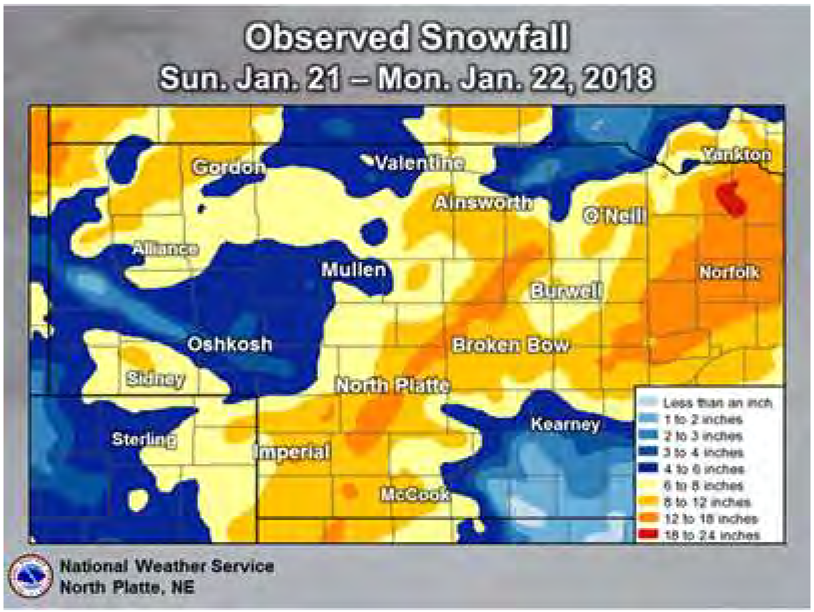


Figure 4.1 Snow fall values for the January 2018 event.

as the storm system moved northeastward across Nebraska, the MDSS forecasts for precipitation types were very accurate to was observed falling at NWS ASOS locations.

The forecasts in the MDSS are highly dependent on the data that are input into the system so any changes in the forecasts will have a major impact on what is output by the MDSS. The forecasted snow accumulations for each route (Figure 4.2) can be seen developing as new forecasts are issued by the MDSS at three hourly increments. Route 1, 2, and 3 are located in eastern-northeastern Nebraska, Route 4 and 5 are located parallel to each other in southwestern Nebraska and Routes 6, 7, and 8 are located in central Nebraska (Figure 3.2). The missing forecasted snowfall data in most routes were due to the forecast period within the MDSS not extending the full length of the storm at the beginning in various routes, so forecasted total snowfall accumulations were not obtained. Routes 1, 2, 3, and 8 all start out with predictions for snowfall accumulations of greater than 11.8 inches. The analysis of the snowfall accumulation totals decreased to almost half of what was originally forecasted for these routes. Major decreases in the forecasted snowfall accumulations took place between 18 and 9 hours before the end of the precipitation for the routes that had the initial forecast totaling over 11.8 inches. Routes 1, 2, and 3 in eastern-northeastern Nebraska saw decreases of 5.5-7.1 inches from 18 to 9 hours out while Route 8, which is located a little farther to the west saw a decrease of approximately 2.8 inches during the same time period. Routes 4 and 5, located in southwestern Nebraska, remained relatively consistent with the forecasted total snowfall accumulations.

Routes 6 and 7 show comparable snowfall accumulation patterns although the totals do vary. The routes in central Nebraska, routes 6, 7 and 8 are in similar locations; however, due to the slightly more eastern location of Route 8, the forecast resembles routes 1, 2, and 3. The eastern routes are the

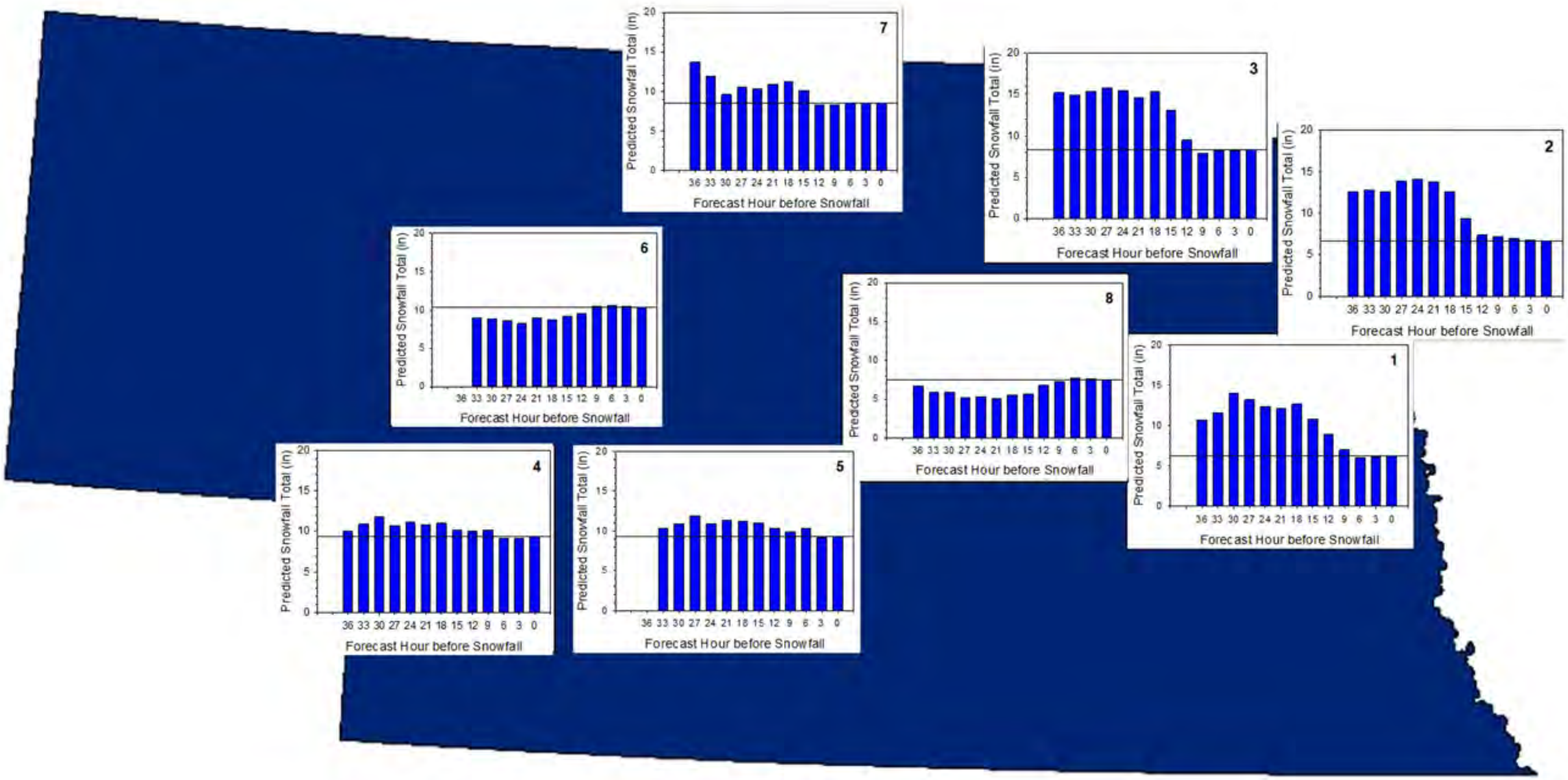


Figure 4.2: Forecasted total snow accumulation from the NDOT-MDSS (blue) as the storm progresses for each route in their respective location throughout Nebraska during the January storm and the analysis of the total snow accumulations from the NDOT-MDSS (black)

least accurate with the forecasts while the central and southwestern routes are much more consistent and accurate. Routes 4 and 5 both have a total deviation of their forecasted snow accumulation of roughly 2.8 inches over the entire time period. The variation of forecasting ability based on the geographic location of the routes could have been caused by the major shifts in the track and timing of the low pressure system (Figure 4.3). The system seems to slow down throughout the 7 days prior to the onset of the storm. The center of the low pressure also shifted from central Iowa to the border of Iowa and Missouri on the day of the event. Although the shift may seem minor, it had an impact on the location of the heaviest snow. The routes in northeastern Nebraska were northwest of the low center, where greater snow accumulations associated with Colorado lows can occur. If any minor shifts in the storm track occurred, the routes would no longer be in a prime location for heavy snowfall. As much as the system had shifted in the forecast period before the event, a minor shift before impacting northeastern Nebraska is very plausible. An increase in the speed of the storm could lead to a large decrease in total snow accumulation for the routes. The storm system would not be over the area for quite as long, leading to lower snowfall totals. Another potential cause of the decrease in forecasted total snowfall accumulations for Routes 1, 2, 3, and 8 is because the transition from rain to snow took longer than was originally predicted by the MDSS. Rain started in these routes at approximately 0900 LST 21 January. When the rain started, the forecasted start time of snowfall was 1800 LST 22 January. The analysis of the start time of the snowfall was 0400 LST 22 January, which means that the rain lingered ten hours longer than was expected in eastern Nebraska decreasing snowfall totals.

The progression of the January storm from 0900 LST 20 January to 2100 LST 22 January within the MDSS (Figure 4.4) highlights the changing weather conditions across Nebraska. Precipitation, mostly rain (eastern) and freezing rain (western) is taking place across Nebraska starting at 0300 LST 21 January. Freezing drizzle was discussed in the AFDs prepared by all 4 NWS offices that contain an

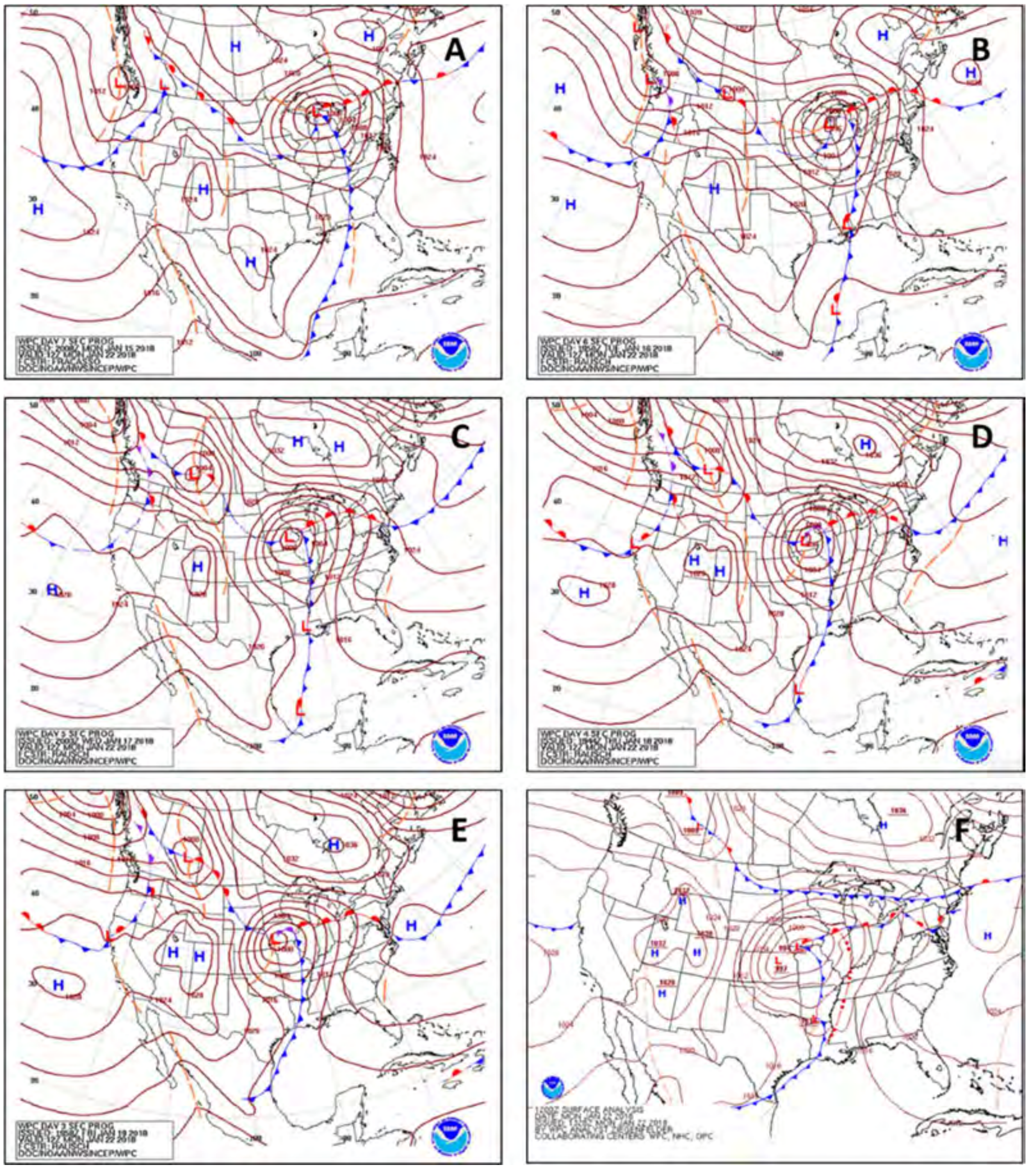


Figure 4.3: The progression of the forecast for the low pressure center of the winter storm that occurred on 22 January 2018. A) 15 January 2018, surface map forecast 7 days out. B) 16 January 2018, surface map forecast 6 days out. C) 17 January 2018, surface map forecast 5 day out. D) 18 January 2018, surface map forecast 4 days out. E) 19 January 2018, surface map forecast 3 days out. F) 22 January 2018, surface map of actual location of the center of the low during the winter storm (WPC 2019)

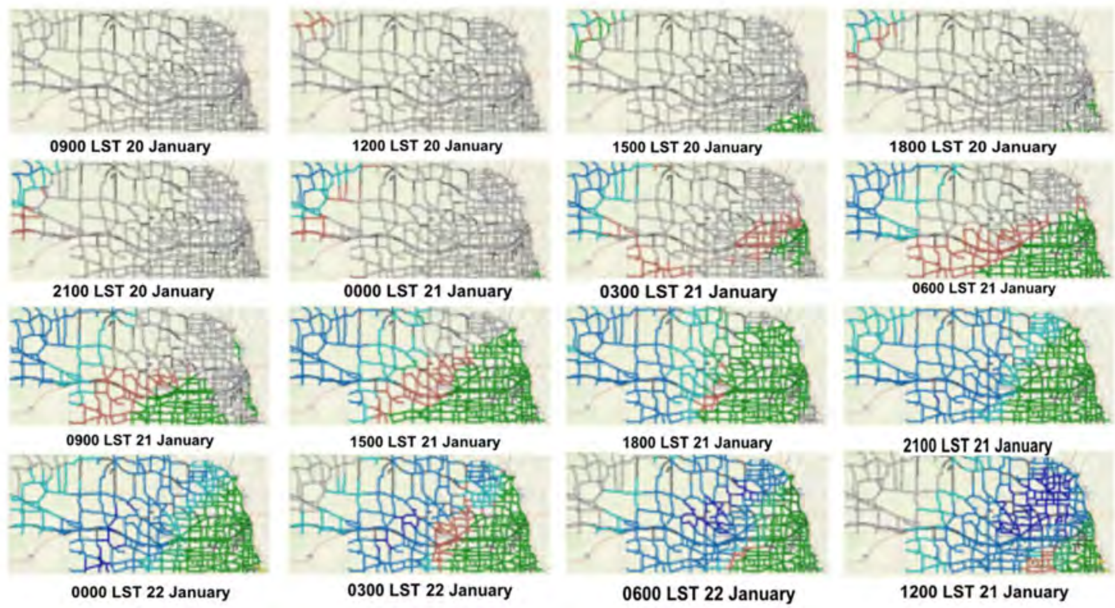


Fig. 4.4: Progression of the January storm through time using the current conditions of each segment (*WebMDSS* 2018)

identified study route as a potential hazard (Tables 4.2-4.5). The MDSS seemed to do a satisfactory job of picking up on freezing drizzle. The freezing drizzle changes over to snow at approximately 1500 LST 21 January in central Nebraska (Figure 4.4). There is still rain present in the eastern and southeastern parts of the state. Three hours later, heavy snow is present from 1800 LST to 1200 LST 22 January in central and northeastern Nebraska. The areas of heavy snowfall amounts shown within the MDSS are consistent with the snowfall totals provided by the KLBF NWS (Figure 4.1). The southeastern part of Nebraska receives mostly rain with some snow mixed in at the very end of the storm (Figure 4.4). The lack of snowfall in southeastern Nebraska shown by the MDSS is also consistent with the totals from the NWS. During the January storm, the main maintenance action that was done was patrolling.

During the January storm, all routes had differences of 5 hours between the forecasted start times and the analysis of the start times within the MDSS (Table 4.6). The minor differences between the forecasted and the analysis of the start times in the MDSS shows that the forecast was relatively accurate. The accuracy of a start time is based off of the time difference that occurred between the forecasted and analysis of the start times in the MDSS. Routes 1 and 3 had forecasted start times greater than 7 hours when compared to the analysis of the start times within the MDSS. The MDSS start time analyses were comparable with the radar observed start times. A change in the timing of the storm could be a cause of the erroneous forecasted start times produced by the MDSS for the eastern routes; however, Route 2 is in the vicinity of Route 1 and 3, although it did not see a timing issue. The differences in start times between the MDSS and the radar could be due to the inability of the MDSS to forecast the heavy snow, which is what can be detected more easily by the radar. Route 6 was the most accurately predicted, with no differences in any of the start times.

Table 4.2: NWS Sioux Falls forecast for the January storm.

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

Table 4.3: NWS North Platte forecast for the January storm.

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

Table 4.4: NWS Omaha/Valley forecast for the January storm.

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

Table 4.5: NWS Hastings forecast for the January storm.

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

Table 4.6: Differences in start times for January Storm (Hrs)

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

Differences in forecasted end times within the MDSS analysis and radar observations were also found for the studied routes (Table 4.7). The variations between the forecasted and analysis of the end times within the MDSS (Table 4.7) are larger than the start times (Table 4.6). There was never an instance where the forecasted end times within the MDSS occurred during the same hour as the analysis of the end times within the MDSS. The forecasted end times were always earlier than the analysis of the end times within the MDSS (Table 4.7). The discrepancy in the forecasted end times could have been caused by the storm slowing down over Nebraska, causing the storm duration to be extended. In many cases, light flurries occurred after the heavy snow ended, which would cause the storm to be extended longer in time than was forecasted. Light flurries at the end of the storm may also be the cause of differences in the analysis of end times within the MDSS when compared with the radar observed end times. The analysis end times within the MDSS always ended later than what were observed by the radar. Flurries may not have been picked up by the radar depending on the height of the radar beam and distance away from the radar. When the forecasted end time within the MDSS was compared to the radar observed end time, there was less variation than when the forecasted end time within the MDSS was compared to the analysis of the end time within the MDSS. These minor inaccuracies were probably caused by the MDSS predicting when the heavy snow would end rather than the flurries. The radar's ability to pick up on the heavy snow may have caused the forecasted start times within the MDSS and the radar observed end times to align relatively well since flurries were not forecasted well by the MDSS and may not be visible in the radar images.

The overall accuracy for predicting total snowfall accumulation varied from route to route. Some of the miscalculations were potentially based on track and timing changes at the various locations of the routes. Routes farther to the west were more accurately predicted than the routes to the east. The location of the route did not appear to have any major influence on the start and end time differences.

Table 4.7: Difference in end times for January Storm (Hrs)

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

It could potentially be said that the routes farther to the east were again the least accurate of all locations because of the large amount of variation, although, other routes in different locations also experienced moderate differences in their start and end times. Because of the way the MDSS saves events, the forecasts for the western routes also had a shorter lead time before the storm impacted them, making forecasts in the western part of the state slightly more accurate due to the shorter lead time. Start times, for the most part, were more accurate than end times in every category that was analyzed. Another limitation was the location of the route with respect to the radar because snowfall would have not been picked up in some cases due to the precipitation occurring below the beam of the radar.

Wind speeds and gusts from all 8 routes in the MDSS were compared to ASOS stations data in the route's general area. Routes 1, 2, and 3 are located in the same general area, so the reports from the ASOS station located at Wayne Municipal Airport (KLCG) were used for comparison (Figure 3.3). During the January storm, the Route 3 MDSS sustained winds best followed the data from the KLCG ASOS station because they are very closely located (Figure 4.5a). Route 1, located to the southwest of the KLCG ASOS station, had lower sustained winds than what the ASOS station reported during most hours. They both followed the same general pattern except for between 0600-0700 LST 22 January. The MDSS sustained winds decreased in Route 1 to 16.1 mph while the KLCG ASOS was reporting sustained winds of 27.6-28.8 mph. Route 2 had much lower winds than both the KLCG ASOS and Routes 1 and 3 between 0800-1200 LST. The cause for the difference of approximately 17.3 mph is unknown. The wind gusts from the MDSS and the KLCG ASOS followed a similar pattern to the sustained winds. Route 2 generally had lower wind gusts and Route 3 had gusts very similar to what the KLCG ASOS was reporting. Route 1 and 3 were reporting much higher wind gusts than the KLCG ASOS while Route 2 was reporting much lower wind gusts 25-30 hours after the storm started. There was only one notable difference in the

Route 2 winds at 64 hours from the start of the saved storms that seemed abnormal. All of the other wind gusts appeared to be similar to what they were when the storm was not taking place.

Routes 4 and 5 were grouped with the KLBF ASOS station (Figure 3.3). The routes were in agreement within the MDSS, which is expected due to their close proximity and same orientation (Figure 4.5b). The route values within the MDSS were in agreement with the KLBF ASOS values given for winds. The KLBF ASOS values were slightly higher in most hours than both routes. Between 0800-0900 LST 22 January, no data were reported from the KLBF ASOS. There were no major inconsistencies in the wind gusts reported for Routes 4 and 5 and what the KLBF ASOS reported. Towards the end of the storm, gusts did not meet the criteria to be reported by either source.

Routes 6 and 7 had a centrally located ASOS station at Ainsworth Regional Airport (KANW) (Figure 3.3). The two routes were not right beside the KANW ASOS, although the routes were within a reasonable distance. Route 6 located to the southwest of the KANW ASOS was more in agreement with the KANW ASOS data reports than Route 7 (Figure 4.5c). Route 7 located to the northwest of the KANW ASOS had lower sustained winds with a large decrease occurring from 0000-0400 LST 22 January. The overall pattern was not as aligned as the other routes and their ASOS stations; however, this may be caused by the greater distance between the MDSS routes and the KANW ASOS. The gusts from Route 7 were consistently lower than the gusts reported from Route 6 and the KANW ASOS. Route 6 was reporting higher wind gusts than the KANW ASOS at the start of the storm; however, as the storm progressed, the gusts started to become more similar in value. Towards the end of the storm, the wind gusts were not high enough to be reported by either the MDSS or the KANW ASOS. Route 8 was not close enough to any of the ASOS stations that the other routes were grouped with, so it was individually grouped with the Albion Municipal Airport (KBVN) (Figure 3.3). The MDSS values for wind speed are not quite in agreement with the values from the KBVN ASOS (Figure 4.5d). At 0500 LST 22 January, the MDSS

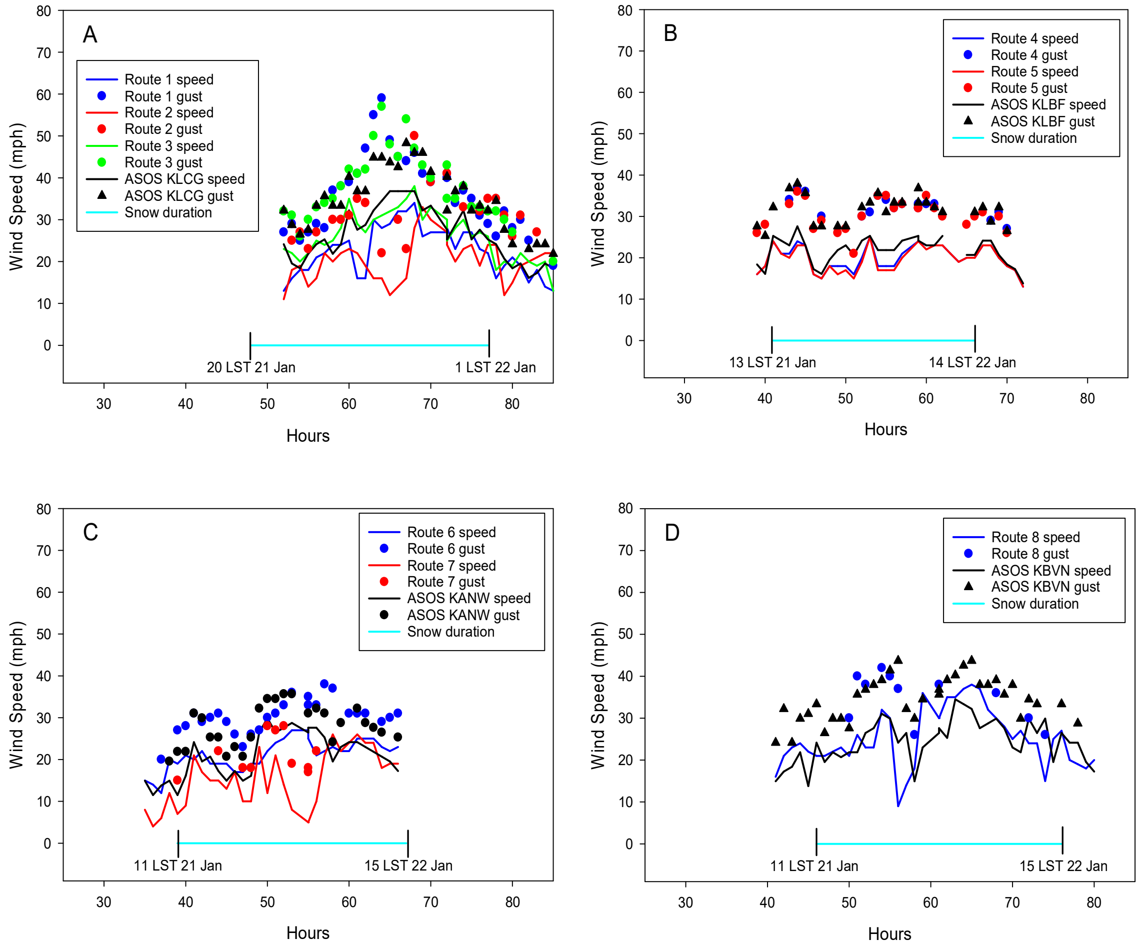


Figure 4.5: Sustained wind speeds and wind gusts during the January storm. A) Route 1 (blue), Route 2 (red), Route 3 (green), and KLCG ASOS station (black). B) Route 4 (blue), Route 5 (red), KLBF ASOS station (black). C) Route 6 (blue), Route (7), and KBVN ASOS station (black). D) Route 8 (blue) and KANW ASOS station (black). The storm duration was plotted (light blue) to show when the storm was taking place per each route.

reported sustained winds at 9.2 mph while the KBVN ASOS has the sustained winds at 24.2 mph. The MDSS and KBVN ASOS wind speeds throughout the storm follow the same overall pattern; however, there are inconsistencies when looking more in detail the sustained winds being reported by both the KBVN ASOS and the MDSS. The wind gusts reported by the MDSS in Route 8 are relatively similar to what was being reported by the KBVN ASOS. There were no major inconsistencies between the two, although there were no wind gusts that met the criteria to be considered high enough during certain periods in the storm.

The ASOS stations that were used to find the accuracy of the MDSS wind data were also the ones used for the analysis of the temperature data in the MDSS. During the January storm, Routes 1, 2, and 3 as well as the KLCG ASOS station have temperatures that were in agreement up until 60 hours from the start of the storm (Figure 4.6a). Route 1 sees a temperature decrease while the KLCG ASOS station sees a temperature increase. Routes 2 and 3 are decreasing at a relatively steady rate at this time. After the sharp increase in temperatures at the KLCG ASOS station, there is a large decrease where it drops down 9-12 $^{o}$F lower than all of the routes. Route 3 increases to approximately what the other routes are seeing within the MDSS. Routes 4 and 5 were perfectly in agreement within the MDSS during the January storm (Figure 4.6b). The KLBF ASOS station followed the same pattern as the routes up until 40 hours from the start of the storm. At approximately 70 hours from the start of the storm, both Route 4 and Route 5 had a large decrease in temperature; however, the KLBF station stayed warmer. The KLBF ASOS station is in exactly the same location as both routes so this result shows some inaccuracy.
The temperatures from Routes 6 and 7 followed the same pattern as the KANW ASOS station, although all three temperatures were a few degrees off from one another (Figure 4.6c). This slight difference occurred throughout most of the saved storm. Temperatures in Route 6 were consistently lower than the other two temperatures, especially at the end of the saved storm where Route 6’s temperatures

plummet close to 18 $^{o}$F below what is being reported at the KANW ASOS station and the analysis of the temperatures by the MDSS at Route 7. The temperatures from the KANW ASOS station and Route 7 were in good agreement throughout the saved storm. The pattern of the air temperatures reported by the KBVN ASOS station was very similar to the analysis of the air temperatures by the MDSS for Route 8 (Figure 4.6d). The temperatures in the MDSS were slightly lower than the air temperatures at the KBVN ASOS station. There are two peaks that occur in the analysis of the air temperature between 50 and 60 hours from the start of the saved storm that were not seen at the ASOS station. Another peak in the analysis of the air temperatures by the MDSS occurred around 80 hours from the start of the saved storm. This was followed by a decrease in the air temperature that was also not seen by the KBVN ASOS station. Throughout the storm duration in Routes 1, 2, and 3, there were no large deviations from the normal temperature; however, the KLCG ASOS station observed a major increase in temperature at 66 hours from the start of the saved storm then it decreases very rapidly until the end of the storm. The issues between Routes 4 and 5 and the KLBF ASOS station began approximately when the storm began. After the storm began at 1300 LST 21 January, the route and the ASOS temperatures were not in agreement through the end of the saved storm.

Routes 1, 2, and 3 are grouped with the RWIS station (Figure 3.3). The Emerson RWIS station did not have data available for the April storm, so the Scribner RWIS was chosen in its place due to the similar location and pavement temperature values. The pavement temperatures in Routes 1, 2, and 3 in the January storm were very in agreement with the Scribner RWIS station although the RWIS station had slightly lower pavement temperatures (Figure 4.7a). The pavement temperatures from the Emerson RWIS station were very similar to the pavement temperatures at the Scribner RWIS station. The only area of divergence of the road temperatures occurs from 60 to 84 hours from the start of the storm, although the difference was not very large. The Wellfleet RWIS station was grouped with Routes

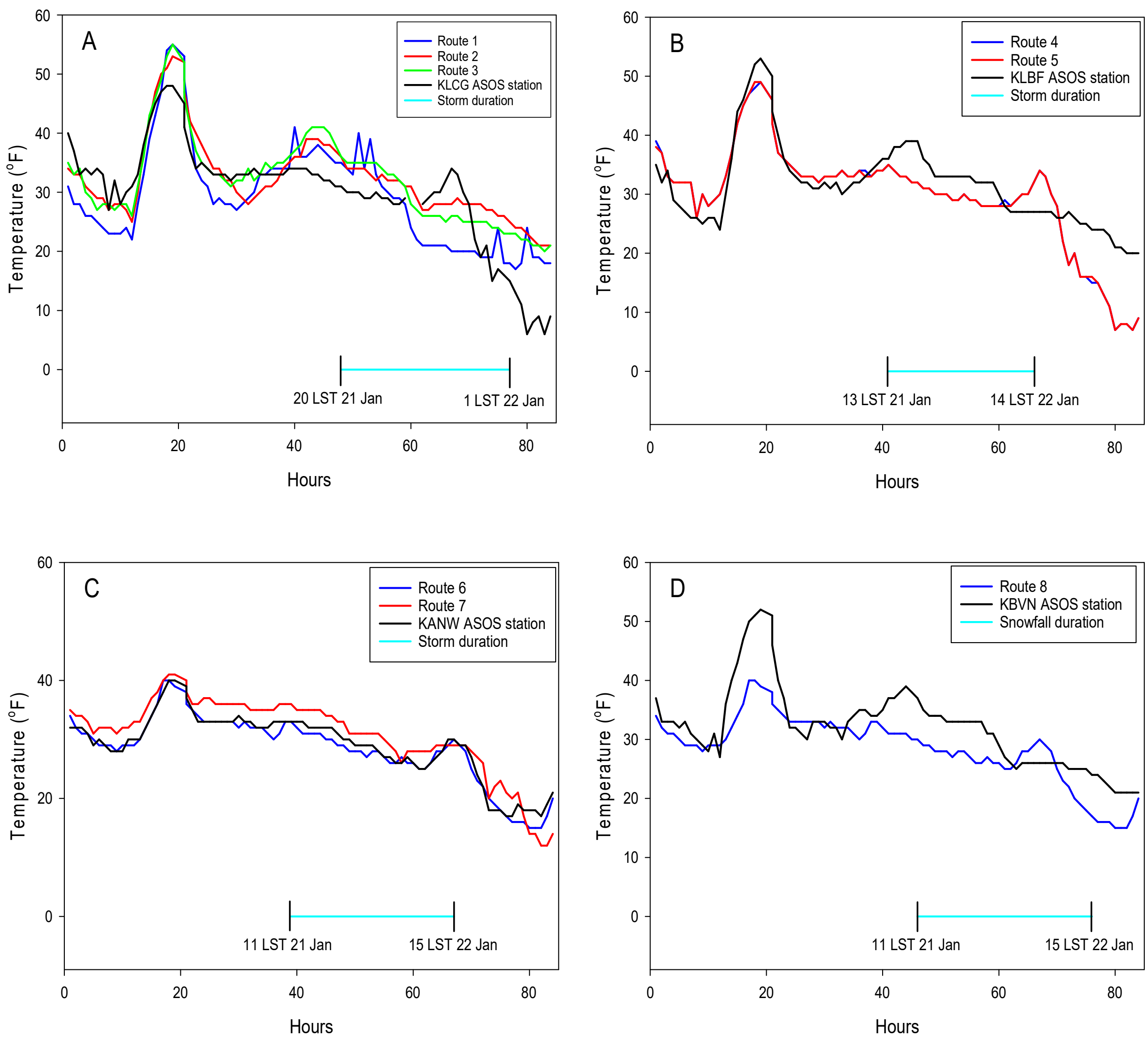


Figure 4.6: Temperatures during the January storm. A) Route 1 (blue), Route 2 (red), Route 3 (green), and KLCG ASOS station (black). B) Route 4 (blue), Route 5 (red), KLBF ASOS station (black). C) Route 6 (blue), Route (7), and KBVN ASOS station (black). D) Route 8 (blue) and KANW ASOS station (black). The storm duration was plotted (light blue) to show when the storm was taking place per each route.

4 and 5 in the MDSS (Figure 3.3). The pavement temperatures in Routes 4 and 5 were in agreement in the January storm up until approximately 70 hours from the start of the storm (Figure 4.7b). The

pavement temperatures obtained from the Wellfleet RWIS station were in agreement with both routes until up to 70 hours from the start of the storm as well. Route 6 and 7 were grouped with the centrally located North Thedford RWIS station (Figure 3.3). The North Thedford RWIS station pavement temperatures are lower than the pavement temperature both Routes 6 and 7 although they did follow the same overall pattern (Figure 4.7c). The inconsistency of the RWIS station could be due to its farther distance to the study routes. Route 8 was grouped with the Cedar Rapids RWIS station due its very close proximity (Figure 3.3). Route 8’s pavement temperatures agreed extremely well with the Cedar Rapids RWIS station (Figure 4.7d). There are almost no differences in the values. The January pavement temperatures from all routes and ASOS stations had no major deviations from the normal patter observed when the storm was occurring to when it was not.

It is very important for an RWIS and a similarly located ASOS station to have the same or relatively similar temperatures. Different temperatures could mean that all variables are inconsistent which could lead to different weather conditions than what is being reported. The Scribner RWIS station was compared to the KLCG ASOS station. Both stations followed the same pattern until about 60 hours from the start of the January storm (Figure 4.8a). The ASOS temperature then spiked and proceeded to drop down to 7-16 $^{o}$F below the temperature observed at the Scribner RWIS station. The Scribner RWIS is located approximately 40 miles south of the KLCG ASOS station (Figure 3.3) so that may be what caused the difference in the two stations. The Wellfleet RWIS station was compared to the KLBF ASOS station. The station temperatures are in agreement up until 40 hours from the start of the storm (Figure 4.8b). The KLBF ASOS station reports slightly warmer temperatures until the Wellfleet RWIS temperatures spike at approximately 65 hours from the start of the storm. After this spike, the KLBF ASOS station goes

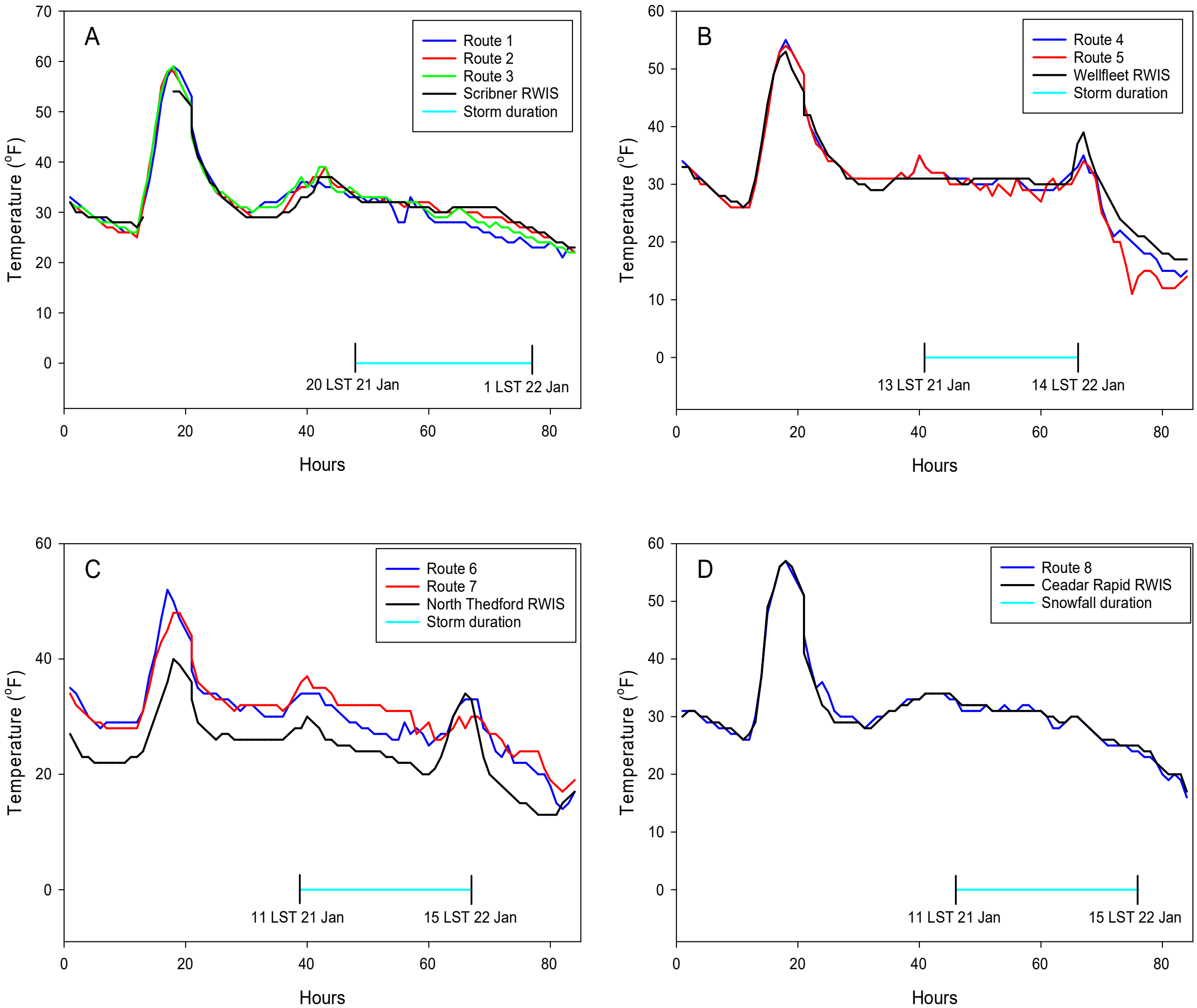


Figure 4.7: Pavement temperatures during the January storm. A) Route 1 (blue), Route 2 (red), Route 3 (green), and Scribner RWIS station (black). B) Route 4 (blue), Route 5 (red), and Wellfleet RWIS station (black). C) Route 6 (blue), Route (7), and North Thedford RWIS station (black). D) Route 8 (blue) and Cedar Rapids station (black). The storm duration was plotted (light blue) to show when the storm was taking place per each route.

back to being slightly warmer than what was being reported at the Wellfleet RWIS station. The differences are relatively small between these two stations. The KANW ASOS station reported more warming at approximately 20 hours from the start of the storm in comparison to the North Thedford RWIS (Figure 4.8c). Throughout the rest of the storm, there was not much of a difference in temperature; however, the KANW ASOS station generally reported slightly warmer temperatures than what was being reported at the North Thedford RWIS station. The Cedar Rapids RWIS station was compared to the KBVN ASOS station. The temperatures followed relatively the same pattern aside from a few spikes in temperature from both stations (Figure 4.8d). The first peak that differs between the station starts at 11 hours from the start of the storm. The Cedar Rapids RWIS station is reporting temperatures that are 4-9 $^{o}$F less than the temperatures being reported at the KBVN ASOS station. The temperatures decrease rapidly and end up 1- 4 $^{o}$F cooler for the next 15-20 hours. The second spike in temperature starts at approximately 60 hours from the start of the storm where temperatures at the KBVN ASOS station are 1-9 $^{o}$F warmer than the Cedar Rapids RWIS temperatures.

### 4.1.b 13-16 April 2018 event

The storm system first brought snow and high winds to the western part of Nebraska on 13 April 2018 and moved eastward throughout the day. NEWINS also observed the snowfall in the western part since NEWINS calculated a category 3 event in District 5 (Table 4.1). Heavy snow fell in central Nebraska during 14 April with snow totals ranging from 8 – 18 inches by 15 April (Figure 4.9). NEWINS also observed the increase intensity with values increasing to 4 and 5 within Districts 6, 7 and 8 (Table 4.1). Many road closures were reported across Nebraska during the event, including Interstate 80. Closures were caused by the heavy snow along with snow drifts that reached over a meter in height in many

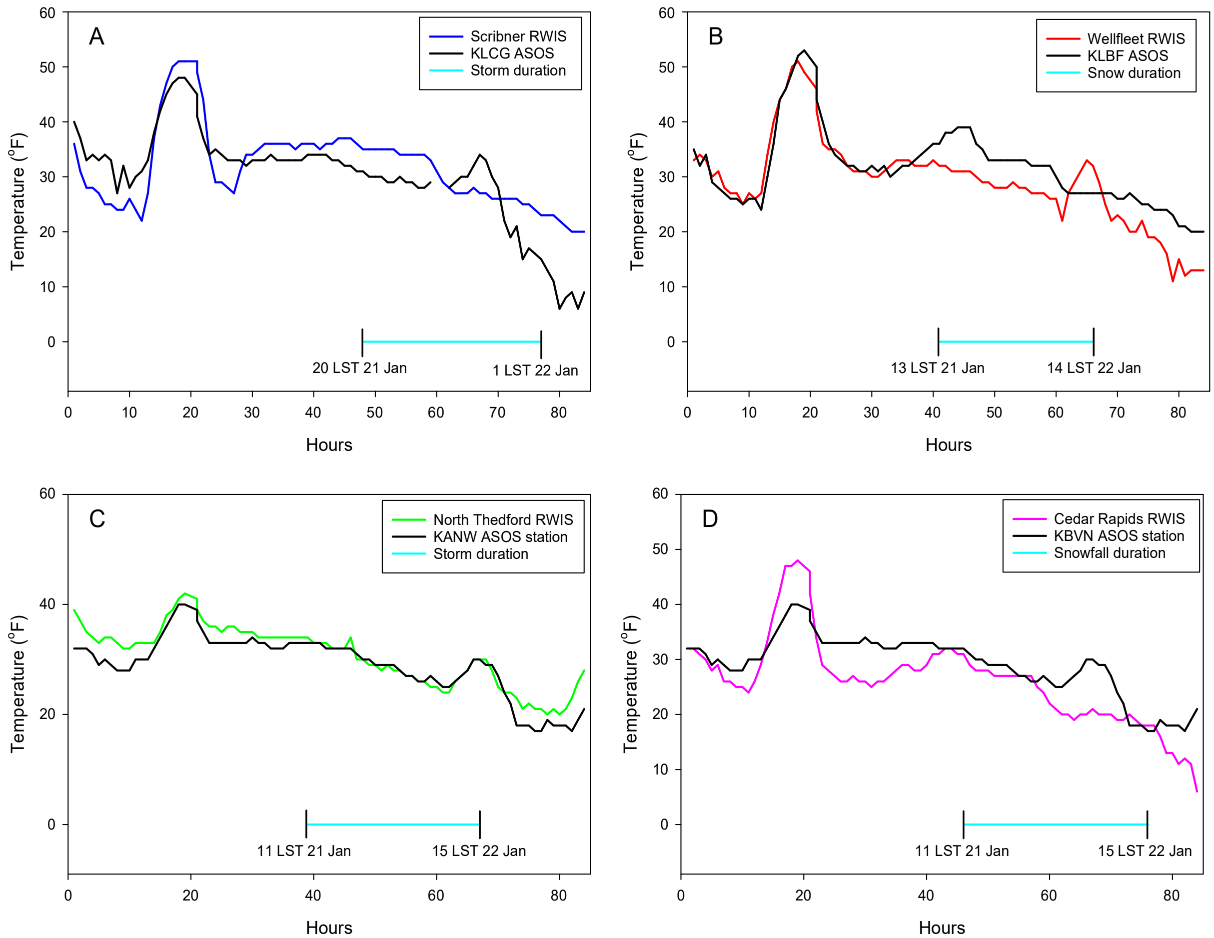


Figure 4.8: Air temperatures during the January Storm. A) Scribner RWIS station (blue) and KLCG ASOS station (black). B) Wellfleet RWIS station (red) and KLBF ASOS station (black). C) North Thedford RWIS station (green) and KBVN ASOS station (black). D) Cedar Rapids RWIS station (magenta) and KANW ASOS station (black).

places. Temperatures dropped well below and high profile vehicles had difficulty time traveling because of high winds that accompanied the event.

The forecast for the April storm did not change too much over the 7 days prior to the event and this can be seen in the MDSS forecasted total snow accumulations. The evolution of the forecasted total snow accumulations for each route within the MDSS (Figure 4.10) shows slight variations as the storm moves toward Nebraska. Routes 1, 2, 3, and 8, all had similar forecasts with Route 3 predicted to receive the highest total snowfall accumulation of approximately 9.8 inches. Route 6 and 7, also had very similar forecasts which is expected due to their similar geographic locations. The central part of Nebraska had the highest snowfall accumulation analysis and were well represented by the MDSS forecasts.

Routes 4 and 5, which run parallel to one another, had a much higher forecasted total snowfall accumulation than what actually occurred. Big decreases in forecasted total snowfall accumulation took place 18-12 hours prior to the end of the storm in each route. Route 4 saw a decrease of approximately 4.3 inches while Route 5 saw a decrease of 3.4 inches. Route 4 saw only 2.6 inches while Route 5 saw 4.2 inches. Since these routes are located parallel to each other, it is expected that they have the same or extremely similar forecasts. It was originally hypothesized that since the MDSS, compaction, melt, and treatment are taken into account, that Interstate 80 (Route 5) would see less total snow accumulation than US-30 (Route 4) due to the higher LOS leading to more treatment; however, Interstate 80 actually saw the higher total snowfall amount of the two routes. With a difference of 1.6 inches, there may have been a variation with the model within the MDSS. The snowfall gradient was looked at to determine if there was an acute snow gradient in the area; however, there was no snow gradient that could have produced that much of a difference between the two routes for most of the region. Route 4 saw only 3 hours of snowfall rates exceeding 0.3 in $hr^{-1}$ while Route 5 saw 6 hours exceeding that snowfall rate. The other routes had a relatively consistent forecast for total snowfall accumulation. All routes, with the

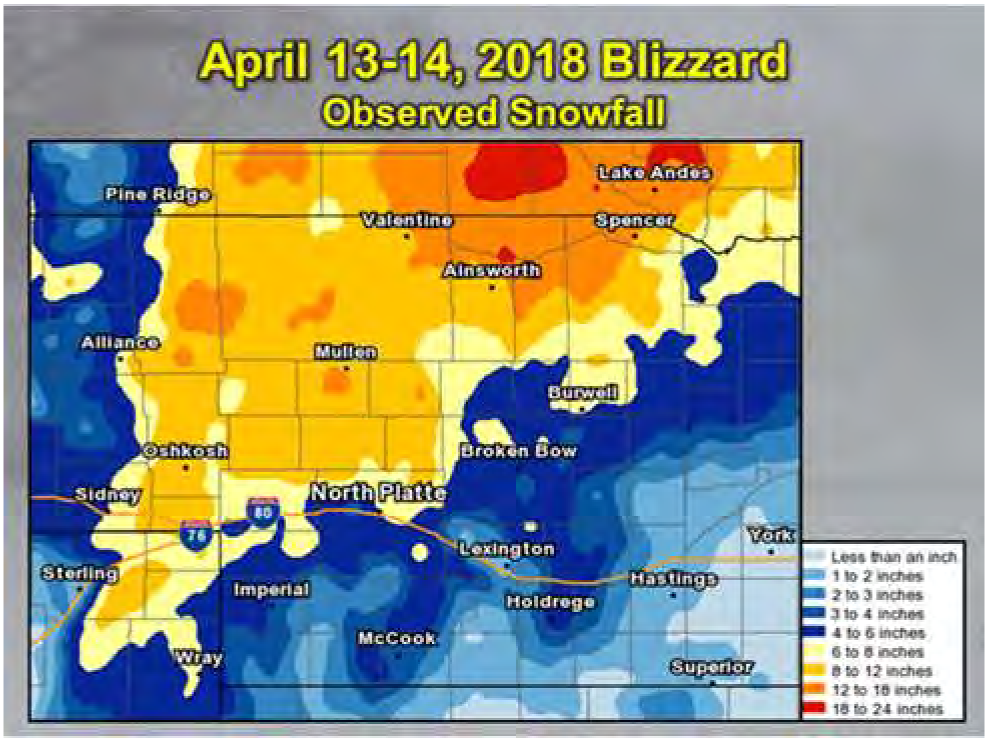


Figure 4.9 Snowfall values for the April 2018 event.

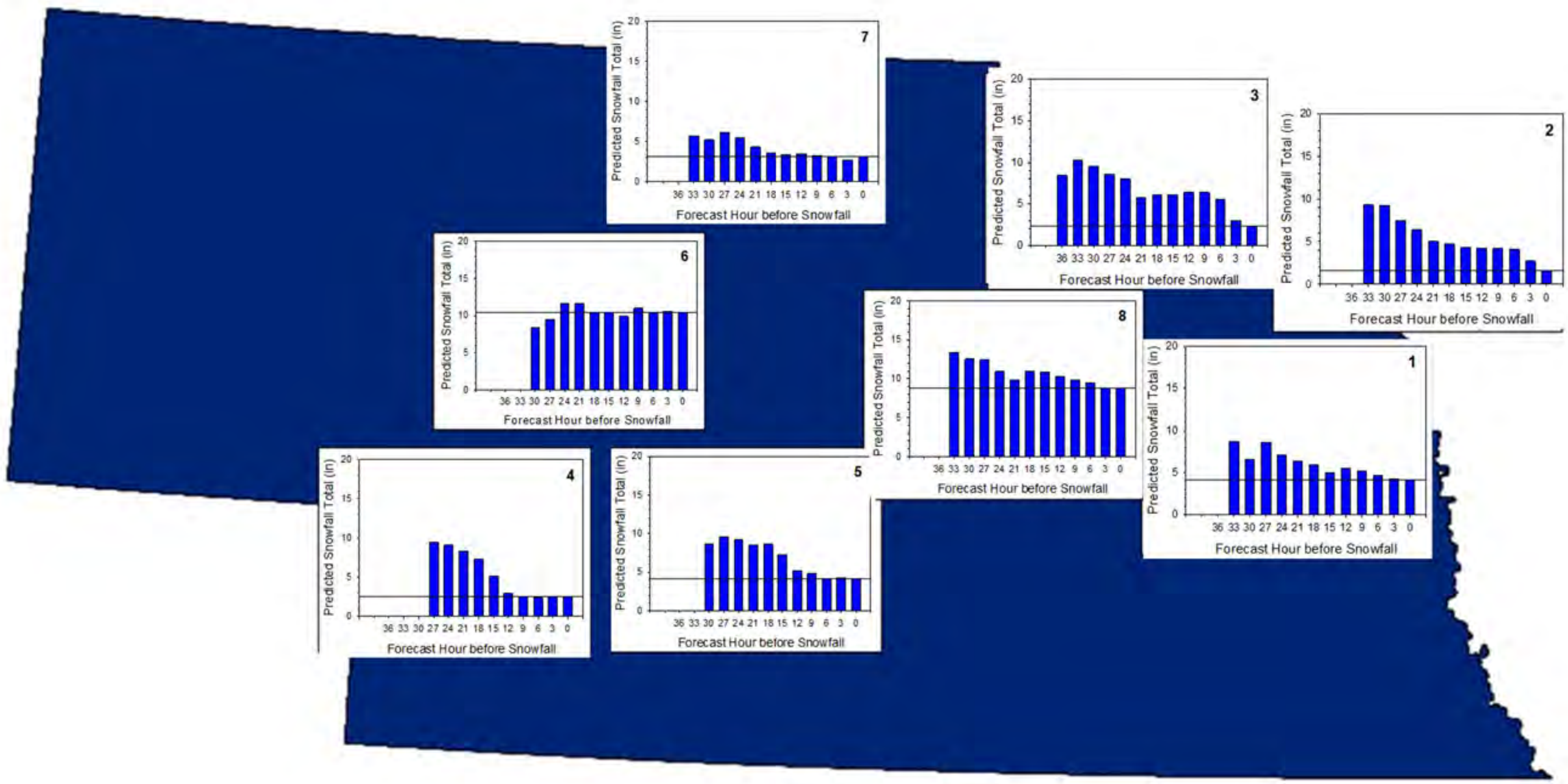


Figure 4.10: Forecasted total snow accumulation from the NDOT-MDSS (blue) as the storm progresses for each route in their respective location throughout Nebraska during the April storm and the analysis of the total snow accumulations from the NDOT-MDSS (black)

decreases were minor. The reason for the decrease in Routes 4 and 5 does not appear to be a timing issue or an issue with the transition from rain to snow. The rain ended and transitioned to snow within an hour of when the MDSS forecasted it to. The snow rate decreased earlier than was expected. The heavier snow rates of over 0.3 in hr-1 were forecasted to end at 0800 LST 14 April; however, they ended at approximately 0200 LST 14 April according the MDSS. This would have led to decreasing snowfall totals in both of these routes not just one of the routes. After further investigation and discussions with Iteris it was determined that the differences in the snow accumulations was a result of the lengths of the Route 4 and 5 not being the same distance. Snowfall accumulations within MDSS are an average across the length of the route. So, in this case Route 4 was longer and crossed the snowfall gradient more and thus had a reduced snowfall accumulation. It was not a meteorological condition per say, it was how the accumulations were calculated and the slight snowfall gradient in the region that caused the variations. During the April storm, the MDSS forecasted start times were within five hours of the MDSS analysis of the start times in Routes 2, 3, 4, 5 and 8 (Table 4.8). Routes 6 and 7 had five to six hour differences in their forecasted and their analysis of the start times within the MDSS. The biggest difference was Route 1 with a nine hour difference between the forecasted and the analysis of the start times within the MDSS. When looking into a reason for why Route 1 had such a large difference in comparison to the other routes, it was noted that the rain transitioned over to snow earlier than was predicted. The early transition led to a much earlier start times analyzed within the MDSS than was forecasted. There does not appear to be a link to the geographic location with respect to the difference in start within the MDSS. The MDSS forecasted start time agreed well with the radar observed start times. The largest difference that occurred was in Route 8 with a five hour difference. Routes 1 and 2’s the MDSS forecasted start time agreed perfectly with the radar observed start time. This result shows that the MDSS did an acceptable job of predicting the onset of heavier snow for the April event with only moderate variations in Routes 6 and 7. The MDSS analysis of the start times also agreed relatively well with the radar observed start times with the radar observed start times with the exception of Routes 1 and 8. Routes 1 and 8 both saw differences of nine hours. The MDSS analysis of the storm starting much earlier than was observed by radar. All other routes had differences of less than five hours. Any differences in start times did not appear to have much relation to the geographic location of the route. Routes 4 and 5 had the same analysis and forecasted start times within the MDSS which is expected because they are so close together.

The difference in end times was found between the same variables as the start times (Table 4.9). The accuracy of the forecasted end times within the MDSS was comparable to the accuracy of the forecasted the MDSS start times. Routes 1, 2, and 3, located in eastern Nebraska, all had major issues with the MDSS forecasted versus the MDSS analysis of the end times. The differences were all over five hours. Routes 4, 5, 6, 7 and 8 all had differences of four hours and under, which shows that there was a lot more accuracy with the forecast of end times with these routes. The reasoning behind the major differences observed in Routes 1, 2, and 3 were caused by the storm speeding up when it got to eastern Nebraska. The MDSS forecasted that the end time would be much later than was actually reported by MDSS, which is why an increase in speed of the system is expected to have occurred. An increase can also be seen when looking at the MDSS forecasted versus radar observed end times. There is also a major difference in these variables in Routes 1, 2, 3 and 8, which is also located more to the east than all other routes. The large differences between the MDSS forecasted end times and radar observed end times shows that the MDSS did not forecast the increase in speed of the system very well. The differences for these routes ranged from 10.5 to 17 hours. This is a major inaccuracy. Routes 4, 5, 6 and 7 did not have any major differences between the MDSS forecasted end times and radar observed end

Table 4.8: Difference in precipitation start times for April Storm (Hrs)

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

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

During the April storm, Route 3, the route closest to the KLCG ASOS was once again the most agreeable with the data from the KLCG ASOS (Figure 4.11a). The route that had the least agreement with the data from the KLCG ASOS was Route 1 which is located to the southwest of the airport. Route 1 saw winds that were much lower than what was being reported by the KLCG ASOS. Route 2 followed the same overall pattern as Route 3 and the KLCG ASOS; however, the winds were lower during most hours. The KLCG ASOS reported wind gusts were surprisingly lower during most hours than all three routes. There was no pattern to which route had the highest wind gusts during the event. Hours 30 to 54 from the start of the storm, Route 2 generally had the highest wind gusts while Route 3 did a marginally better job of being in agreement with the KLCG ASOS. The analysis from Routes 4 and 5 were in agreement within the MDSS as well as with the ASOS station at KBLF (Figure 4.1b). There were no major differences in the sustained winds. From 9 to 17 hours out from the start of the storm, the KLBF ASOS was reporting considerably lower wind gusts than what was being outputted by the MDSS in both Routes 4 and 5. Nine to ten hours after the storm started in Nebraska, the KLBF ASOS was reporting

Table 4.9: Difference in precipitation end times for April Storm (hours)

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

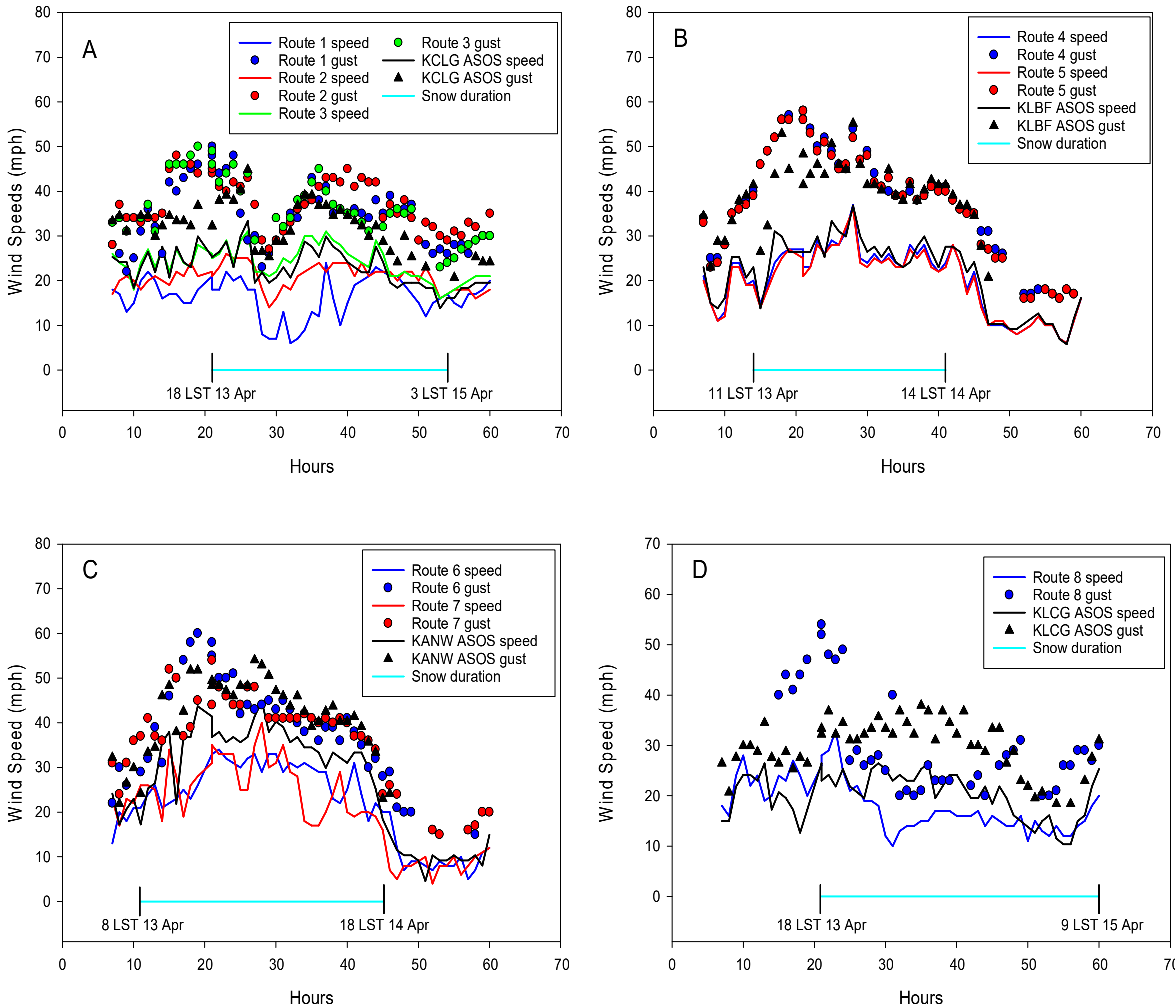


Figure 4.11: Sustained winds and wind gusts in the April storm. A) Route 1 (blue), Route 2 (red), Route 3 (green), and KLCG ASOS station (black). B) Route 4 (blue), Route 5 (red), KLBF ASOS station (black). C) Route 6 (blue), Route (7), and KBVN ASOS station (black). D) Route 8 (blue) and KANW ASOS station (black). The storm duration was plotted (light blue) to show when the storm was taking place per each route.

16.8-20.1 mph less than what the MDSS was outputting. After this period, the wind gusts started to become more similar.

The analysis of the winds by the NDOT MSS at Route 7 shows that there were many spikes in the winds; however, these spikes rarely were greater than the winds reported by the KANW ASOS station (Figure 4.11c). The analysis of the winds by the MDSS at Route 6 show a smoother increase and decrease in the speeds in comparison to Route 7. There is one large spike that occurs at 40 hours from the start of the saved storm. The winds and gusts follow the same overall pattern although, during the storm, the winds seem to not be as in agreement as when the storm is over. From the beginning of the saved storm to 13 hours from the start of the saved storm, the winds reported by the KBVN ASOS station and the analysis of the winds by the MDSS were in good agreement (Figure 4.11d). The MDSS analysis of the winds and gusts in Route 8 then increases by a few mph until 27 hours from the start of the saved storm. The KBVN winds increase to greater than the Route 8 wind speed. This occurs for a majority of the time the storm is occurring. At approximately 47 hours from the start of the saved storm, the winds and gusts from the two sources are much more in agreement until the end of the saved storm. During the storm, Route 1 saw a large decrease in the winds and the KLCG ASOS station remained relatively constant while the storm was occurring. Other than Route 1's decrease in wind speed, there were no other notable differences between when the storm was occurring and when it was not.

During the April storm, the temperatures obtained from the KLCG ASOS station, Route 2 and Route 3 were all in agreement (Figure 4.12a). The temperatures in Route 1 were slightly lower and had more erratic changes from 45 to 66 hours from the start of the storm. The reason for the differences in Route 1 is unknown. The temperatures for Routes 4 and 5 were almost perfectly in agreement with each other as well as the KLBF ASOS station (Figure 4.12b). There are only minor differences present. The air temperatures reported by the KANW ASOS station agreed very well with the analysis of the air temperature by the MDSS (Figure 4.12c). There are only minimal differences, which is expected because of the proximity of the routes to the ASOS station. The analysis done by the MDSS has the exact same pattern as the air temperature reported by the KBVN ASOS station; however, the air temperatures reported by the KBVN ASOS station was approximately 1- 4 $^{o}$F higher than the analysis of the air temperatures by the MDSS (Figure 4.12d). The reason for the difference in the temperatures is unknown. During the duration of the storm, Route 1 saw an interesting pattern of small temperature spikes that were not in the other routes nor at the KLCG ASOS station. In all other routes in the April storm, there were no major differences that occurred while the storm was taking place.

The pavement temperatures from Routes 1, 2, and 3 are in agreement during the April storm in the MDSS, although pavement temperatures from Scribner peak 18 $^{o}$F higher than both routes 17-23 hours from the start of the storm (Figure 4.13a). This could have been caused by the more southern location of the RWIS station. The pavement temperature in Routes 4 and 5 are very similar within the MDSS (Figure 4.13b). The Wellfleet RWIS station pavement temperatures are slightly higher than both of the routes. This could be caused by the more southern location of the RWIS (Figure 3.3). The pavement temperature in Routes 6 and 7 within the MDSS followed the pattern of the pavement temperatures of the North Thedford RWIS station relatively well (Figure 4.13c). There were a few areas of missing data from the RWIS station; however, most of the RWIS data saw the same peaks and dips as both routes. The inconsistency of the two routes and the RWIS station can most likely be attributed to the distance between them (Figure 3.3). Route 8's pavement temperatures matched the Cedar Rapids RWIS station very well in the April storm (Figure 4.13d). The only small inconsistency is present at the very end of the storm from hours 63 to 66 from the start of the storm. The April pavement temperatures from all routes and all ASOS stations had no major differences from the normal pattern observed when the storm was occurring to when it was not.

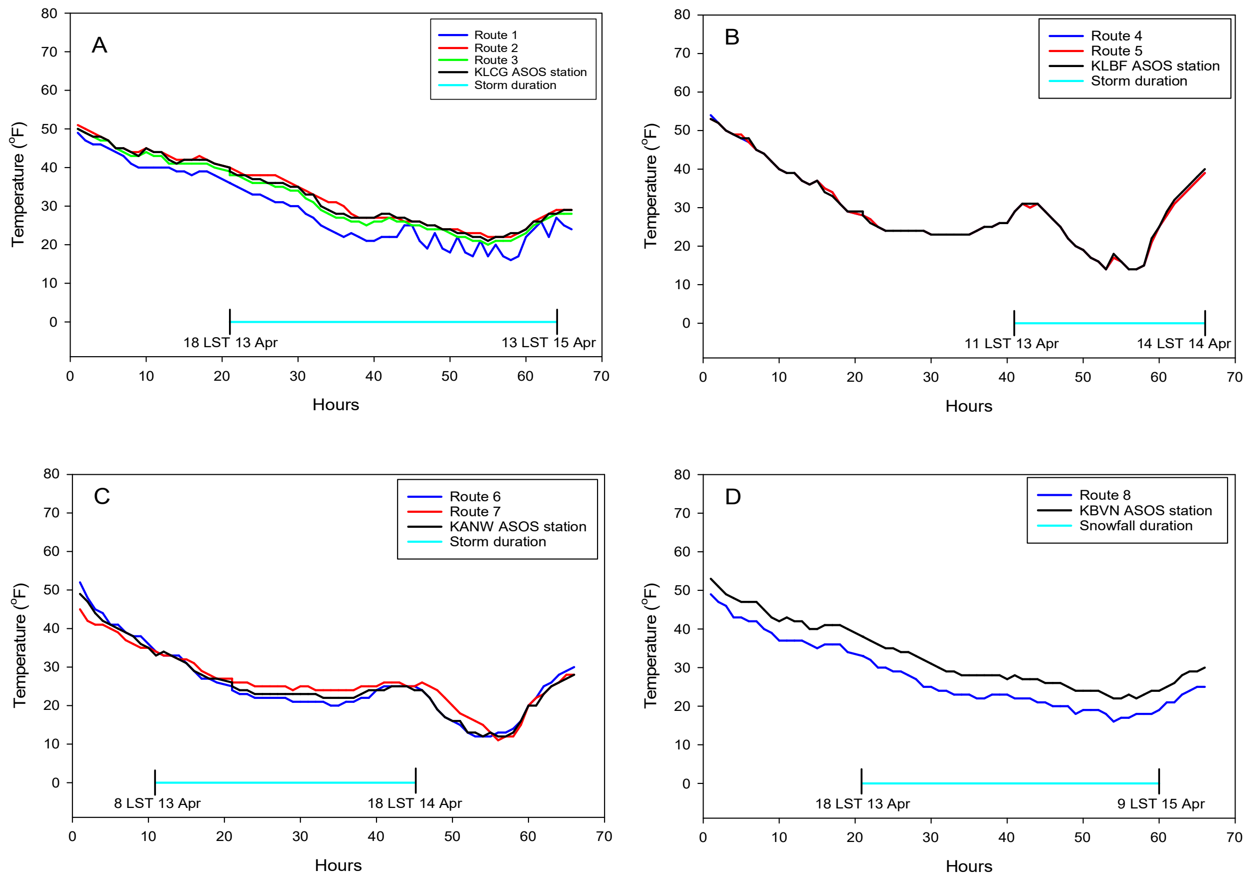


Figure 4.12: Temperatures during the April storm. A) Route 1 (blue), Route 2 (red), Route 3 (green), and KLCG ASOS station (black). B) Route 4 (blue), Route 5 (red), KLBF ASOS station (black). C) Route 6 (blue), Route 7 (red), and KANW ASOS station (black). D) Route 8 (blue) and KBVN ASOS station (black). The storm duration was plotted (light blue) to show when the storm was taking place per each route.

During the April storm, the RWIS and ASOS station temperatures agreed very well in most geographic locations. The Scribner RWIS station spiked at approximately 15 hours from the start of the storm while the KLCG ASOS temperature steadily decreased (Figure 4.14a). This was most likely caused by the more southern location of the Scribner RWIS station (Figure 3.3). The only other large difference occurred between the North Thedford RWIS station and the KBVN ASOS station (Figure 4.14c). Both stations have initial temperatures between 50-59 $^{o}$F; however, the temperatures quickly diverge. The North Thedford RWIS reported much lower temperatures than what was being reported at the KBVN ASOS station. There was also missing data from the North Thedford RWIS, so comparisons weren't made from 21 to 35 hours from the start of the storm. The cause of the differences in temperature is unclear because there are varying distances between the stations and the routes (Figure 3.3), although the difference in temperatures should not be that much. The other ASOS and RWIS stations had very similar temperatures to one another.

In general, it was found during the case studies that the meteorological observations within MDSS very well represented the weather conditions observed along the various routes. The forecasted snowfall amount was close to what was observed for most locations, though there were other locations that the amount forecasted was much more than observed. This over forecasting was a tribute to the slower moving system. If there were variations in snowfall amount, they were a result of differences in the start and end times of the precipitation for individual routes investigated. The amounts also varied between the two events. For the most part, the closer in time to the snowfall event, the worst MDSS forecasted the event. With longer lead times, the forecasts were more accurate. Some of these inaccuracies were probably caused by the actual events, i.e. storm movement, others might have been MDSS; however, no definitive conclusions could be drawn from these two events.

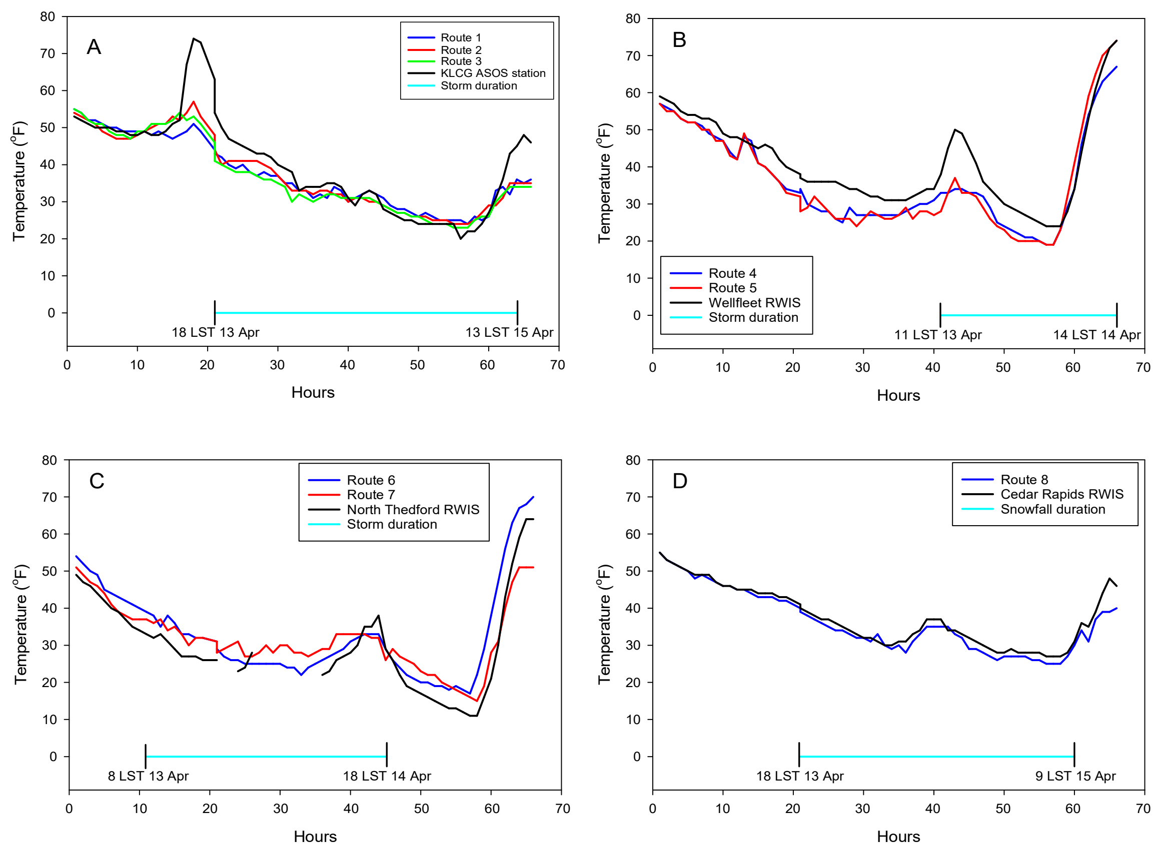


Figure 4.13: Pavement temperatures during the April storm. A) Route 1 (blue), Route 2 (red), Route 3 (green), and Scribner RWIS station (black). B) Route 4 (blue), Route 5 (red), and Wellfleet RWIS station (black). C) Route 6 (blue), Route (7), and North Thedford RWIS station (black). D) Route 8 (blue) and Cedar Rapids station (black). The storm duration was plotted (light blue) to show when the storm was taking place per each route.

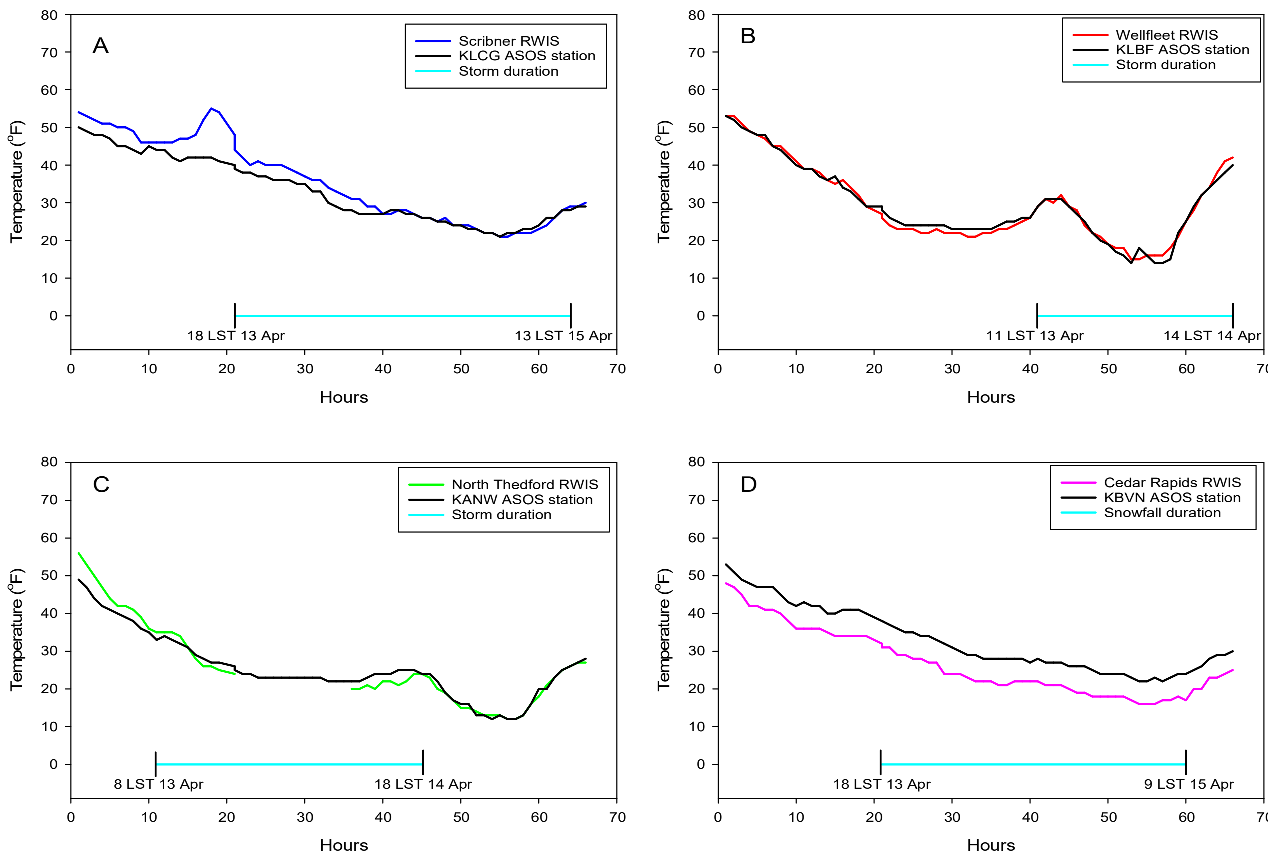


Figure 4.14: Air temperatures during the April Storm. A) Scribner RWIS station (blue) and KLCG ASOS station (black). B) Wellfleet RWIS station (red) and KLBF ASOS station (black). C) North Thedford RWIS station (green) and KBVN ASOS station (black). D) Cedar Rapids RWIS station (magenta) and KANW ASOS station (black).

### 4.2 Storms moving across the Lincoln region

For further verification of the MDSS parameters, several new case studies were investigated to increase the knowledge gained from the initial two cases discussed above, through different implementations were completed to broaden the assessment of MDSS. Basically, the initial case studies indicated forecast differences in the snow timing of the events. These new cases will elaborate on this question. Does MDSS forecast the starting and ending times of snowfall and the total snowfall amount correctly? Are there any issues with MDSS snowfall forecasts? To answer these questions, we selected routes that were all in District 1, representing the Lincoln region which could be verified by the meteorological data from the Lincoln Airport.

#### 4.2.a 25-26 November 2018 event

The 25-26 November 2018 case study event was a Colorado low which moved over District 1, producing heavy snowfall (Figure 4.15), caused blowing and drifting snow and have a large impact on transportation. NEWINS values also identified the impacts of the event, with NEWINS values of 4 and 5 calculated for the two days of the event (Table 4.1). While original forecast had the event moving further to the north over the Lincoln metroplex, the actual storm track was a little further to the south and east of Lincoln. The NEWINS values would have been higher if the entire District would have been influenced by the storm. The region still received a large snowfall; however, conditions could have been much worse with a more northerly track. The resultant change in storm track can been seen in the MDSS forecasts. As was done with the previous case studies, atmospheric parameters, temperature, dewpoint temperature, and wind speeds, were analyzed at 3, 6, 9, and 12-hour prior intervals within MDSS and compared to NWS ASOS observed values, which spanned snowfall start (2 LST) to snowfall end (9 LST),

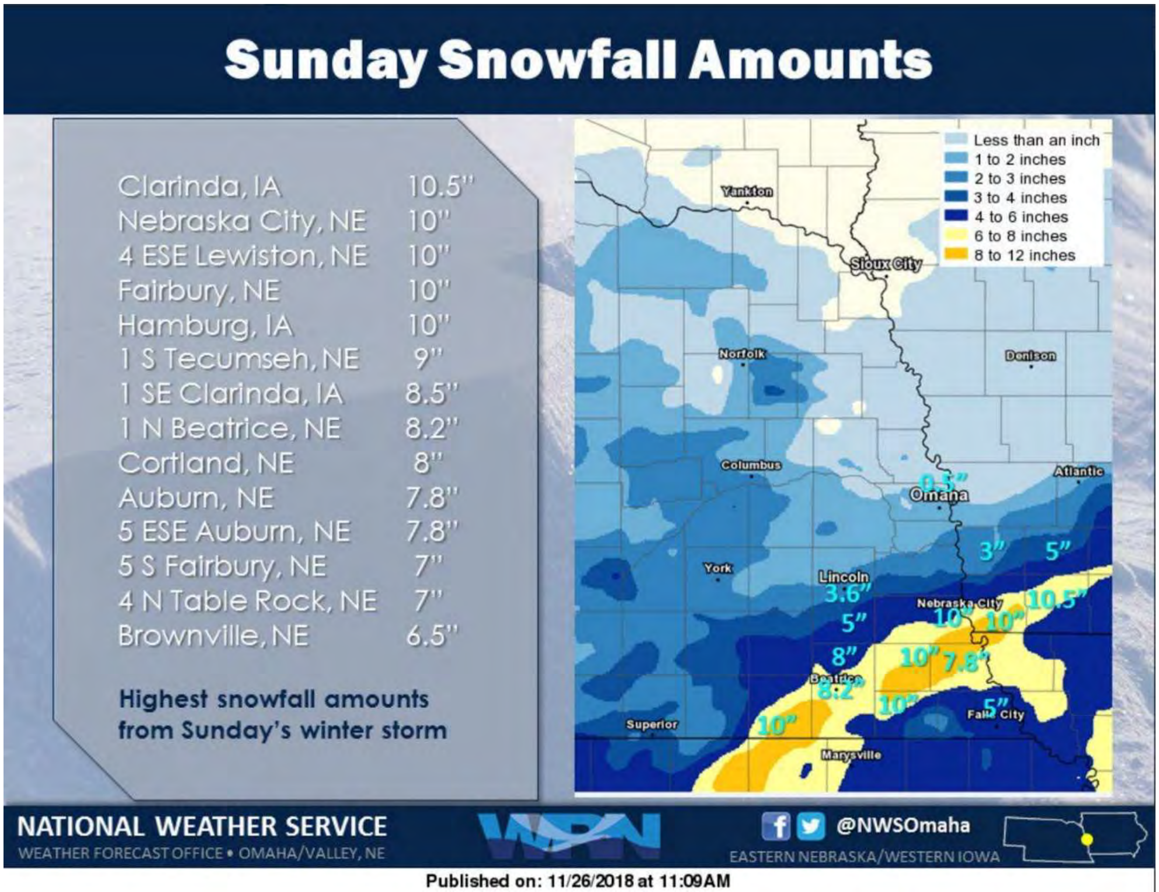


Figure 4.15: Total snowfall accumulation map across the NWS Omaha CWA for 24-25 November 2018 (from NWS Omaha/Valley).

on the morning of 25 November 2018. In addition, hourly forecasts for snow conditions were obtained and analyzed for each event.

MDSS temperature values for the two interstate routes (W80 and P80) and three highway routes (HW34, HW77 and HW33) were consistently low compared to ASOS observed values across the majority of the forecast runs (Figures 4.16, 4.17). The most accurate temperature forecasts at the P80 road section are at the 12-hour prior forecast. The 12-hour prior forecast was almost perfectly collocated with the ASOS observed temperature, which indicates that the 12-hour prior forecast by the MDSS for P80 may in fact be more accurate than the forecasts closer to the snowfall start time. In comparison, routes HW33 and HW77 were more accurate at the 9-hour forecast time frames. Some of the inaccuracies could be caused by the more southernly track taken by the storm system and may not be a result of the MDSS. HW77 may be representing the shift in the storm track. The length of the route might also be responsible for the difference in forecasted temperatures. HW34 is closest to the Lincoln Airport, the forecast verification location, so proximately to the ASOS site might also be some of the differences. It should be pointed out that temperatures calculated in 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.

Dewpoint temperature forecasts by the MDSS had a much smaller margin of variation across the board with regards to routes (Figures 4.18, 4.19). The most accurate forecasts by the MDSS system was for the P80 section 12-hour prior forecast. This 12-hour prior forecast perfectly forecasted the dewpoint for P80 and was only 2 $^{o}$F under forecasted for the other routes. Notable under forecasting throughout all of the forecast runs for the other routes was observed especially for the 9-hour forecast. The smaller margin of dewpoint temperature variation would indicate that the MDSS was predicting a slightly more saturated lower atmosphere than actually ended up being present. Whether this forecasted presence of

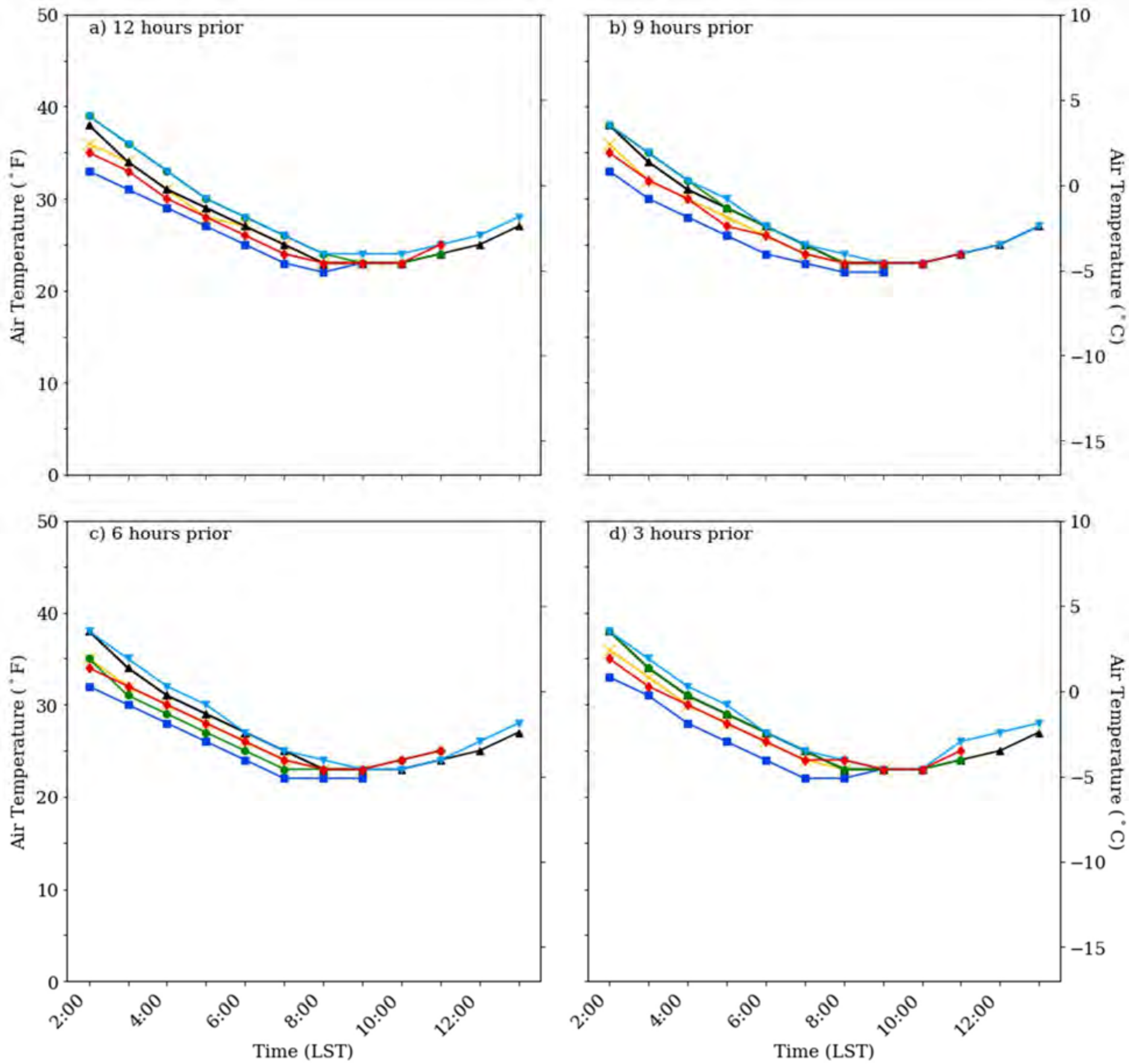


Figure 4.16: 24 November 2018 hourly temperature forecasted by NDOT-MDSS at (a) 14 LST forecast run (12-hours prior to snowfall start), (b) 17 LST forecast run (9-hours prior to snowfall start), (c) 20 LST forecast run (6-hours prior to snowfall start), and (d) 23 LST forecast run (3-hours prior to snowfall start) for W80 (yellow), P80 (blue), HW34 (red), HW33 (green), and HW77 (light blue) compared to ASOS observed (black). Date and time run from start of snowfall to end of snowfall.

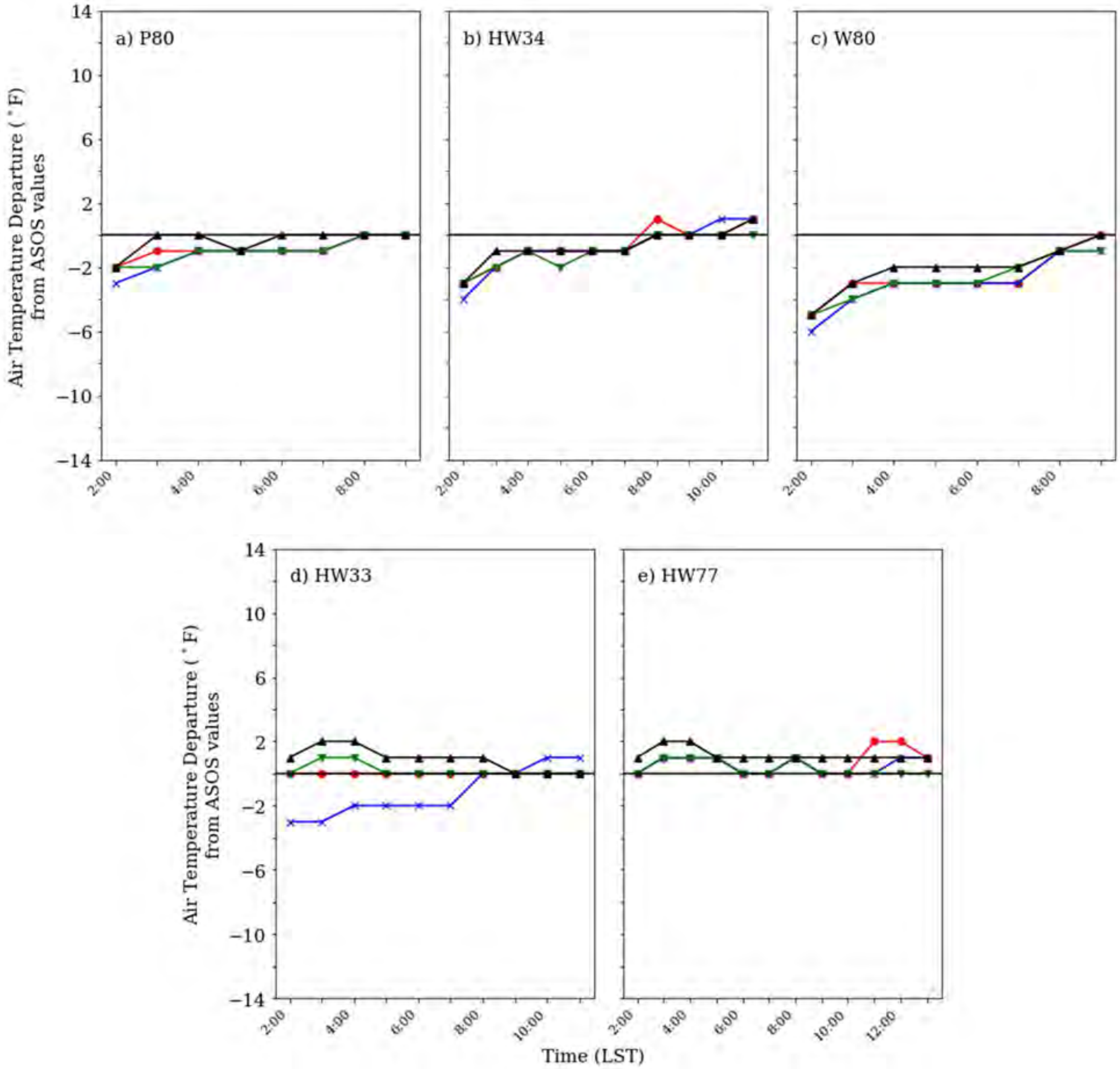


Figure 4.17: Difference graphs of the MDSS forecasted temperature departure for 24 November 2018 from the observed ASOS values at (a) W80, (b) P80, (c) HW34, (d) HW33, and (e) HW77 for 3-hours (red), 6-hours (blue), 9-hours (green), 12-hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

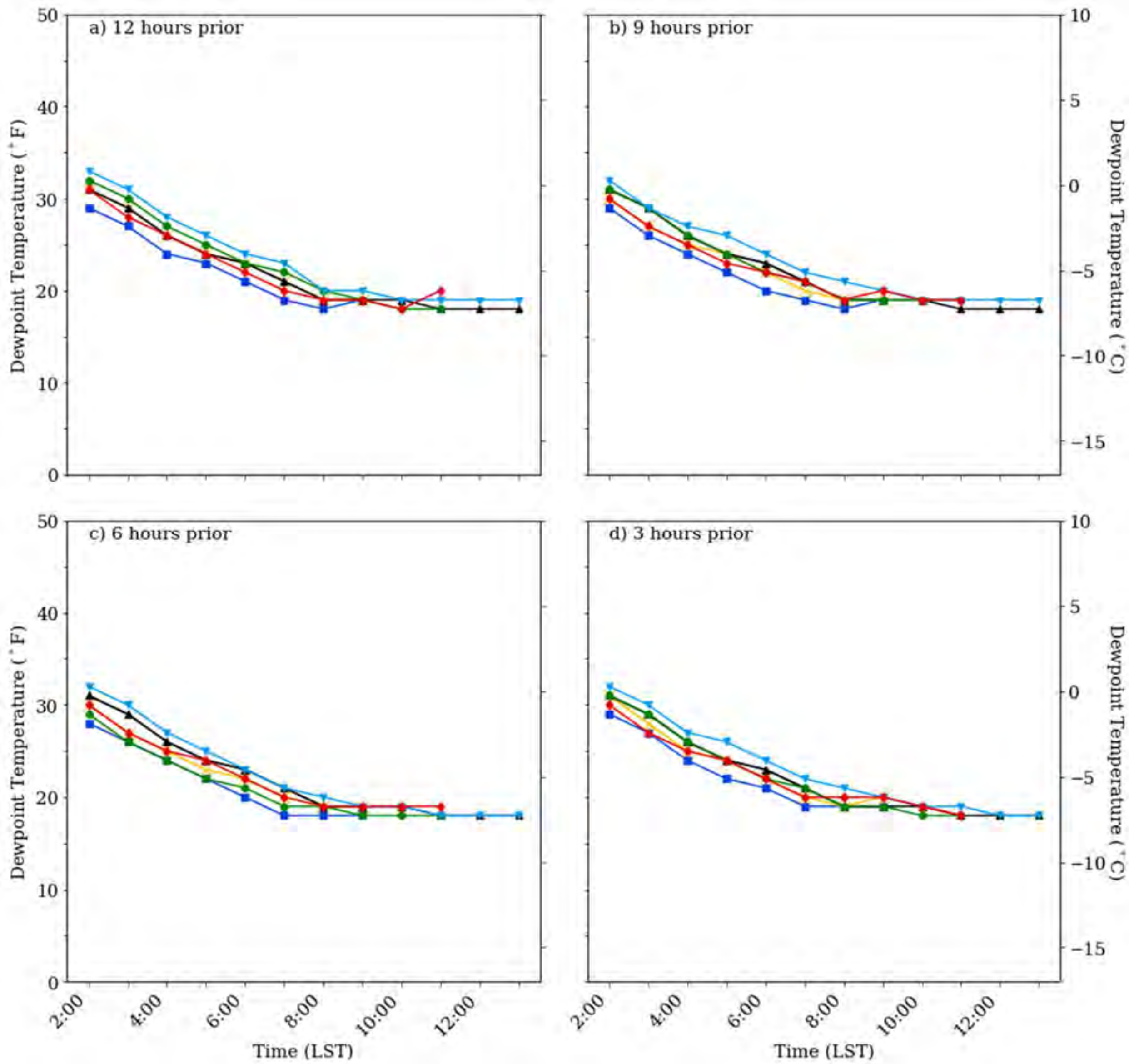


Figure 4.18: 24 November 2018 hourly dewpoint temperature forecasted by NDOT-MDSS at (a) 14 LST forecast run (12-hours prior to snowfall start), (b) 17 LST forecast run (9-hours prior to snowfall start), (c) 20 LST forecast run (6-hours prior to snowfall start), and (d) 23 LST forecast run (3-hours prior 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 start of snowfall to end of snowfall.

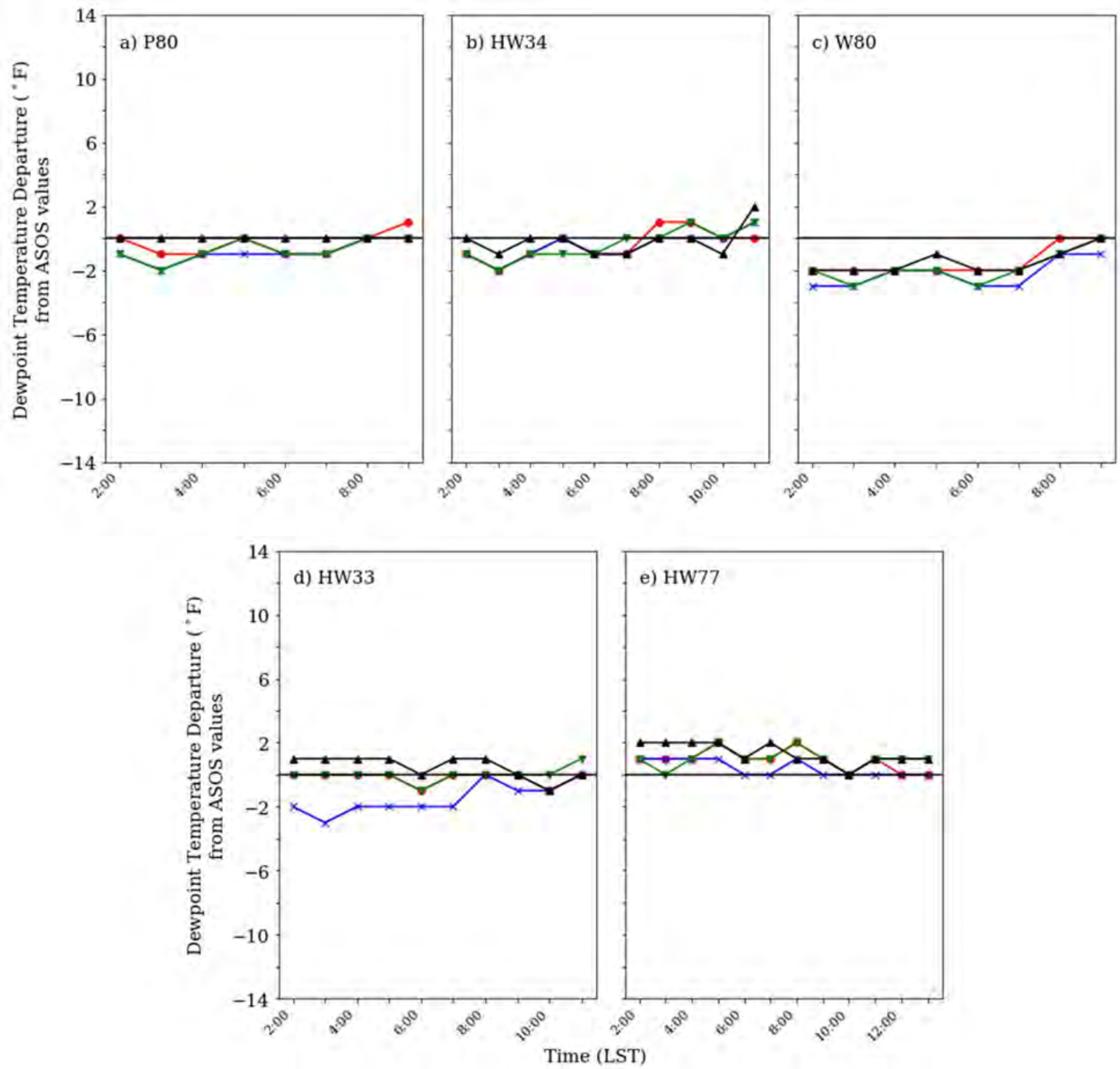


Figure 4.19: Difference graphs of the NDOT-MDSS forecasted dewpoint temperature departure for 24 November 2018 from the observed ASOS values at (a) P80, (b) HW34, (c) W80, (d) HW33, and (e) HW77 for 3-hours (red), 6-hours (blue), 9-hours (green), 12-hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

marginally more moisture led to 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 MDSS seems to have issues predicting the wind speed accuracy (Figures 4.20, 4.21). However, the largest deficits were for HW33 between the forecasted times with a swing in wind speeds around 6.9-9.2 mph. Routes P80, W80 and HW34 were all under forecasted in the speeds, though most were within 4.6 mph. The most accurate route was HW77. The forecast variations are in and of themselves rather nominal and did not indicate any preference to forecast time. 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 MDSS performed well.

A more introspective examination can be conducted by analyzing the data as a departure from ASOS. At W80 (Figures 4.17, 4.19, 4.21), it can be clearly seen that all three of the variables of temperature, dewpoint, and wind speed were under forecasted for the route. Temperature and dewpoint forecasts both improved as they converged toward the end of the event. On the other hand, wind speed was consistently under forecasted and never rebounded or increased in accuracy towards the ASOS values with time. The P80 departure schematics showed a different story. Forecasted values for temperature and dewpoint fell right around a departure value of zero with increasing accuracy across all runs as the event came to a close. The wind speed differential demonstrated the same consistency trend

The MDSS snowfall accumulation forecasts (Figure 4.22) and forecasted event length (Figures 4.23, 4.24) indicated consistency between the showcased routes. While the snowfall total accumulation values differed from route to route, the incremental increases and decreases by the forecast run follow a nearly identical pattern. The three-hour spike prior to snowfall onset was consistent across the routes

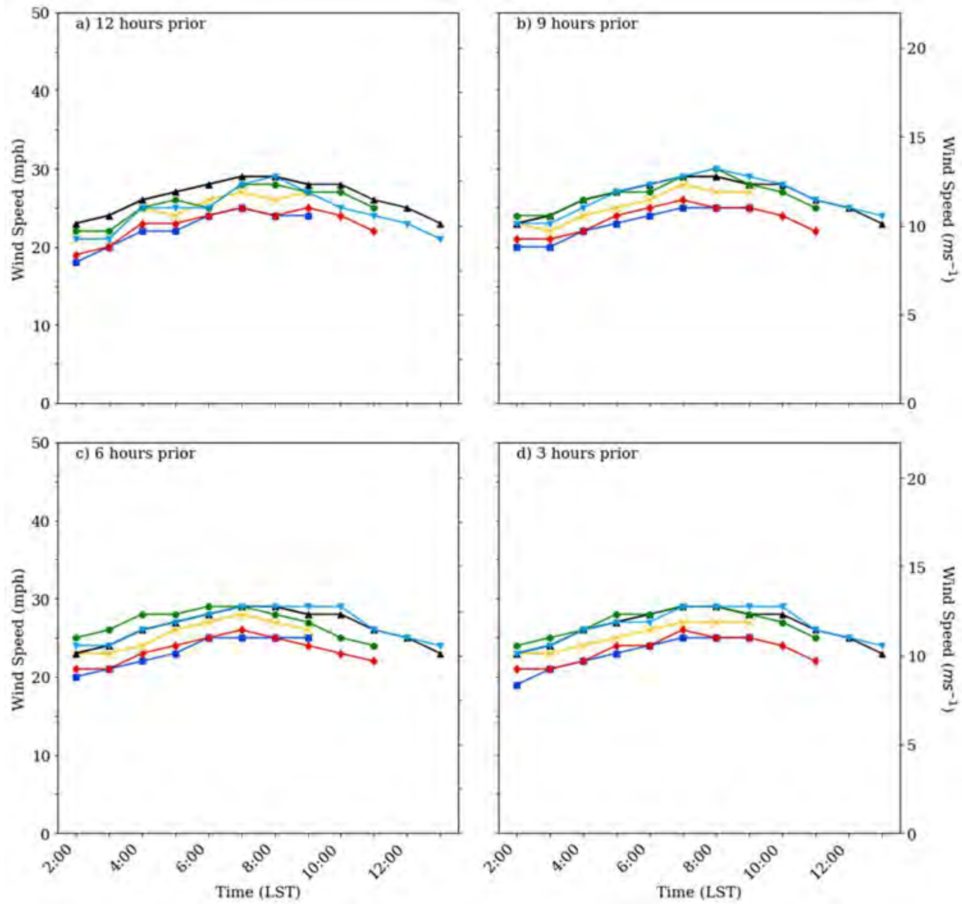


Figure 4.20: 24 November 2018 hourly wind speed forecasted by NDOT-MDSS at (a) 14 LST forecast run (12-hours prior to snowfall start), (b) 17 LST forecast run (9-hours prior to snowfall start), (c) 20 LST forecast run (6-hours prior to snowfall start), and (d) 23 LST forecast run (3-hours prior to snowfall start) for W80 (yellow), P80 (blue), HW34 (red), HW33 (green), and HW77 (light blue) compared to ASOS observed (black). Date and time run from start of snowfall to end of snowfall.

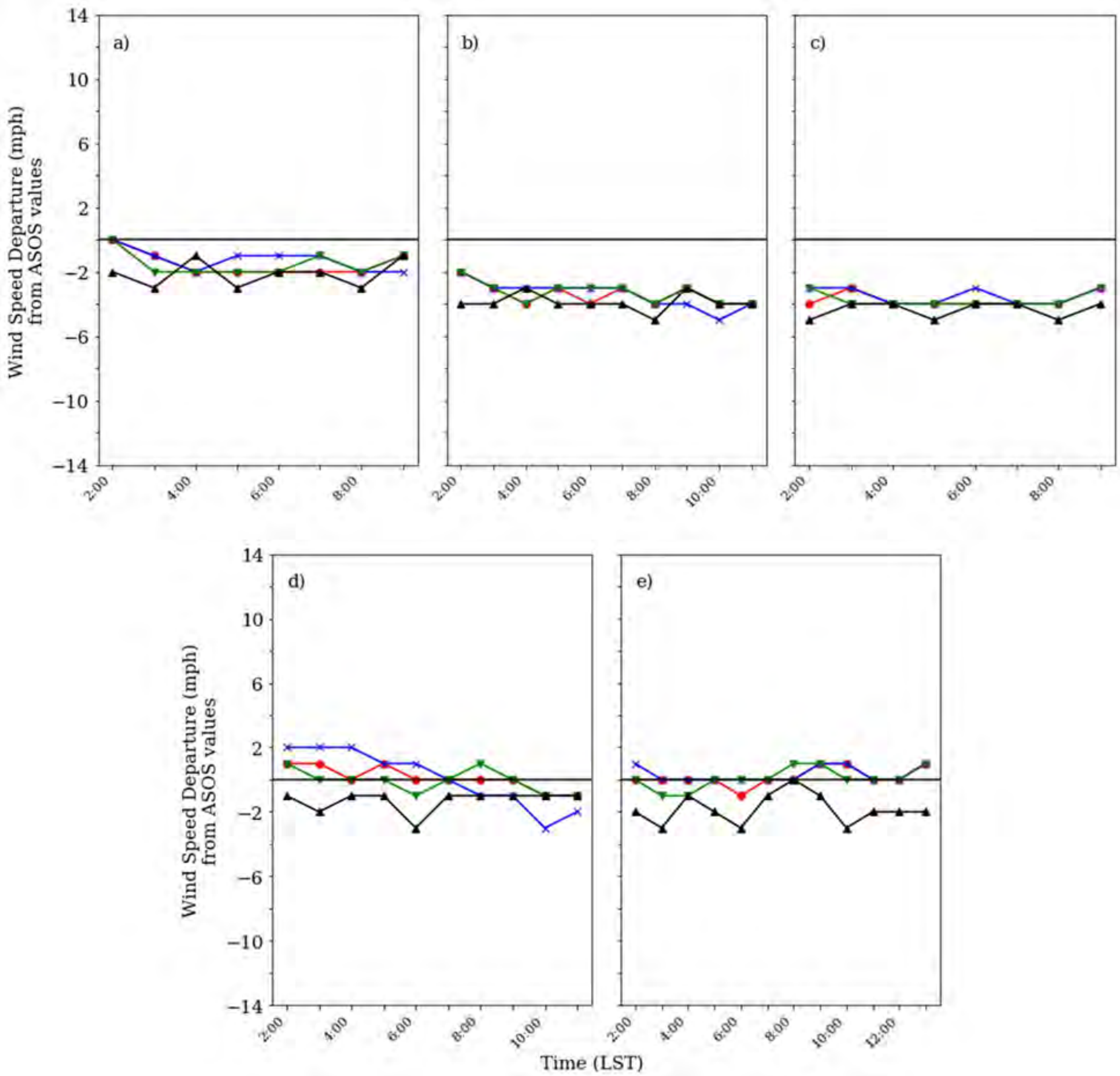


Figure 4.21: Difference graphs of the NDOT-MDSS forecasted wind speed departure for 24 November 2018 from the observed ASOS values at (a) P80, (b) HW34, (c) W80, (d) HW33, and (e) HW77 for 3-hours (red), 6-hours (blue), 9-hours (green), 12-hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

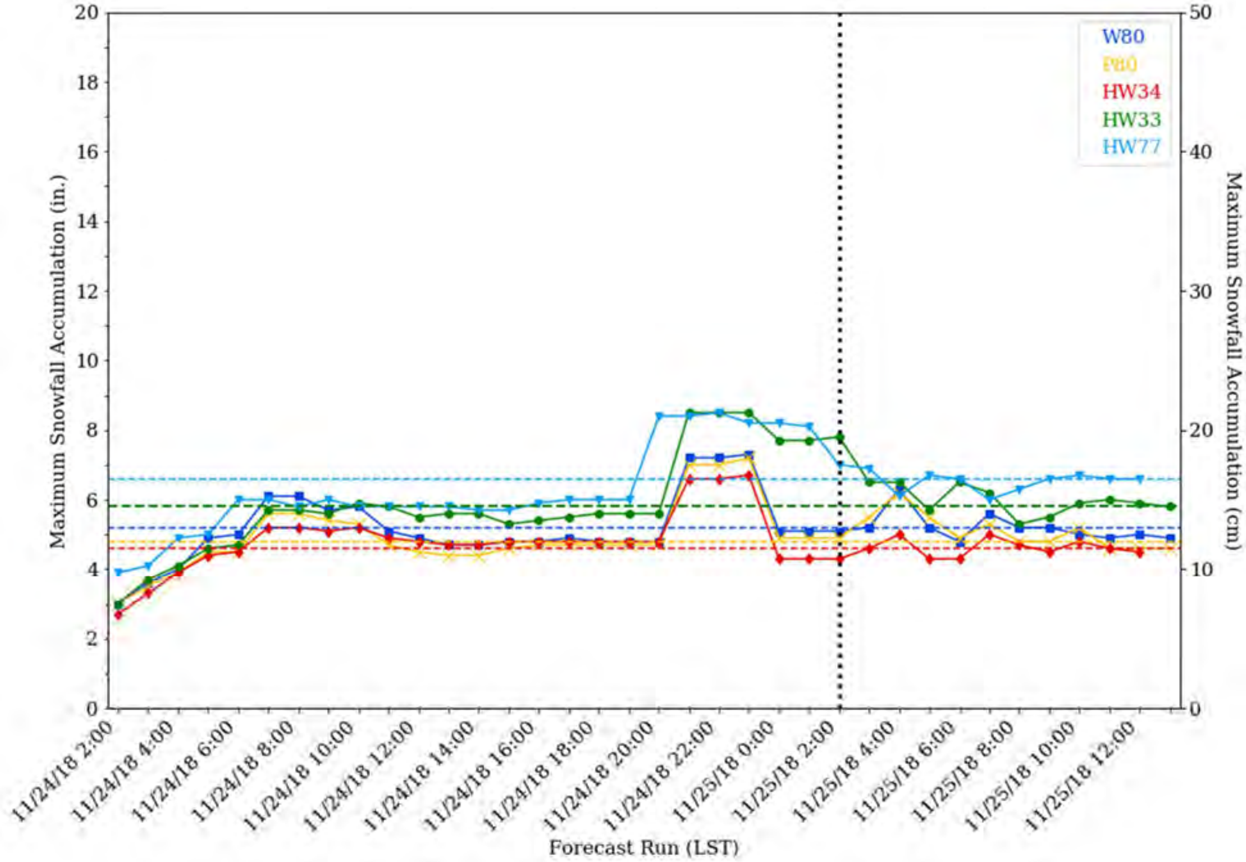


Figure 4.22: 24 November 2018 Maximum NDOT-MDSS forecasted snowfall accumulation for the individually observed routes per forecast run. The vertical dotted line denotes snowfall start time. The color-coded horizontal lines denote the final snowfall accumulation totals recorded at the snowfall end time for their corresponding routes.

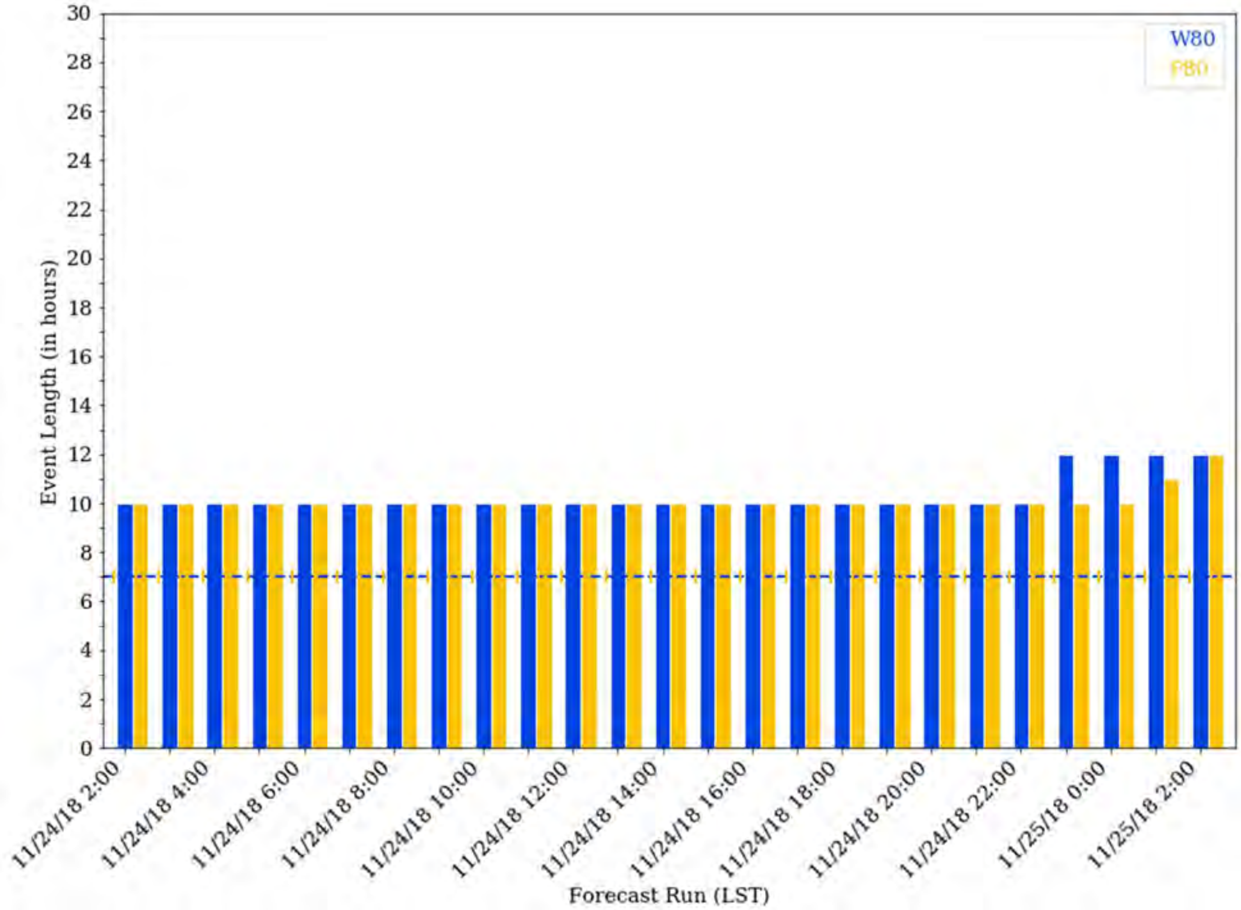


Figure 4.23: 24 November 2018 NDOT-MDSS forecasted event length for the W80 (yellow) and P80 (blue) I-80 interchanges per forecast run. The color-coded horizontal lines denote the final recorded event length for the corresponding routes.

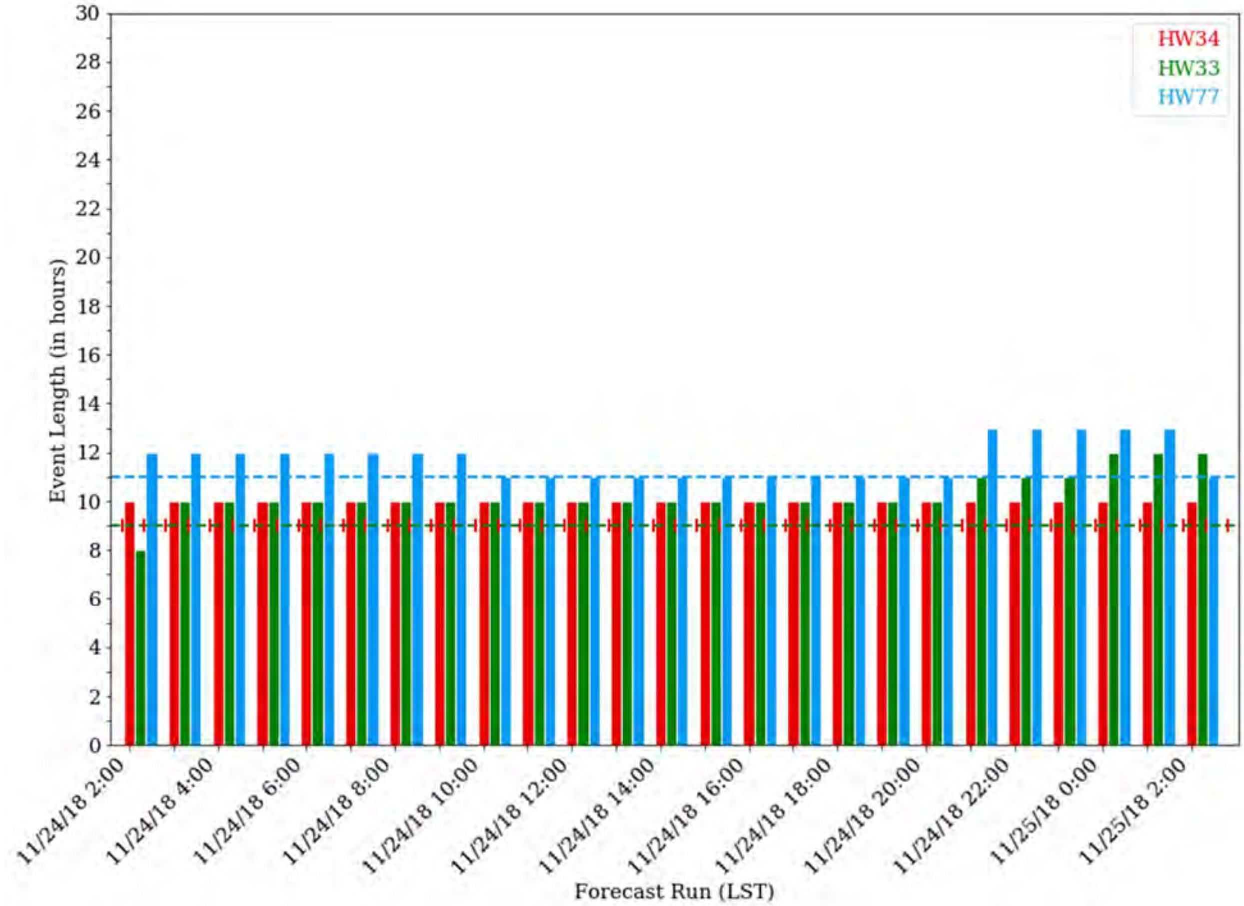


Figure 4.24: 24 November 2018 NDOT-MDSS forecasted event length for HW34 (red), HW33 (green), and HW77 (light blue) per forecast run. The color-coded horizontal lines denote the final recorded event length for the corresponding routes.

even though the increase in snowfall amount did not occur. Besides this three-hour spike, the NODT-MDSS predicted accurately the final snowfall accumulation well in advance of the event. This accuracy is directly caused by the MDSS seeing the event taking place and adjusting its forecast based upon real time observations. The generally similar relationships between the highway and interstate road sections are a positive signal that accentuates the consistency of the MDSS to produce forecasts for different routes in the same area. Even more so, the MDSS forecast followed the gradient of actual snowfall accumulation rather well with totals increasing from south to north (Figure 4.15).

The MDSS forecasted event length prior to and during the event illustrates a less than satisfactory story. A sound grasp as to the event length was not obtained until the snowfall had ended for the interstate road sections (Figure 4.23). The forecasted event length was within two to five hours of the actual event length up until the end of the event. The highway routes (Figure 4.24) exhibited a much higher degree of accuracy across the forecast runs with variations between two to three hours compared to the observed event length. The differential graphs for event end time (observed end time - forecasted end time) aid in identifying whether the variation produced by the forecast was a product of the MDSS incorrectly forecasting for the start or end time (Figure 4.25). The event length graphs showed that the MDSS over forecasted across all of the routes and the differential graphs for the northern routes (W80, P80, HW34) all show that the MDSS over forecasted the end time for this event. The HW33 route oscillated around zero across much of the forecast period while the HW77 route moved between a one hour over forecast and a correct forecast throughout. Both routes correctly forecasted the end time six hours prior to the snowfall ending. From this, it can be easily seen that where the MDSS had the greatest issues forecasting event length corresponded with the MDSS over forecasting the end time for this November event. Even though the margin of variation was not out of reason, the event length is important in drafting maintenance protocols for any given event.

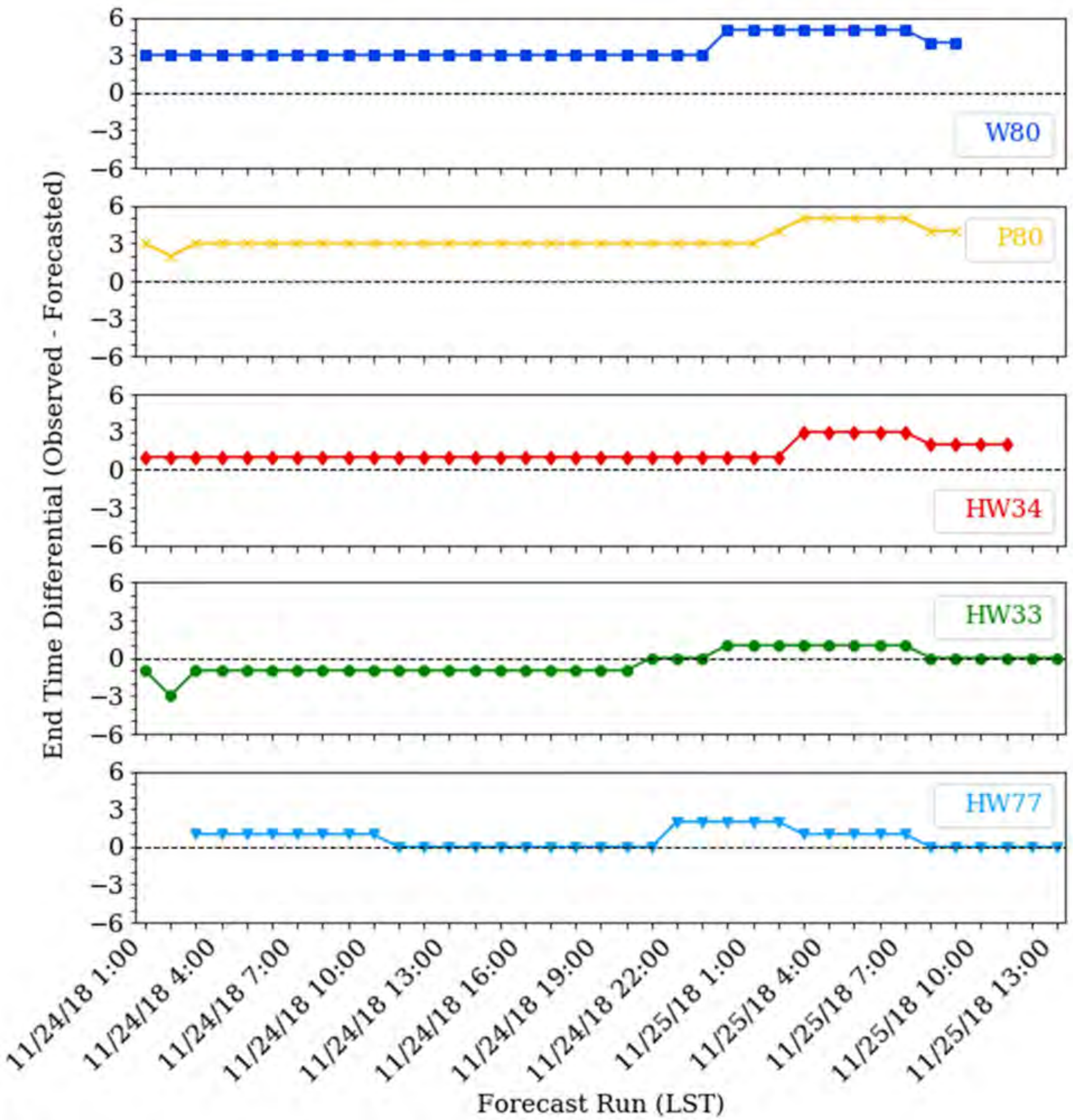


Figure 4.25: 24 – 25 November 2018 snowfall end time difference graphs for the five observed routes from the NDOT-MDSS.

Knowledge of how long maintenance crews may need to be out maintaining the roadways as well as when snowfall is going to begin are critical in designating times for maintenance to begin and end.

Snowfall accumulation forecasts were further compared against the NWS zone forecasts for Lancaster County and ASOS observed snowfall for the Lincoln airport as well as the GFS, 12km NAM, 4km NAM, RAP, and their model average for KLNK at a 12:1 SLR value for the November event (Figure 4.26). The 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 approach illustrates the forecast of the MDSS before the snowfall begins which eliminates the possible corrections that take place as the MDSS sees the snowfall in real time. These snowfall analyses for November were conducted between 02 LST 24 November 2018 and 02 LST 25 November 2018, which encapsulated forecasts at least 24 hours prior to the snowfall onset

Overall, the snowfall accumulation for the November event (Figure 4.22) was forecasted well across the board. The ASOS observed snowfall accumulation for the event was 3.6 inches and is used as the final snowfall accumulation total that is being compared against. The first finding that stands out is the difference in the MDSS final recorded snowfall for each of the road segments compared to the ASOS snowfall total. The snowfall analysis (Figure 4.22) all show final snowfall accumulations of at least 1.0 inch higher 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 at HW34, 1.2 inches at P80, and 1.6 inches at W80.

Model output for the November event was a bit erratic. The GFS was by far the model that was over forecasting total snowfall accumulation for the event (Figure 4.26). Both of the NAM

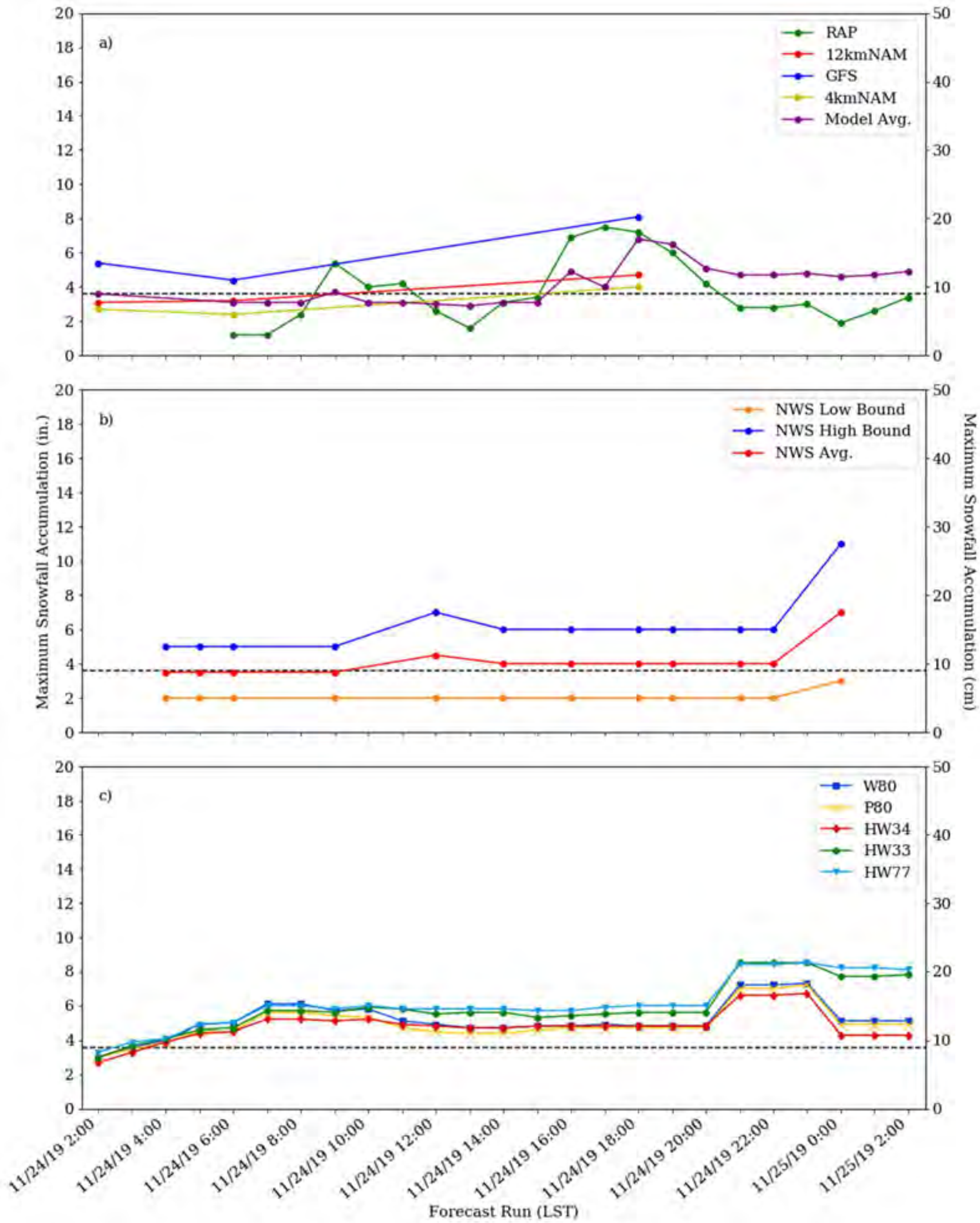


Figure 4.26: 24 – 25 November 2018 case study forecasted snowfall accumulation composite for: a) weather models (RAP, 12kmNAM, GFS, 4kmNAM), b) National Weather Service zone forecast product, c) the NDOT-MDSS.

models also performed well up until the 6 LST 25 November 2018 runs, where both models began to under forecast extensively. The model average ultimately performed well yet was also at the mercy of any drastic changes. For instance, when the GFS and RAP both spiked around the 18 LST 25 November 2018 run, the model average also skewed to its highest point above the ASOS value. When compared against the zone forecast for Lancaster County, the models fell well within the range of snowfall accumulations forecasted by the NWS. One issue with using the zone forecast by county from the NWS is that the snowfall totals are at the mercy of 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 00 LST forecast from the NWS, the same spike in snowfall totals was forecasted by the MDSS as well (Figure 4.26). As illustrated by the NWS observed snowfall plot (Figure 4.15), the axis of highest snowfall totals fell to the southeast of Lincoln/Lancaster County. The model spike in snowfall accumulation can most likely be attributed to all of the models attempting to accurately place the region of highest snowfall accumulation that would affect the southeastern Nebraska region.

### 4.2.b 19-20 February 2019 event

The 19-20 February 2019 case study was also a Colorado low type pressure system which impacted Lincoln with a moderate amount of snow (Figure 4.27). Snow began around at 16 LST 19 February after moving into the region from the southwesterly direction. Snow lasted until 11 LST on 20 February. The NEWINS values also indicate the heavy snowfall which occurred with high NEWINS values in District 1, 2, 3, and 4 (Table 4.1). District 1's value could have easily been much higher, if the value only was for

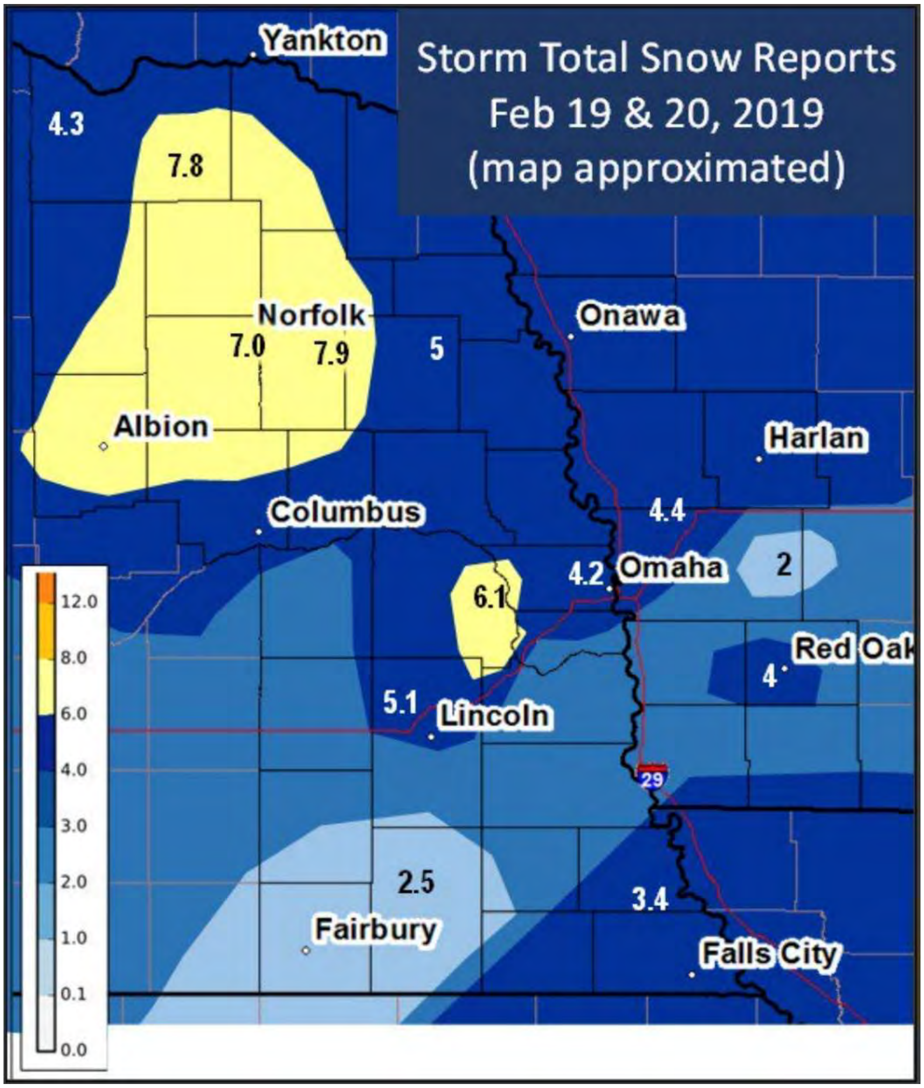


Figure 4.27: Total snowfall accumulation map across the NWS Omaha CWA for 19-20 February 2019 (from NWS Omaha/Valley).

Lincoln. However, the District 1 NEWINS value is reduced because of the lesser amounts of snowfall reported in the southern and southeastern portions of the district (Figure 4.27).

For this event, MDSS forecasted temperatures ranged from 17-27 $^{o}$F, while ASOS observed values varied from 21-26 $^{o}$F (Figure 4.28) for the routes. These colder temperatures highlight that for this Colorado low event, precipitation type was not an issue. For all forecast runs, temperatures for each route were too warm during the start of the snowfall event through the middle of the event (Figure 4.29). From the middle of the event to the end of snowfall, forecasted temperatures were colder than what was observed. Of all the segments examined, HW77 had the highest forecasted temperatures than any other segment (Figure 4.28), which should be expected with the movement of the system.

Analysis of MDSS dewpoint temperatures reveals a range of 15-23 F $^{o}$ during the snowfall period compared ASOS observation from 15-20 $^{o}$F (Figure 4.30), mirroring the temperature forecasts (Figure 4.28), since the two are related. As expected, dewpoint temperatures also are forecasted to be too high (Figure 4.31) for all model runs during the onset of the snowfall. Towards the end of the event, dewpoint temperatures are lower from observed conditions, except for HW77, which is consistently overpredicted for the entire length of the event.

Wind speeds during the event are highly variable for ASOS (Figure 4.32) though the MDSS forecasts are steadier. HW34 produced the slowest wind speeds, while HW33 and HW77 produced the strongest for most of the snowfall hours. Forecasted winds for all cases generally started off stronger in the beginning of snowfall and became less in magnitude towards the end of the event. When the difference in wind speeds from the forecasted to the observed are calculated, the pattern becomes very erratic for all routes (Figure 4.33). There is remarkable consistency which with each forecast run for each route in this event (Figure 4.32).

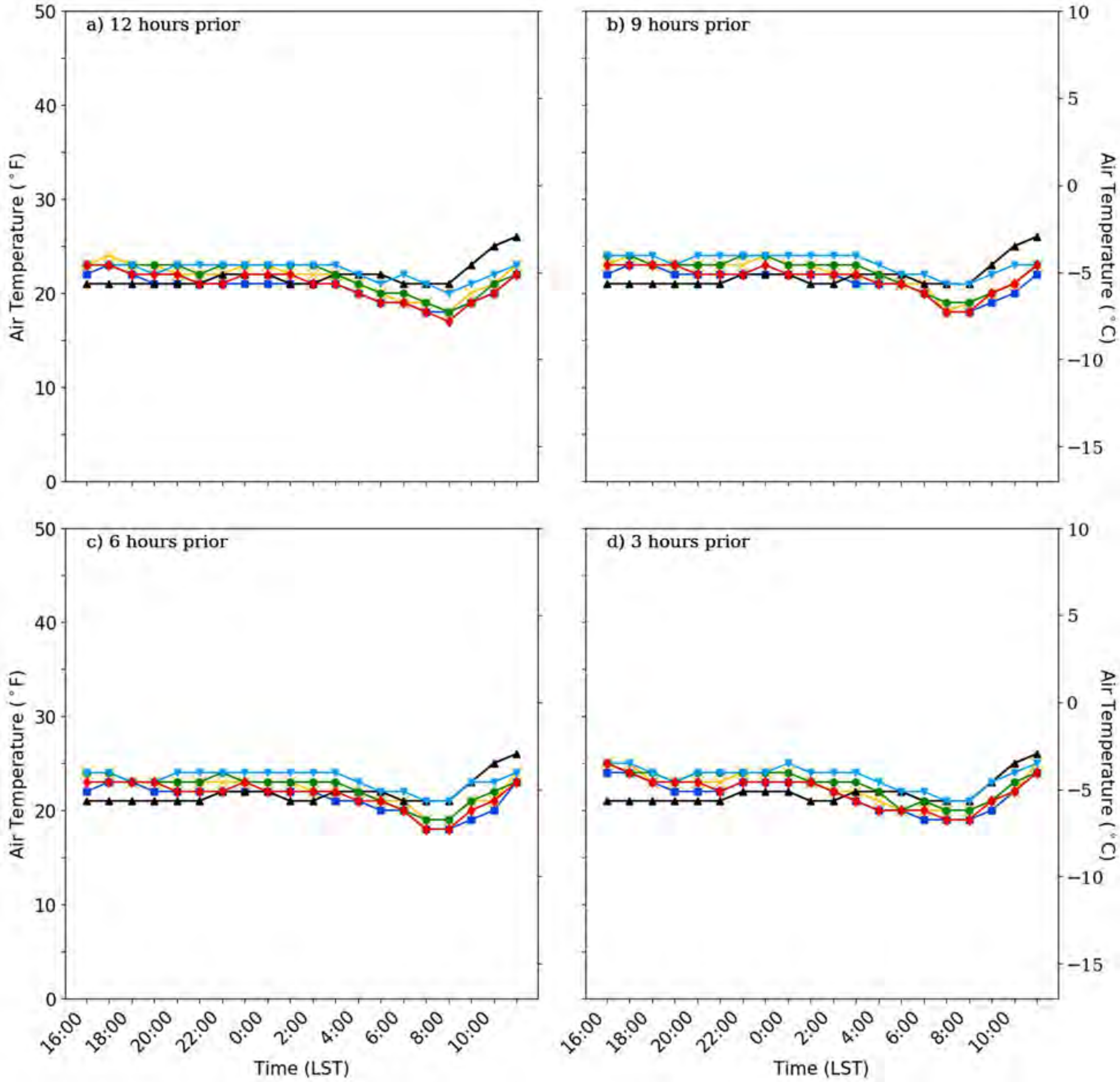


Figure 4.28: 20 February 2019 hourly temperature forecasted by NDOT-MDSS at (a) 13 LST forecast run (12-hours prior to snowfall start), (b) 16 LST forecast run (9-hours prior to snowfall start), (c) 19 LST forecast run (6-hours prior to snowfall start), and (d) 22 LST forecast run (3-hours prior to snowfall start) for W80 (yellow), P80 (blue), HW34 (red), HW33 (green), and HW77 (light blue) compared to ASOS observed (black). Date and time run from start of snowfall to end of snowfall.

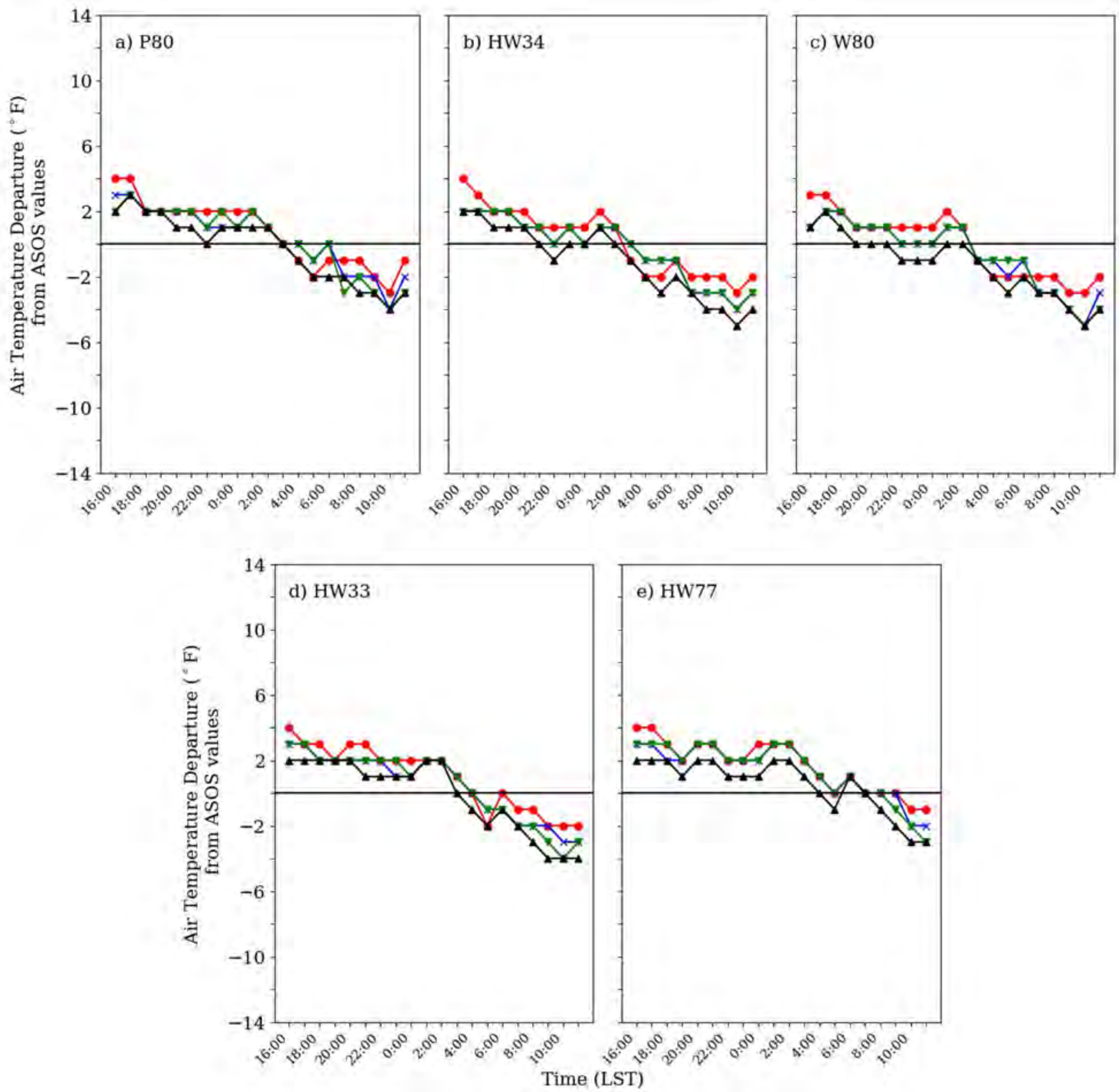


Figure 4.29: Difference graphs of the MDSS forecasted temperature departure for 20 February 2019 from the observed ASOS values at (a) W80, (b) P80, (c) HW34, (d) HW33, and (e) HW77 for 3-hours (red), 6-hours (blue), 9-hours (green), 12-hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

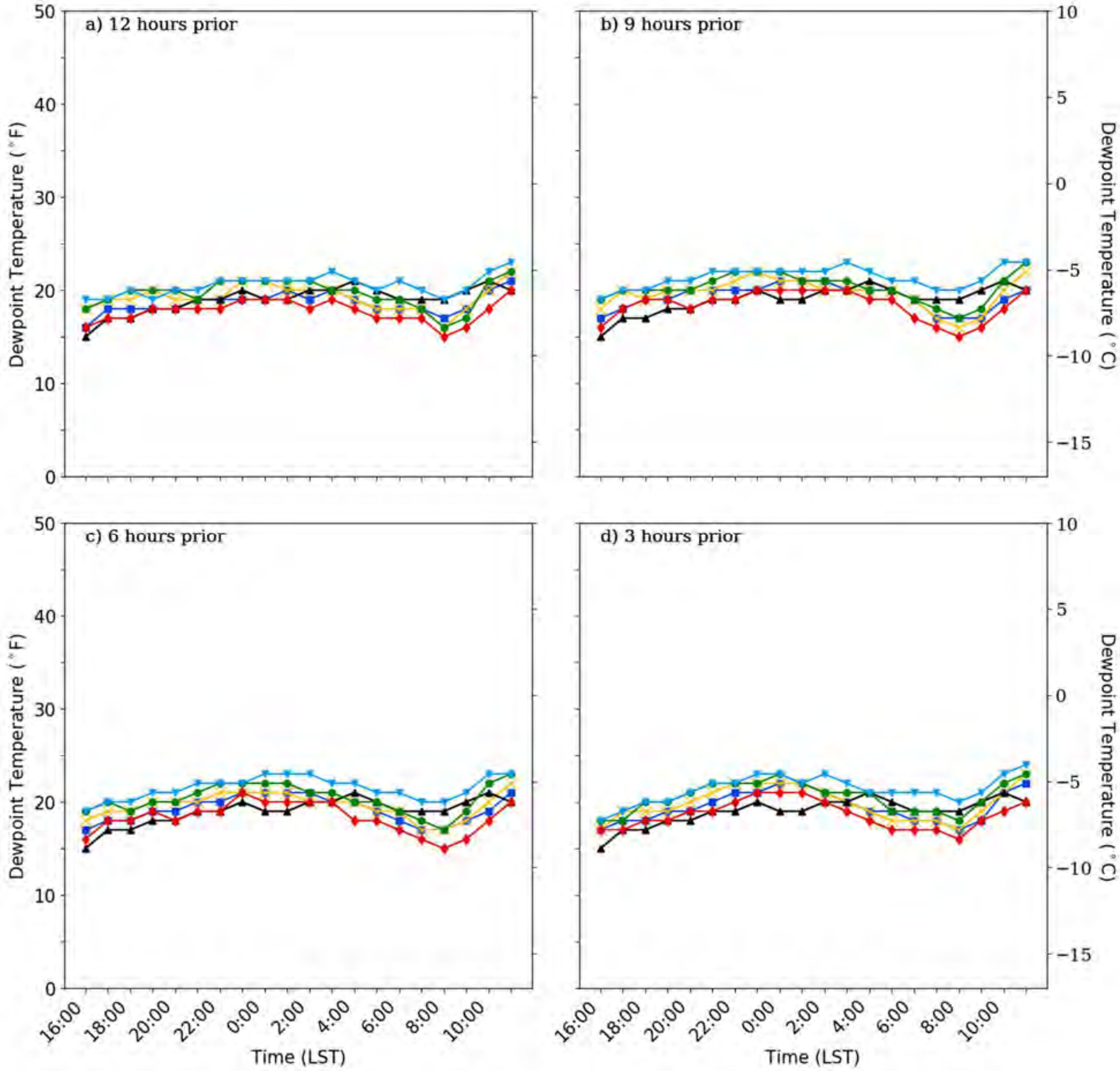


Figure 4.30: 20 February 2019 hourly dewpoint temperature forecasted by NDOT-MDSS at (a) 13 LST forecast run (12-hours prior to snowfall start), (b) 16 LST forecast run (9-hours prior to snowfall start), (c) 19 LST forecast run (6-hours prior to snowfall start), and (d) 22 LST forecast run (3-hours prior 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 start of snowfall to end of snowfall.

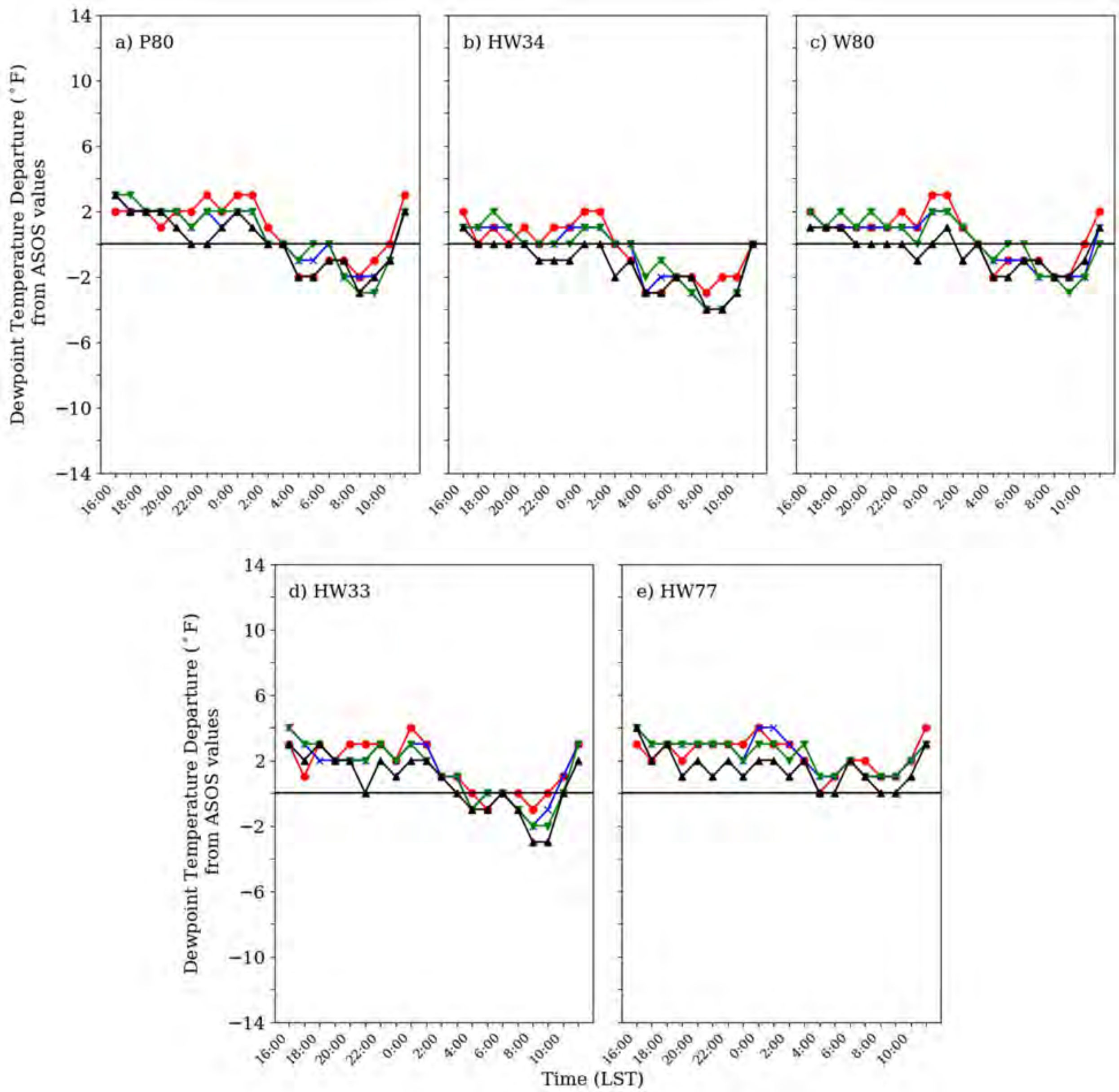


Figure 4.31: Difference graphs of the MDSS forecasted dewpoint temperature departure for 20 February 2019 from the observed ASOS values at (a) W80, (b) P80, (c) HW34, (d) HW33, and (e) HW77 for 3-hours (red), 6-hours (blue), 9-hours (green), 12-hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

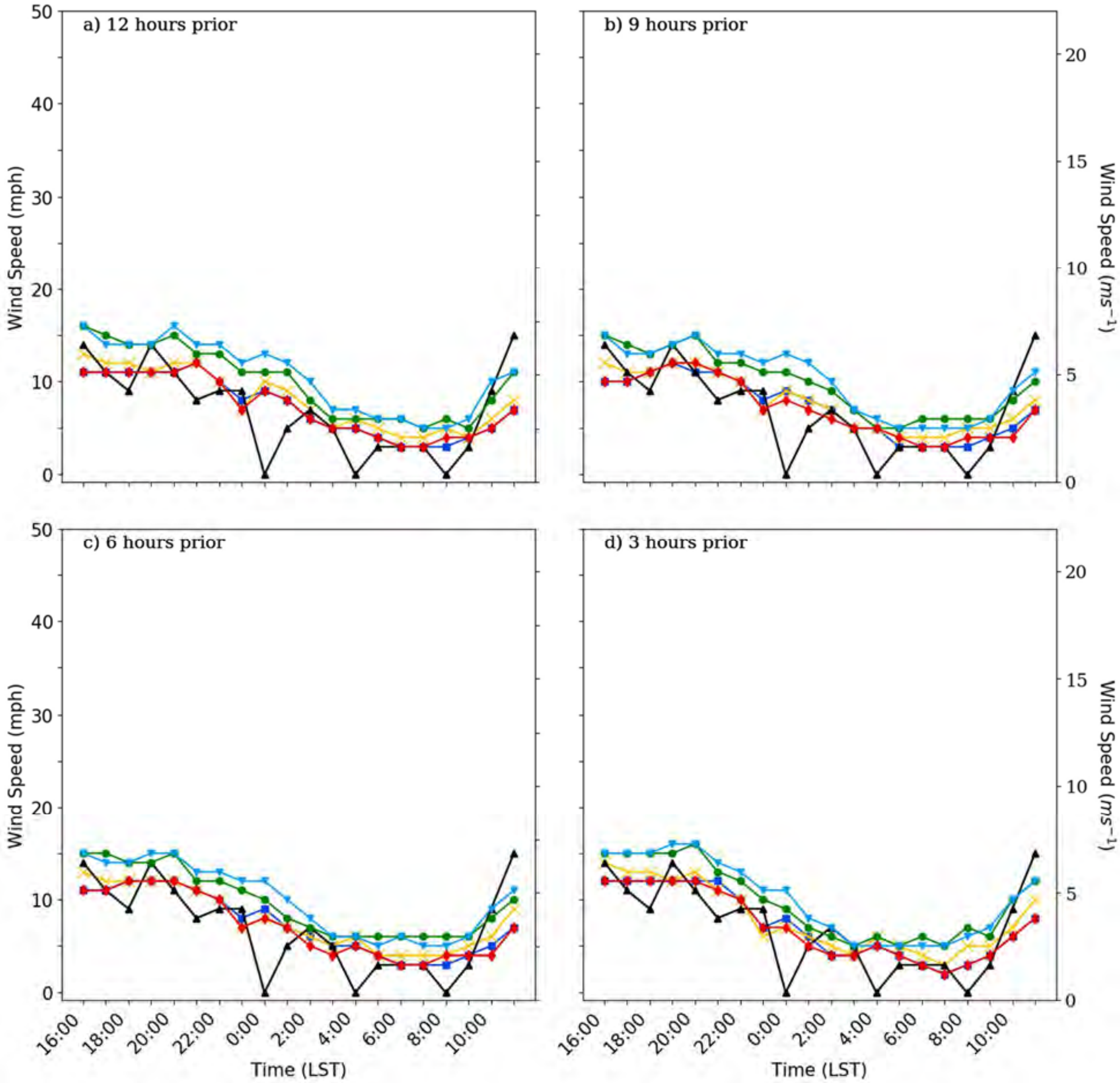


Figure 4.32: 20 February 2019 hourly wind speed forecasted by NDOT-MDSS at (a) 13 LST forecast run (12-hours prior to snowfall start), (b) 16 LST forecast run (9-hours prior to snowfall start), (c) 19 LST forecast run (6-hours prior to snowfall start), and (d) 22 LST forecast run (3-hours prior to snowfall start) for W80 (yellow), P80 (blue), HW34 (red), HW33 (green), and HW77 (light blue) compared to ASOS observed (black). Date and time run from start of snowfall to end of snowfall.

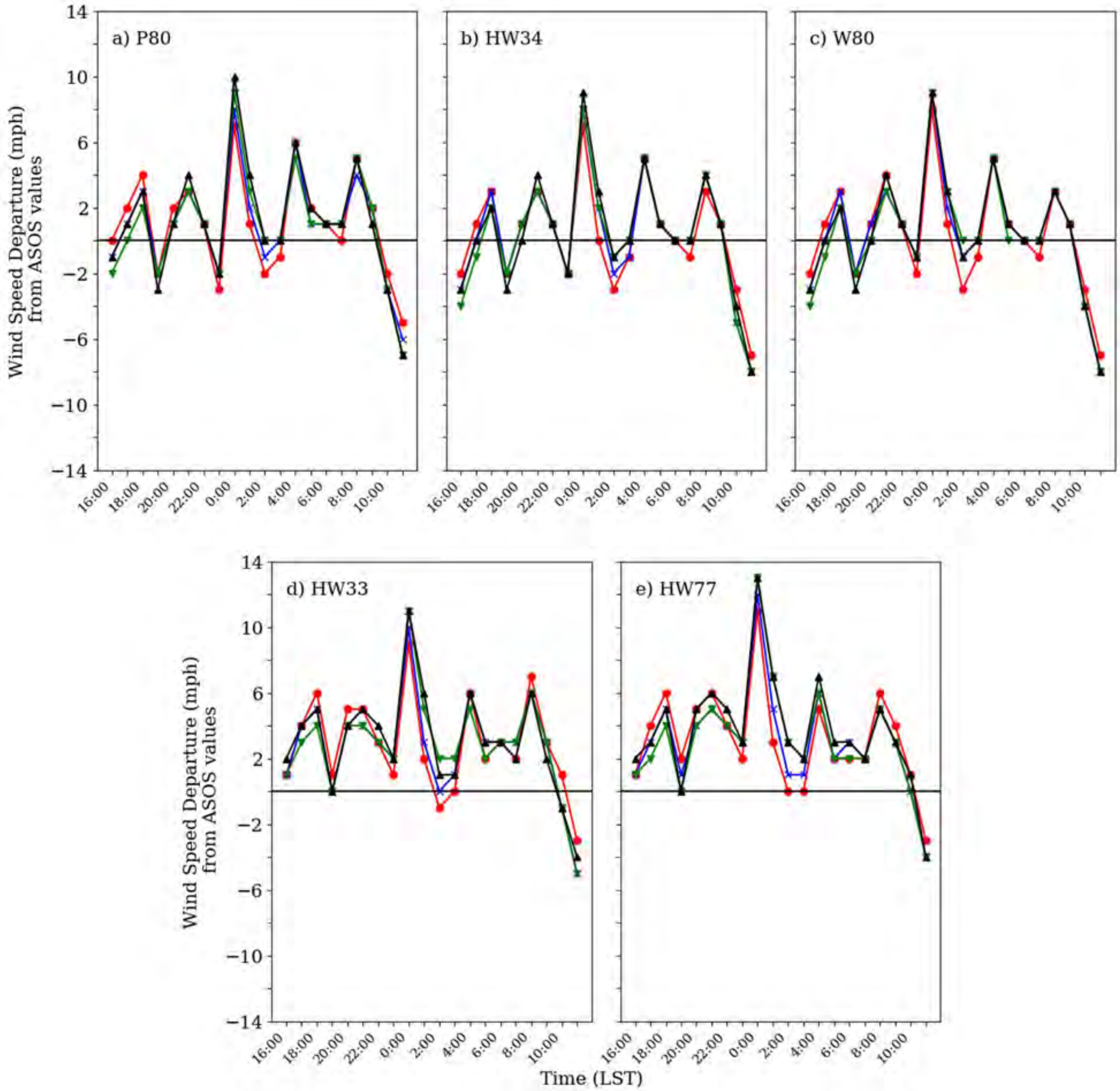


Figure 4.33: Difference graphs of the MDSS forecasted wind speed departure 20 February 2019 from the observed ASOS values at (a) W80, (b) P80, (c) HW34, (d) HW33, and (e) HW77 for 3-hours (red) for 3-hours (red), 6-hours (blue), 9-hours (green), 12-hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

The 19-20 February event saw an amount of 5.1 inches of snow total from system recorded by the Lincoln Airport ASOS (Figure 4.27). The MDSS model forecasts for the amount of snow were generally over forecasted the accumulation (Figure 4.34). Once the snowfall began, the forecasted amounts were closer to what was observed. From the start, to end of the snowfall, the period of snow for the event was 19 hours for all road segments (Figures 4.35, 4.36). For every segment, MDSS overpredicts the event length of which snowfall will fall by two to ten hours or more. Forecasted event length is particular bad for HW33, HW34, and P80 where at least 28 hours of snowfall is predicted compared to the 18 hours observed. The minimum amount of time forecasted is 21 hours, again compared to the actual 18 hours of snowfall. Comparing the forecasting ending time of snowfall to the observed time for each model runs, MDSS shows it will continue to snow for at least an hour after snowfall stops (Figure 4.37). The most accurate forecast for this event is HW77 which has several correct stop times.

MDSS snowfall accumulation forecasts times except one were over forecasting the amount of snowfall for each route compared to the ASOS observation (Figure 4.38). The MDSS forecast accumulations are also compared to the NWS zone forecasts for Lancaster County, where the NWS also over forested the snowfall accumulations. For this case, all numerical weather models (GFS, 12k NAM, 4km NAM, RAP) leading up to the start of snow under forecasted snow accumulation compared to ASOS. Of these models, the GFS does the worst, while the 4km NAM did better for this event.

### 4.2.c 23-24 February 2019 event

The 23-24 February event transitioned from freezing rain and sleet to snow during the late morning on 23 February. By the time the event was over, there was a distinct band of heavy snow

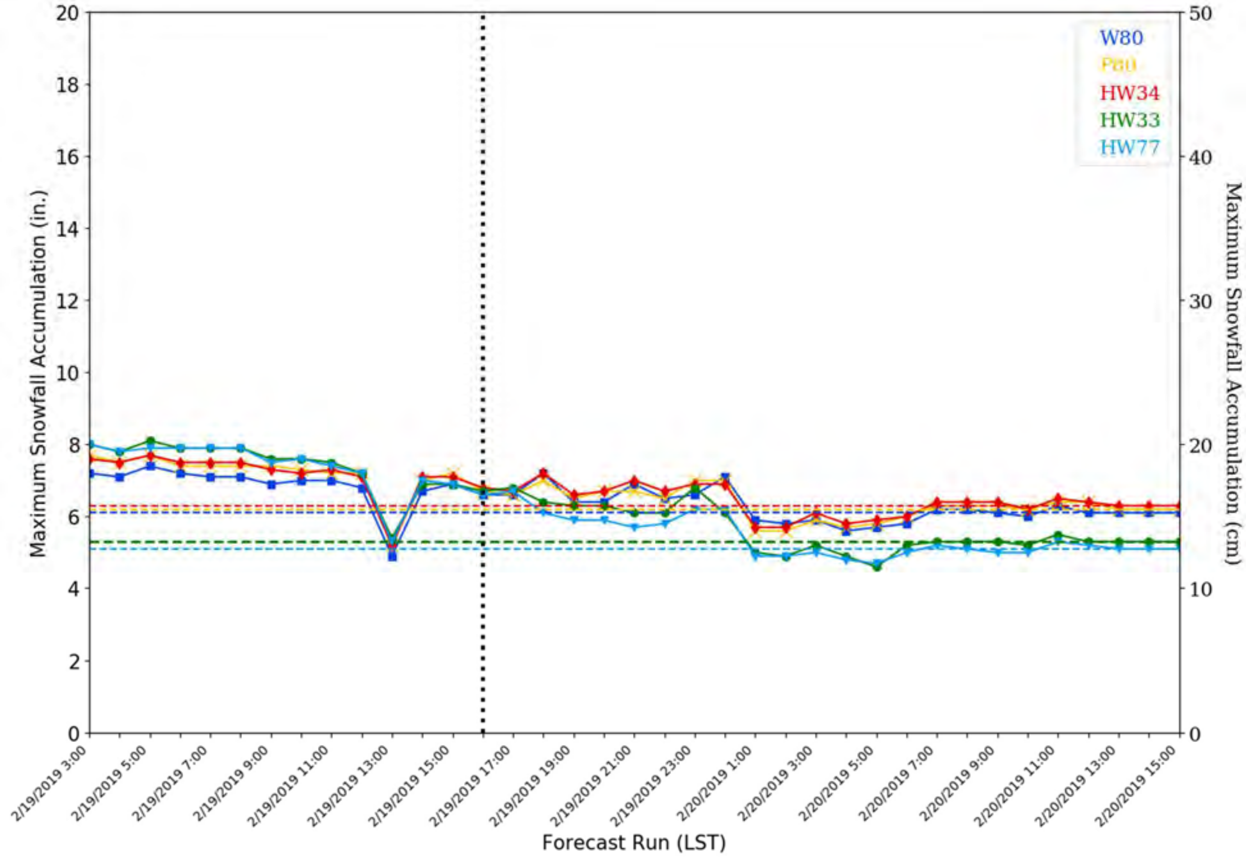


Figure 4.34: 19-20 February 2019 Maximum MDSS forecasted snowfall accumulation for the individually observed routes per forecast run. The vertical dotted line denotes snowfall start time. The color-coded horizontal lines denote the final snowfall accumulation totals recorded at the snowfall end time for their corresponding routes.

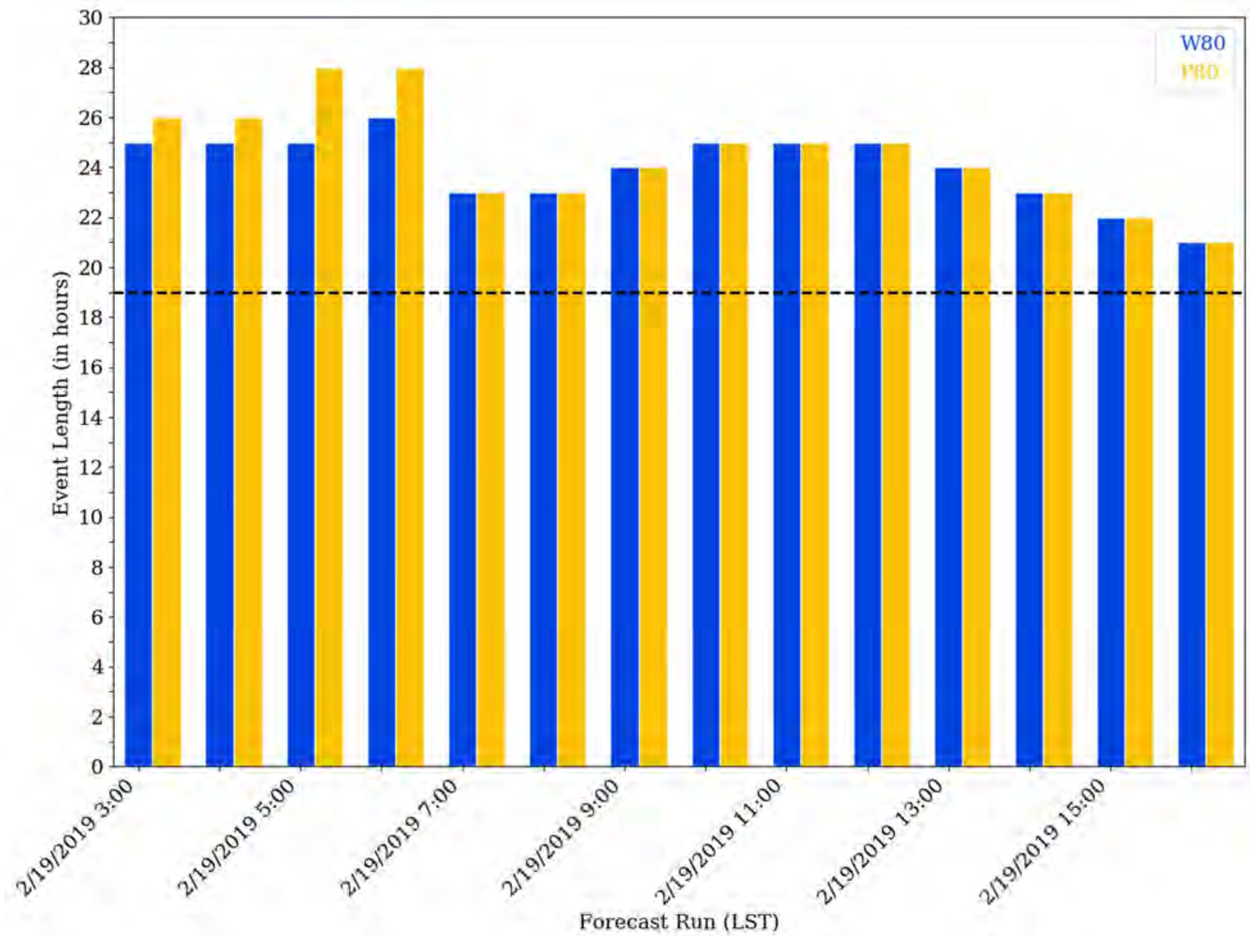


Figure 4.35: 20 February 2019 MDSS forecasted event length for the W80 (yellow) and P80 (blue) I-80 interchanges per forecast run. The color-coded horizontal lines denote the final recorded event length for the corresponding routes.

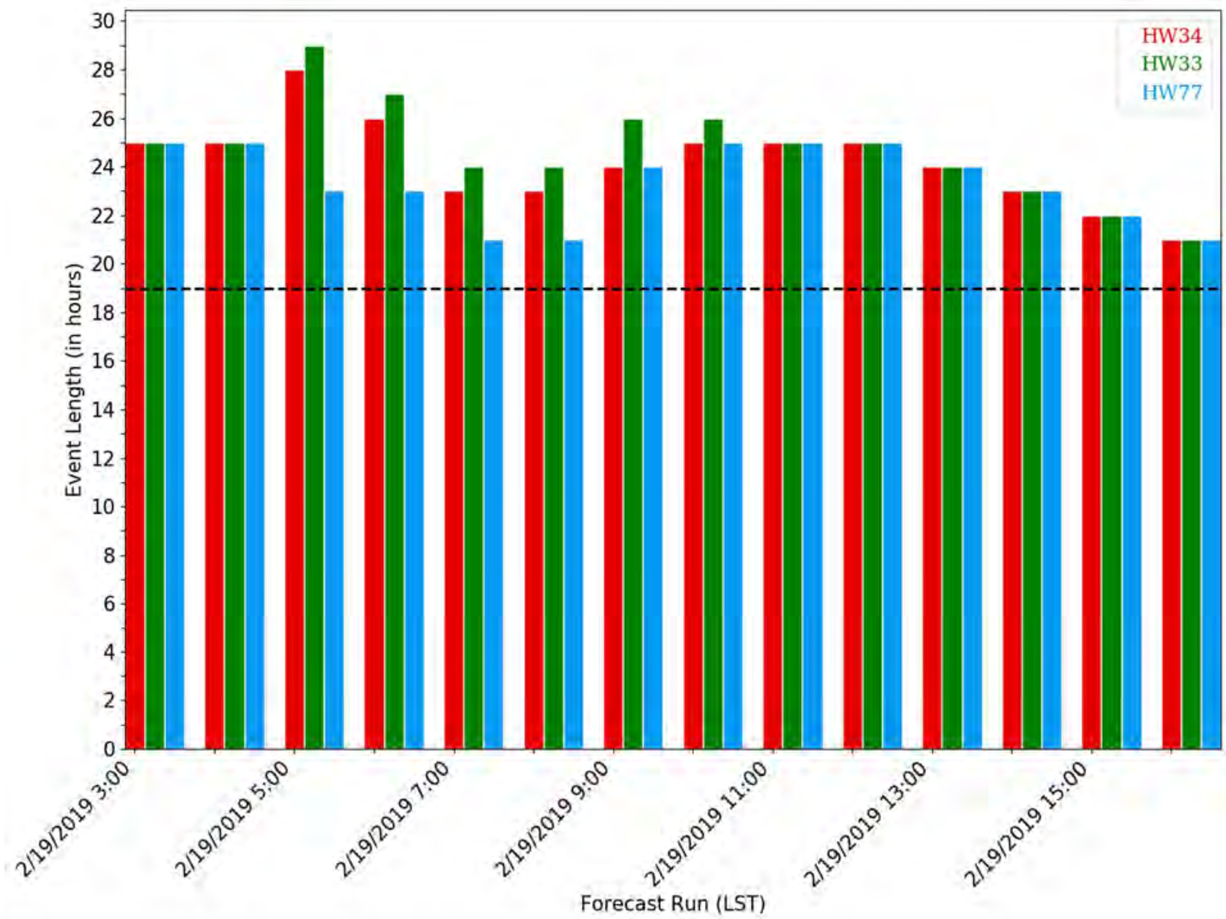


Figure 4.36: 20 February 2019 MDSS forecasted event length for HW34 (red), HW33 (green), and HW77 (light blue) per forecast run. The color-coded horizontal lines denote the final recorded event length for the corresponding routes.

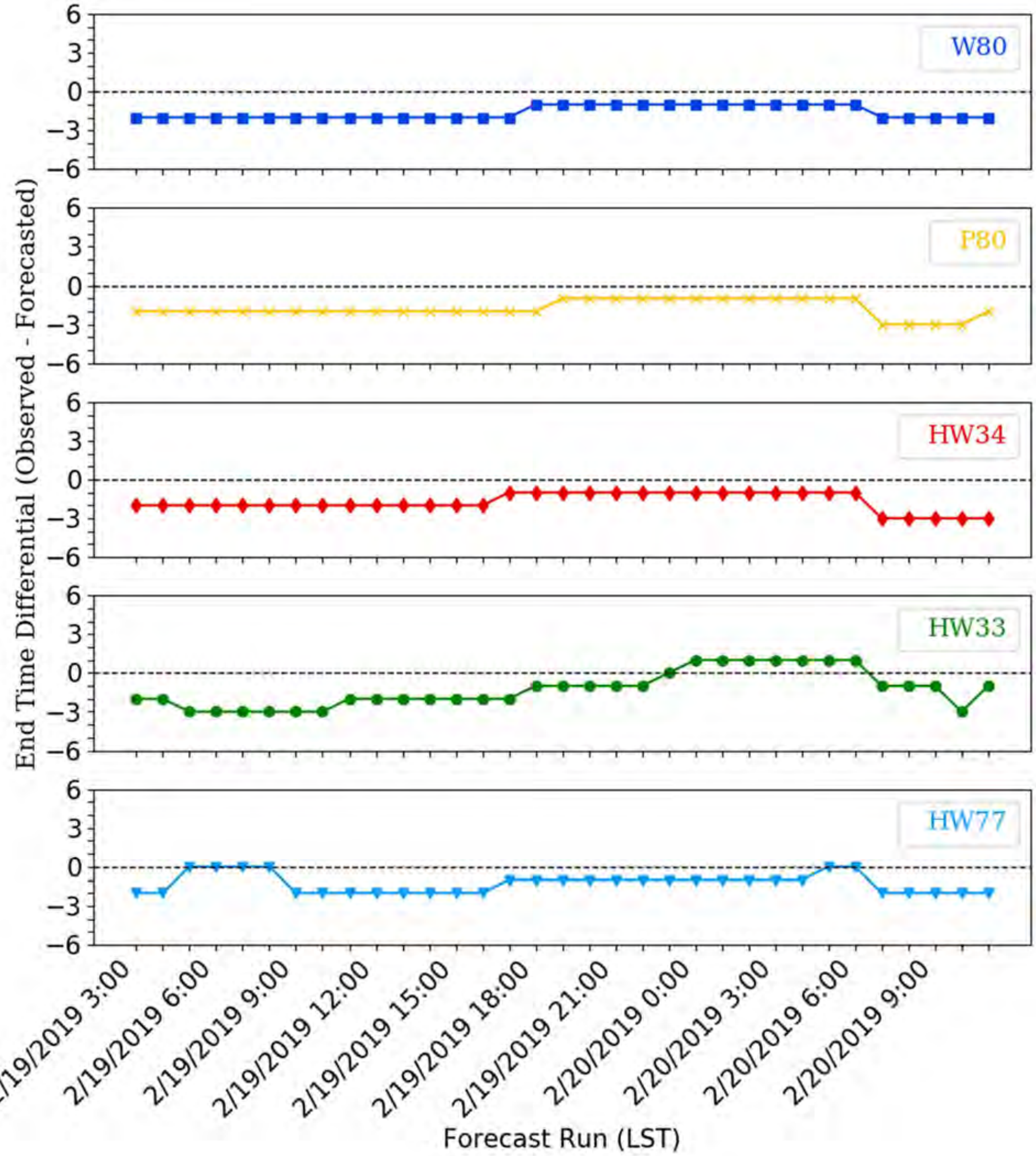


Figure 4.37: 20 February 2019 snowfall end time difference graphs for the five observed routes from the MDSS.

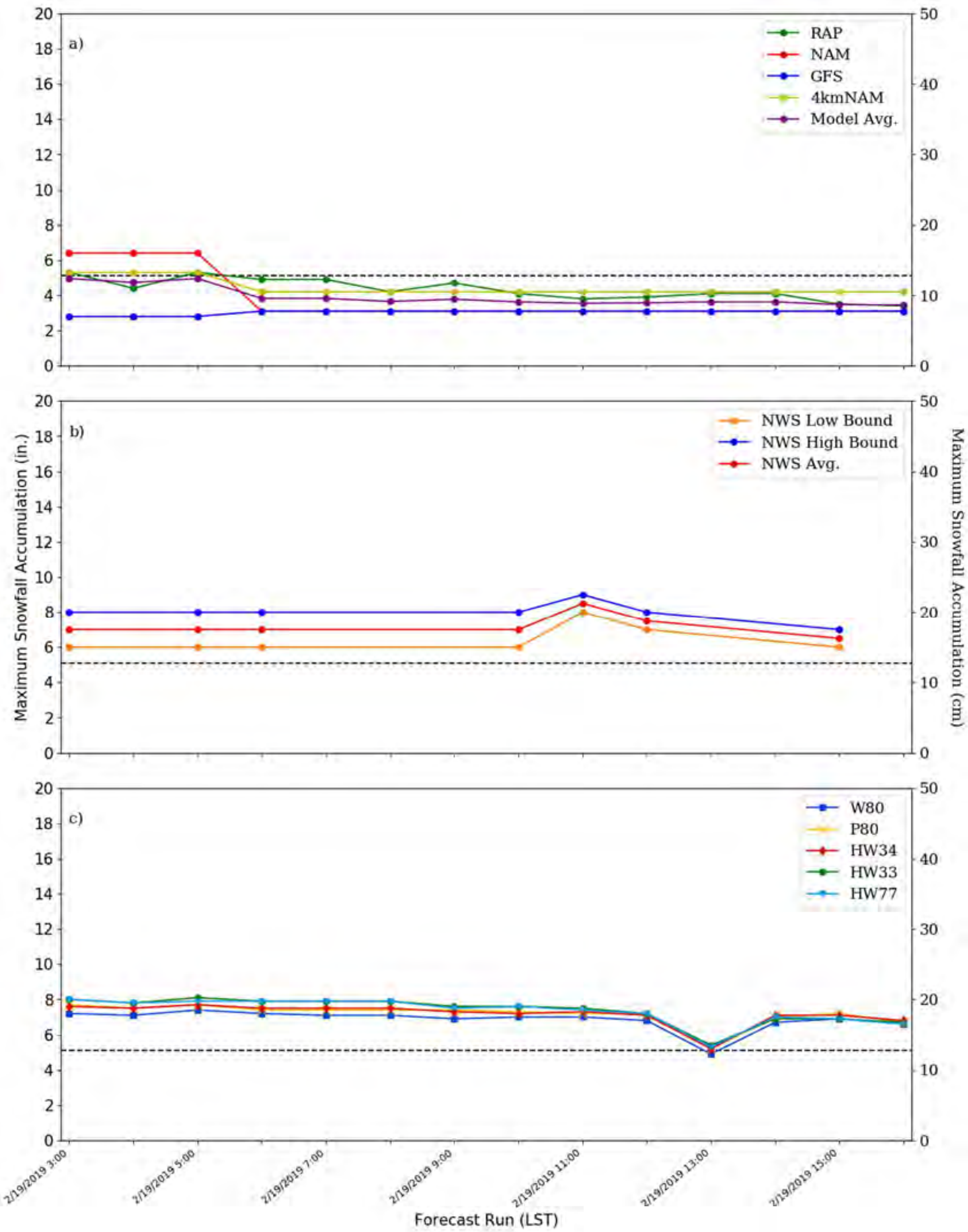


Figure 4.38: 20 February 2019 case study forecasted snowfall accumulation composite for: a) weather models (RAP, 12kmNAM, GFS, 4kmNAM), b) National Weather Service zone forecast product, c) the MDSS.

observed along the Interstate 80 corridor (Figure 4.39). More specifically, a sharp gradient from northwest to southeast occurred with 12.0 inches of snowfall recorded northeast of Lincoln to around 3.0 inches near Falls City. This sharp gradient also affected the NEWINS values for District 1. The largest NEWINS value for District 1 was a value of 4 (Table 4.1). If only Lincoln was considered for the NEWINS value, the value would have been much higher. However, the NEWINS values are determined for the whole district, and since the southeastern portion did not receive the heavy snowfall the District 1 value was only a 4, compared to 6 value for District 2 just to the north. Conditions along the heaviest snow band probably warranted a 6 value in the northern part of District 1.

The MDSS consistently forecasted warmer air temperature values for the February event across all of the forecast times for the routes (Figure 4.40). The forecast temperatures for the W80 route clearly had the larger variations for the different time periods than the other routes and 12-hours prior was arguably more accurate than the 9-hour forecast (Figure 4.41). In general, air temperature forecasts for all the routes followed a similar progression, with temperature forecasts for all hours being better in the earlier part of the storm compared to later in the event.

Dewpoint temperature forecasts by MDSS were all under forecasted compared to the actual values for all routes (Figure 4.42) The W80 route again had the largest variations across all forecast times compared to the other routes. However, the dewpoint temperature variations (Figure 4.43) throughout the event stayed about the same over the event with a sudden drop in dewpoint temperatures for the last few hours of the event. The over forecasted temperatures in conjunction with the under forecasted dewpoint temperatures could be interpreted as the MDSS forecasting for much drier conditions and therefore less snowfall accumulation amounts, except, as will be documented later, this was not the case, more snowfall was actually forecasted.

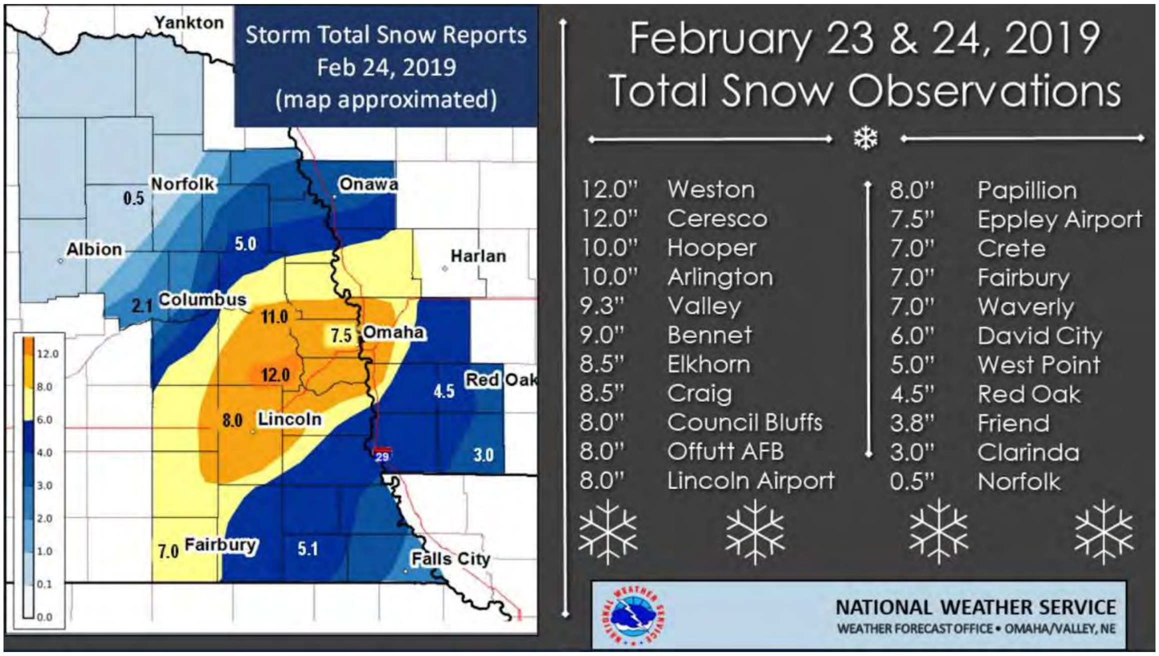


Figure 4.39: Total snowfall accumulation map across the NWS Omaha CWA for 23-24 February 2019 (from NWS Omaha/Valley).

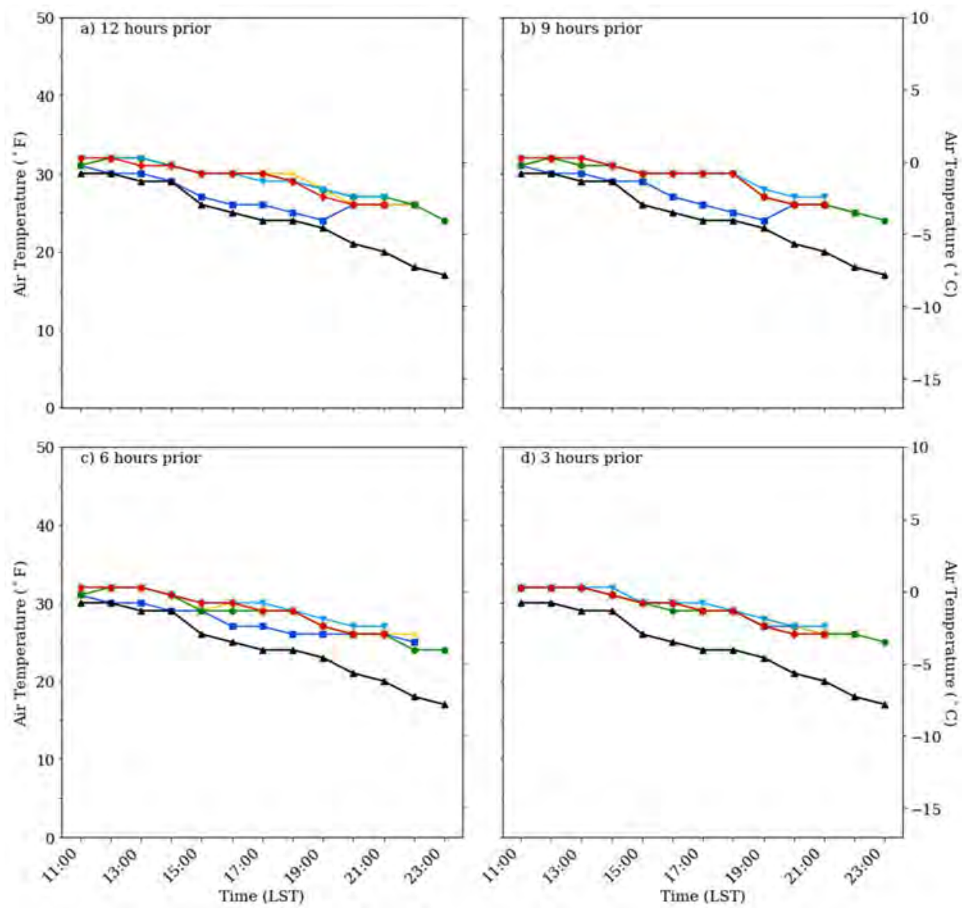


Figure 4.40: 23 – 24 February 2019 hourly temperature forecasted by NDOT-MDSS at (a) 23 LST forecast run (12-hours prior to snowfall start), (b) 2 LST forecast run (9-hours prior to snowfall start), (c) 5 LST forecast run (6-hours prior to snowfall start), and (d) 8 LST forecast run (3-hours prior to 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 start of snowfall to end of snowfall.

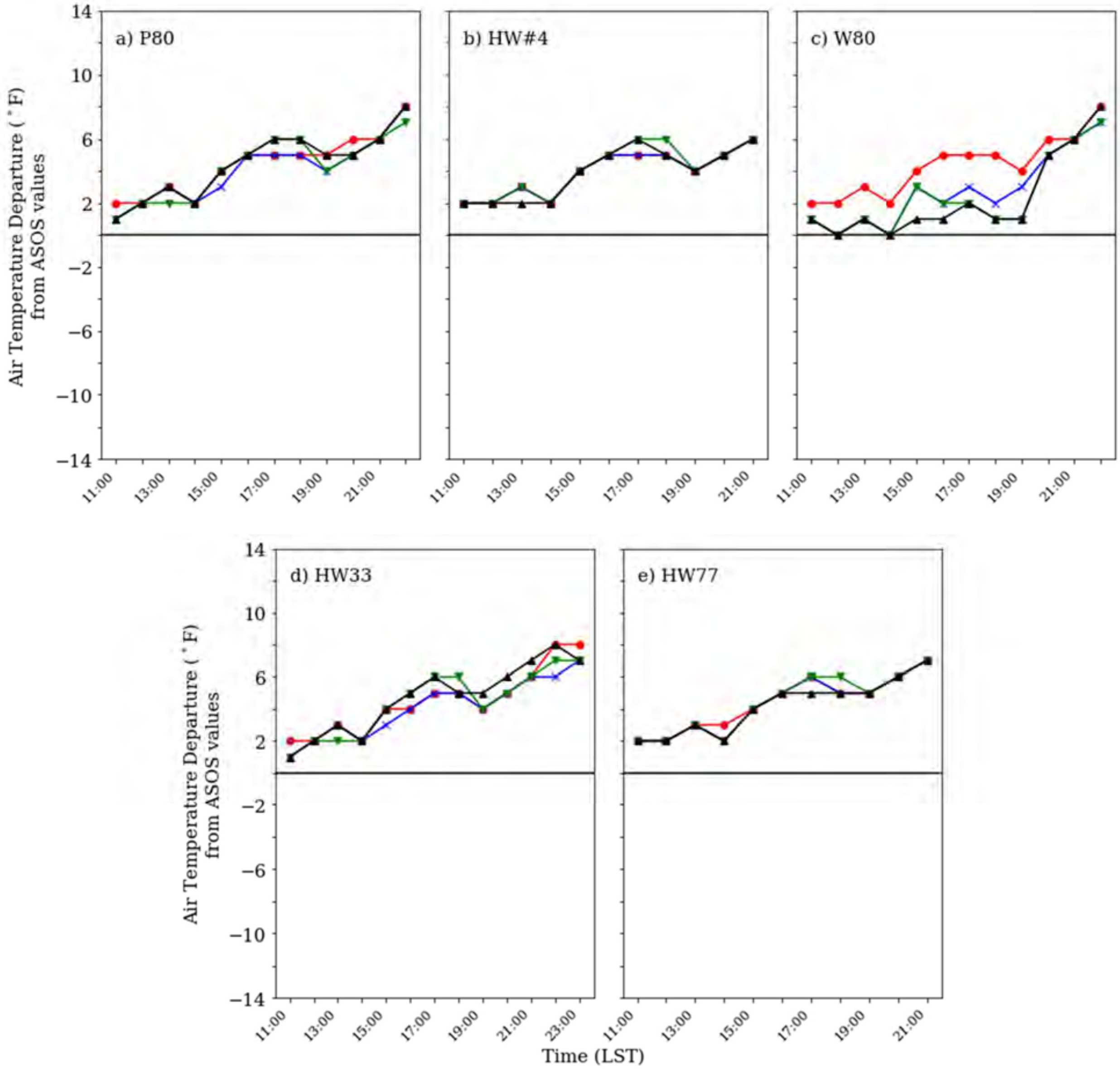


Figure 4.41: Difference graphs of the MDSS forecasted temperature departure for 23 – 24 February 2019 from the observed ASOS values at (a) W80, (b) P80, (c) HW34, (d) HW33, and (e) HW77 for 3-hours (red) for 3-hours (red), 6-hours (blue), 9-hours (green), 12-hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

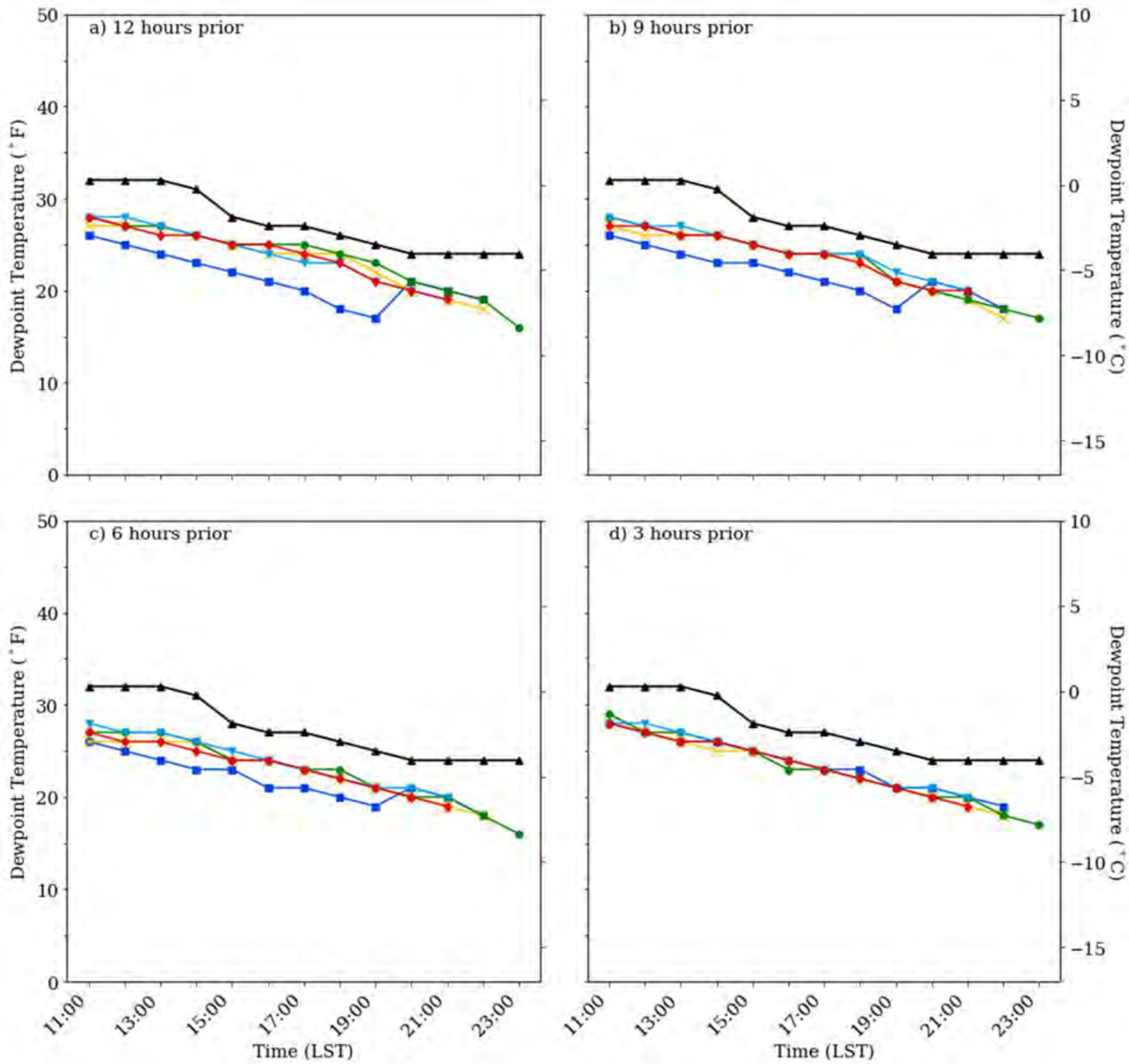


Figure 4.42: 23 – 24 February 2019 hourly dewpoint temperature forecasted by NDOT-MDSS at (a) 23 LST forecast run (12-hours prior to snowfall start), (b) 2 LST forecast run (9-hours prior to snowfall start), (c) 5 LST forecast run (6-hours prior to snowfall start), and (d) 8 LST forecast run (3-hours 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 start of snowfall to end of snowfall.

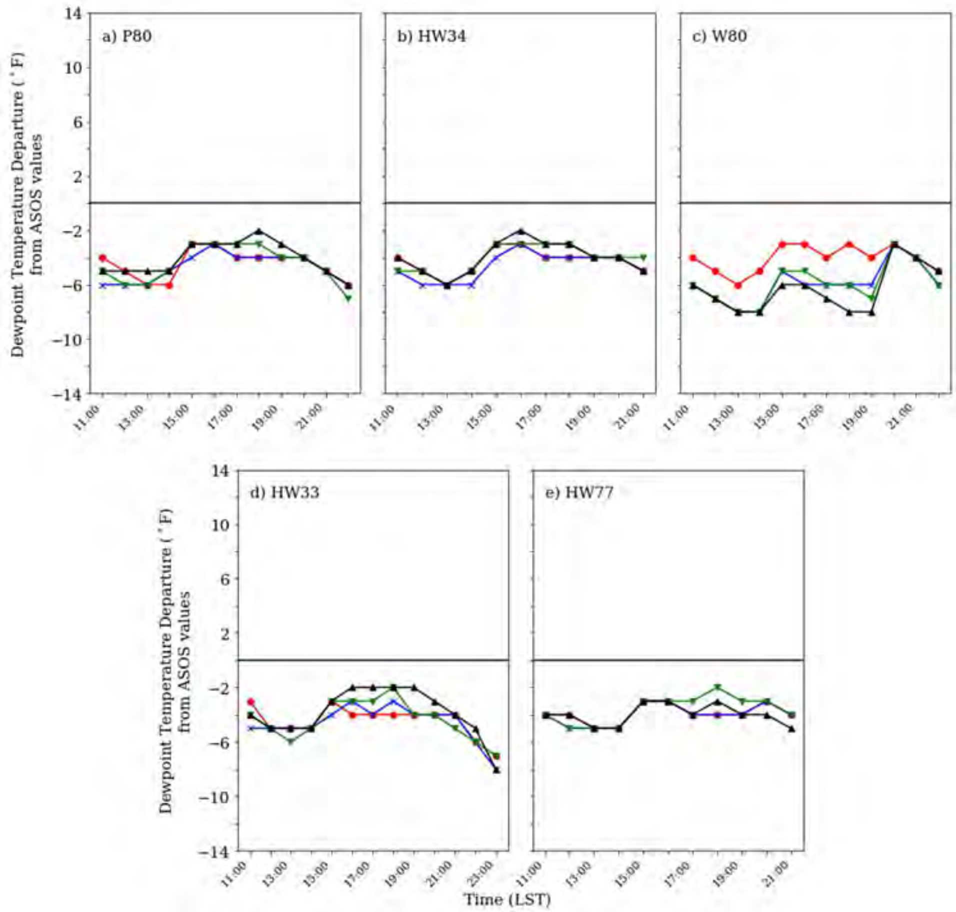


Figure 4.43: Difference graphs of the MDSS forecasted dewpoint temperature departure 23 – 24 February 2019 from the observed ASOS values at (a) W80, (b) P80, (c) HW34, (d) HW33, and (e) HW77 for 3-hours (red), 6-hours (blue), 9-hours (green), 12-hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

MDSS nearly correctly predicted wind speeds for all of the routes early in the event; however, later in the event the differences in forecasted compared to observed wind speeds are much larger (Figure 4.44). While the MDSS did tend to overpredict actual values of wind speed that were observed, the important takeaway was that the MDSS forecasted the wind speed evolution over time moderately well (Figure 4.45). In the beginning of the event the wind speeds increasing with time until a peak and then decreasing incrementally after the peak was forecasted by all of the runs. The main issue with the patterns were that the peak forecasted wind speeds were lagged by 3 hours compared to the ASOS observations (Figure 4.44).

The MDSS over forecasted snowfall (Fig 4.46) from 21 LST 23 February 2019 to 19 LST 24 February 2019 at W80 and from 17 LST 22 February 2019 to 20 LST 24 February 2019 at P80. The most accurate forecast for snowfall accumulation by MDSS is 17 and 18 hours prior to snowfall onset at W80 and P80 respectively. While the MDSS did 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) are produced greater than 10 hours prior to snowfall start. An initial spike in accumulation maxima as snowfall onset occurred is also observed for all three of the highway routes. When all of the observed routes together are compared against each other, it is very evident that the MDSS had outlined a clearly defined pattern that evolved over time. Snowfall accumulation totals (Figure 4.46) also differ in order from highest to lowest from the northernmost routes (W80, HW34, P80) to the southernmost routes (HW33 & HW77) prior to snowfall onset. The final snowfall accumulation amounts displayed the same distribution and also included 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 of snowfall accumulation between P80 at 5.9 inches and HW34 at 7.3 inches, which are separated by 4.5 mi. This large difference is particularly of note because the differences in

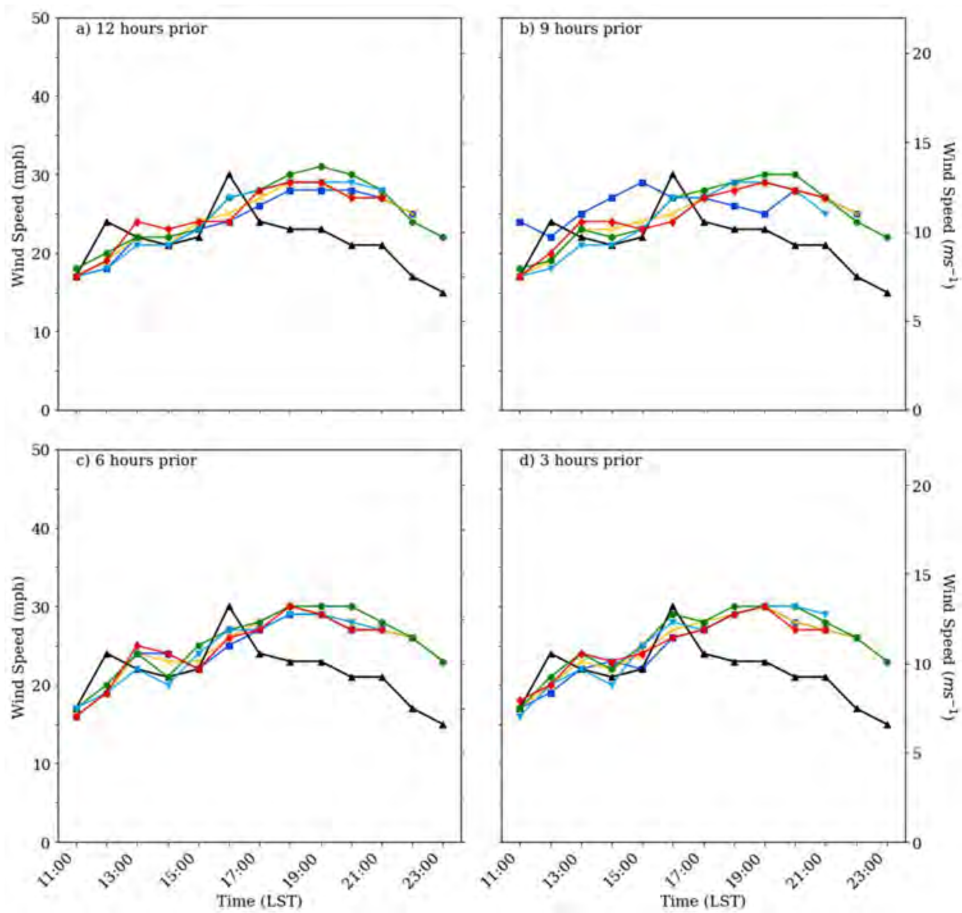


Figure 4.44: 23 – 24 February 2019 hourly wind speed forecasted by NDOT-MDSS at (a) 23 LST forecast run (12-hours prior to snowfall start), (b) 2 LST forecast run (9-hours prior to snowfall start), (c) 5 LST forecast run (6-hours prior to snowfall start), and (d) 8 LST forecast run (3-hours prior to 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 start of snowfall to end of snowfall.

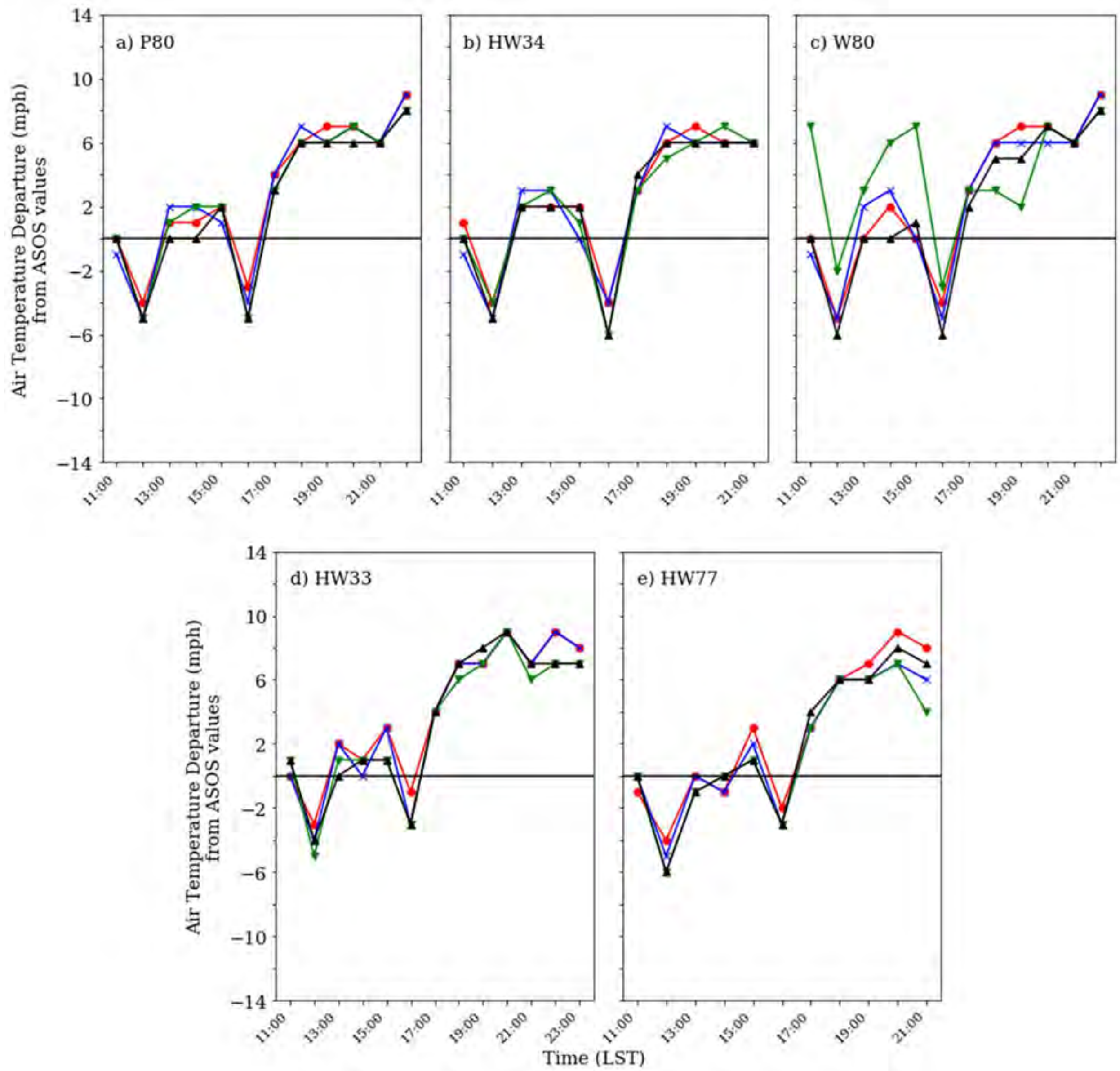


Figure 4.45: Difference graphs of the MDSS forecasted wind speed departure 23 – 24 February 2019 from the observed ASOS values at (a) W80, (b) P80, (c) HW34, (d) HW33, and (e) HW77 for 3-hours (red) for 3-hours (red), 6-hours (blue), 9-hours (green), 12-hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

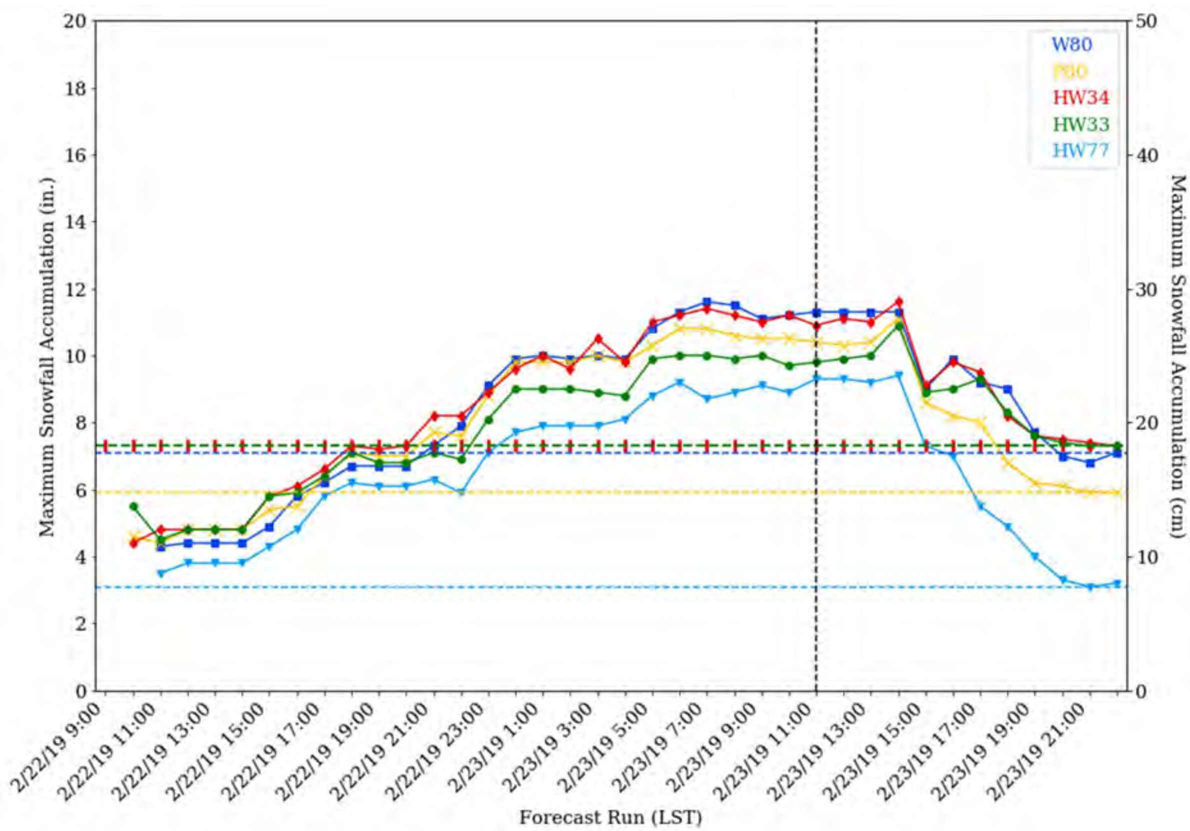


Figure 4.46: Maximum MDSS forecasted snowfall accumulation for the individually observed routes per forecast run. The vertical dotted line denotes snowfall start time. The color-coded horizontal lines denote the final snowfall accumulation totals recorded at the snowfall end time for their corresponding routes.

snowfall accumulation total between the two routes for the other events is much less (Figures 4.22, 4.34). There is no noticeable gradient that encompassed the two routes in question to induce a substantial difference. This could be traced back to the issue of averaging over route length, as the HW34 route is roughly half the length of the P80 route.

MDSS forecasted event lengths (Figures 4.47-4.49) are consistently under forecasted for each of the routes per forecast run leading up to the start of snowfall. The interstate routes, W80 and P80, are two to four hours short for the snowfall period. Variations in the snowfall length for the highway routes spanned one to three hours for HW34 and HW77, while HW33 exhibited a variation margin of two to four hours, which was much more alike to the interstate routes. The main discrepancies in variation among the routes is that the HW34 and HW77 routes both recorded event lengths two hours shorter than the other three routes. A comparison of the differential graphs for the February event demonstrated that P80 and HW34 were accurate over the forecast period (Figure 4.49). That being said, P80 and HW34 still mostly under forecasted the end times, albeit by two hours maximum. The differential graphs for HW33 and HW77 showed a consistent and more substantial under forecasting analog across the forecast period. The outlier from the group for the February event was the W80 route which oscillated between -negative one and one during the forecast period and finally correctly forecasting the end time during its last six forecast runs. The result of under forecasting the event length for this event is also quite notable because comparatively Colorado Low systems will have a longer time span over Alberta Clipper type systems. It is worth noting that while this February case is the equal and opposite of the November event with regards to event length and end time there is still very minimal consistency across the individual routes. One conclusion from the data on both of the events is that there is an analog that shows a better degree of accuracy along the routes that are closer to the higher snowfall totals. This is a positive sign as it is typically easier to develop a forecast for a region within the

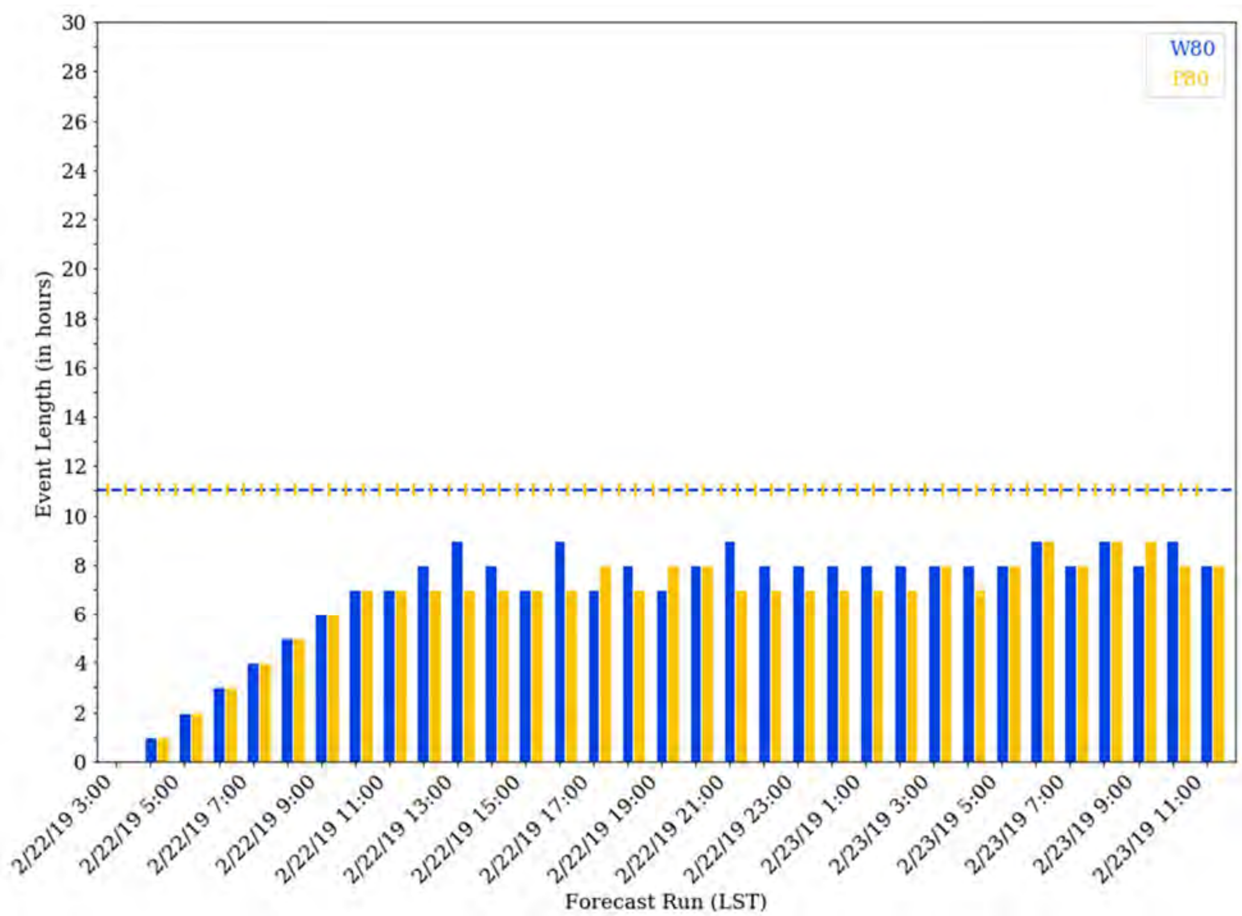


Figure 4.47: MDSS forecasted event length for the W80 (yellow) and P80 (blue) per forecast run. The color-coded horizontal lines denote the final recorded event length for the corresponding routes.

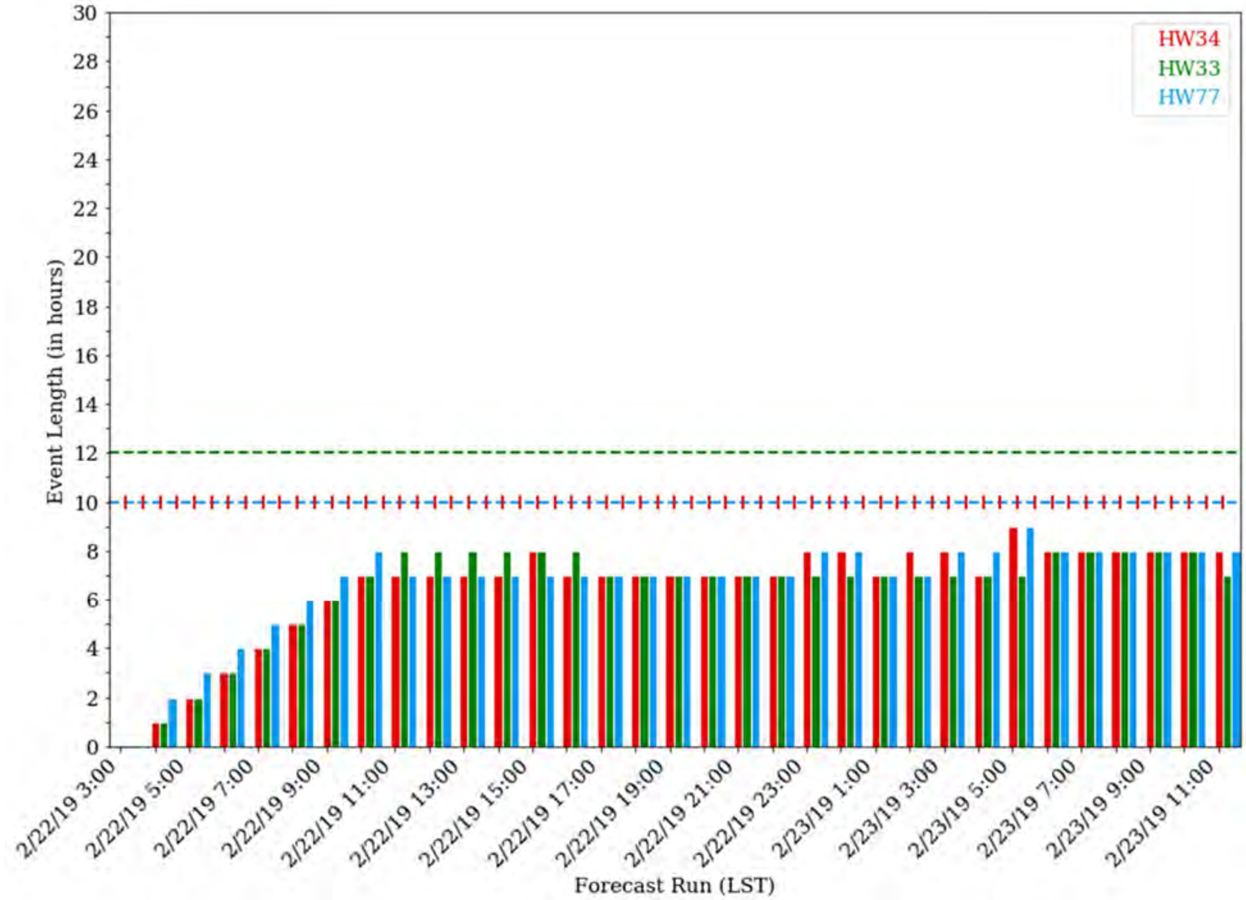


Figure 4.48: MDSS forecasted event length for HW34 (red), HW33 (green), and HW77 (light blue) per forecast run. The color-coded horizontal lines denote the final recorded event length for the corresponding routes.

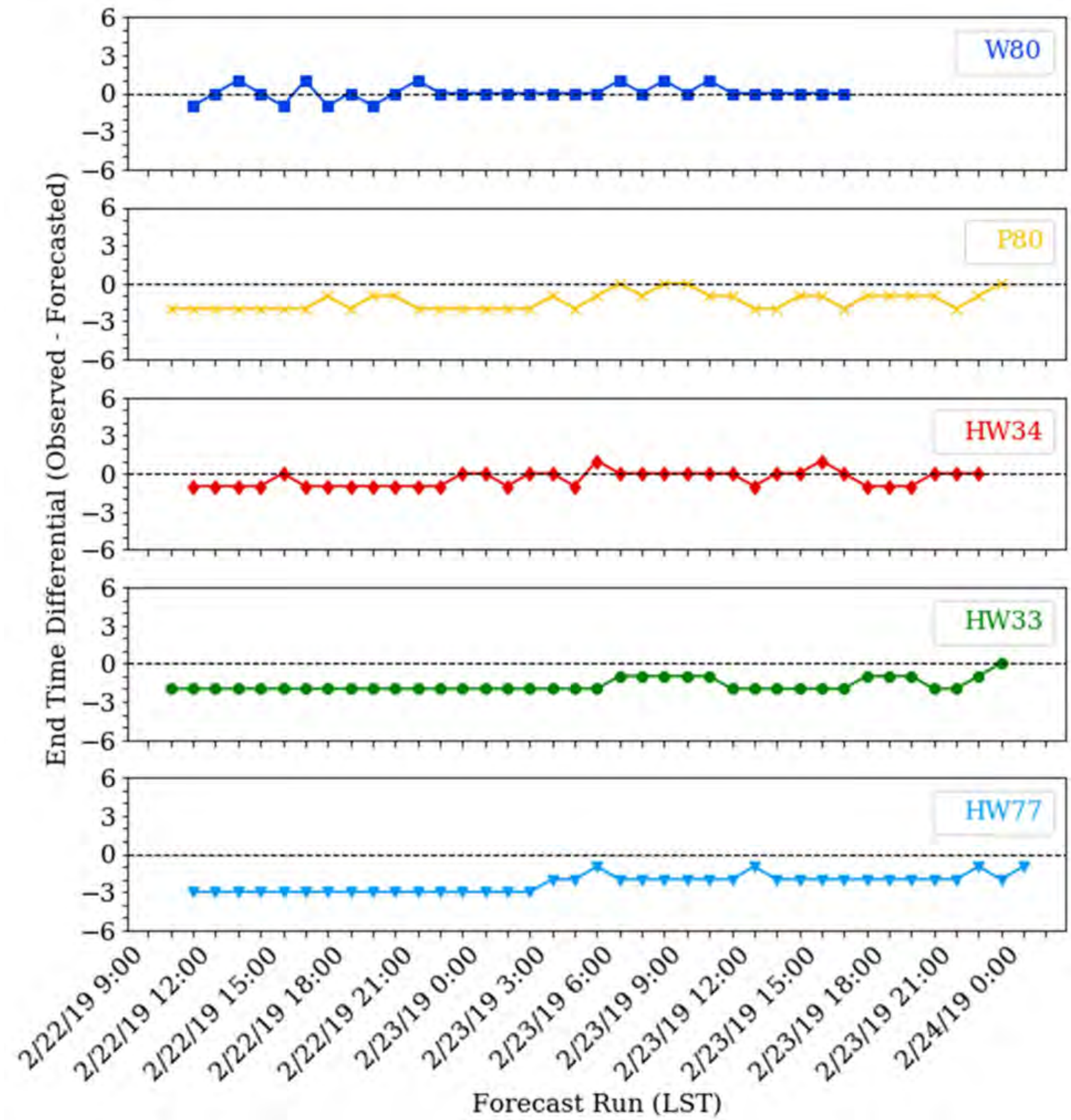


Figure 4.49: 22 – 24 February 2019 snowfall end time difference graphs for the five observed routes from the MDSS.

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.

Snowfall accumulation forecasts were further compared against the NWS zone forecasts for Lancaster county and ASOS observed snowfall for the Lincoln airport as well as the GFS, 12km NAM, 4km 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 (Figure 4.50). The NWS zone forecasts performed well when compared to the final ASOS snowfall total. An initial ramp up in snowfall totals is clearly observed in the earlier forecast runs and by early morning on 23 February 2019, the NWS forecast was within an inch of what would eventually fall at the Lincoln airport. The most noteworthy aspect of the NWS forecast is the spike in forecasted snowfall accumulation right as snowfall was beginning to occur in Lincoln at 11 LST. The spike was not observed in any of the models nor the MDSS, which begs the question of what the NWS was seeing at the time to warrant the increase in forecasted snowfall accumulation. The MDSS (Figure 4.50c) did not show the spike in forecasted snowfall accumulation prior to snowfall onset yet its progression up to snowfall start was similar to the overall pattern exhibited by the NWS forecast. This does not directly show the exact weight that the MDSS gives NWS forecasts in its own forecasts however, it does emphasize the point that the MDSS does take NWS forecasts into strong consideration. The 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 the snowfall begins to occur across the area the forecasted snowfall accumulation totals spiked and then drop off rapidly not long thereafter (Figure 4.50). This shows that the forecasts prior to snowfall onset were less accurate than those produced after the storm had begun to collect real time observations of how the event was unfolding in the area. The two exceptions of note are the snowfall accumulation totals for HW77 and P80.

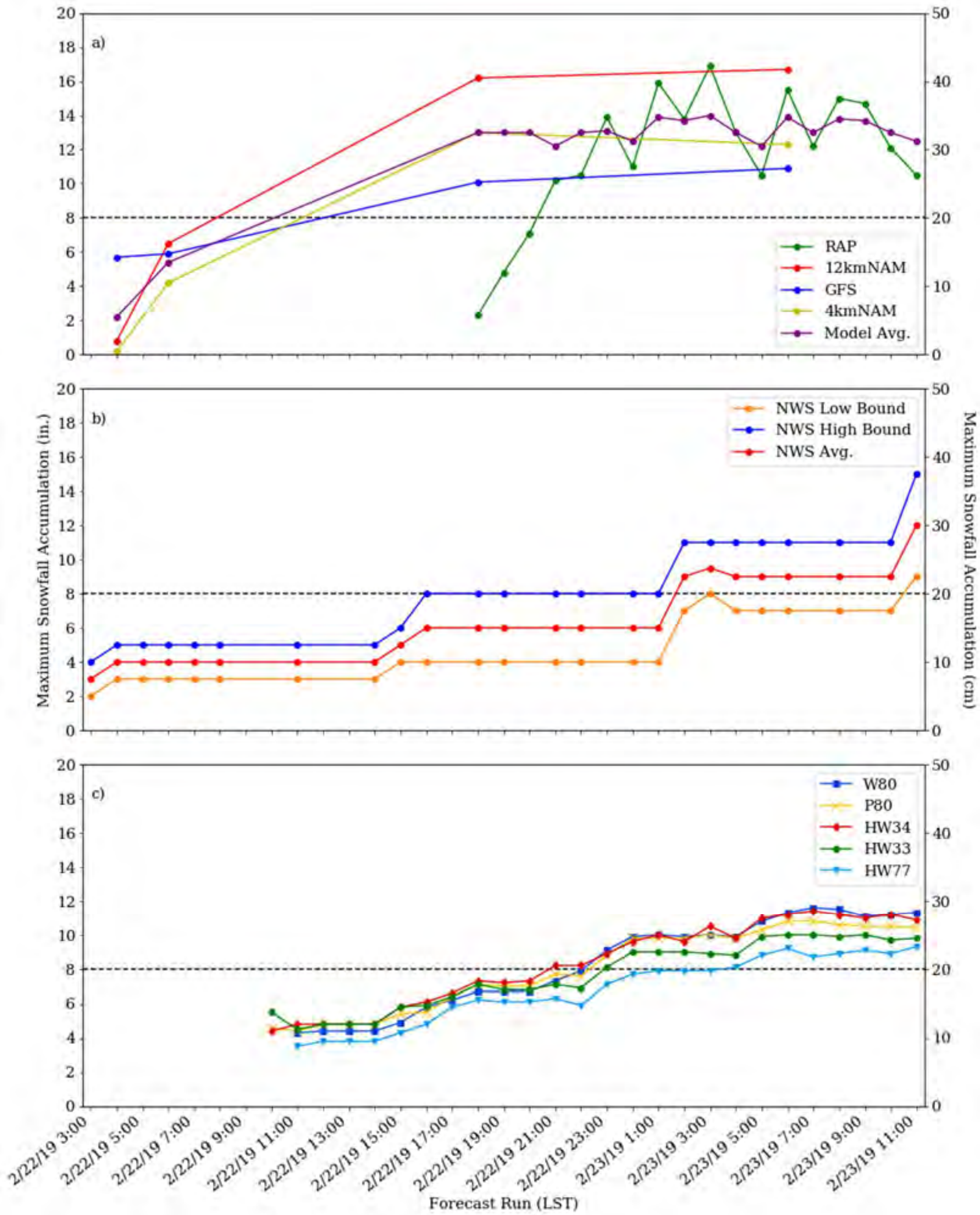


Figure 4.50: 22 – 23 February 2019 case study forecasted snowfall accumulation composite for: a) weather models (RAP, 12kmNAM, GFS, 4kmNAM), b) National Weather Service zone forecast product, c) the MDSS.

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 4.39), the numbers do not line up. Even the southernmost extent of HW77 would still be in the region of at least 5 inches according to the map. The variation observed at the P80 route is even more questionable. 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, the value observed at P80 at the end of the event is 5.9 inches. Of note also, the forecasted values for HW77 and HW33 are actually 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 MDSS still over forecasts total snowfall accumulation compared to the ASOS observations.

Along with radar observations, the MDSS uses visibility to produce an estimate for snowfall accumulation along the routes. Visibility was then analyzed in conjunction with the snowfall accumulation to investigate whether the routes that saw higher amounts of snowfall or more drastic snowfall rates coincided with visibility recorded by the 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 were identical at the same hours. The November event (Table 4.14) displayed similar characteristics, although there was a distinction between the northernmost routes (W80, P80, HW34), where snow began earlier, and 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 showed 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 23 -24 February cases, the MDSS visibility matched up well with the ASOS observed visibility. In the November case where the visibility values were much more representative of the environment, the northern routes, which are much closer in proximity to the ASOS station, corresponded well.

### 4.2.d 15-16 February 2019 event

The 15-16 February event was an Alberta Clipper type event which impacted District 1 with a lighter amount of snow amount event (Figure 4.51) than what is usually observed with a Colorado low type system. The snowfall that fell across the state in the northwestern to southeastern pattern is very typical of an Alberta Clipper type system. Snow accumulations from this event began around at 6 LST and lasted until 16 LST on 15 February before the storm system exited the state. NEWINS values for the different NDOT Districts across the state also indicate less of an impact from this event with values in the 1-3 range (Table 4.1). District 1 has a NEWINS value of 3 for the event. The MDSS temperature forecasts varied for the five segments around Lincoln (Figure 4.52). The MDSS forecasted and ASOS observed air ranged anywhere from 5-16 $^{o}$F, well below freezing so again, precipitation type was not an issue. Colder air temperatures are commonly associated or accompanying with Alberta Clipper type systems.  Forecasts runs for 3, 6, 9, and 12-hour prior to the snowfall start all forecasted temperatures which are colder than what was observed from the ASOS. For the beginning of the event, W80 had the largest departure of values form the observed with values ranging from -2 to -4 $^{o}$F below what was observed (Figure 4.53). For the other routes, W80, HW34, HW33, and HW77, MDSS forecast temperatures became warmer than the ASOS observations near the end of the event. Analysis of MDSS forecasted temperature dewpoints in comparison to ASOS observations lead to some rather interesting

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

| Forecast Hour (LST) | ASOS | W80 | P80 | HW34 | HW77 | HW33 |
|---|---|---|---|---|---|---|
| 2/23/19 11:00 | 2.0 | 10 | 5 | 10 | 5 | 5 |
| 2/23/19 12:00 | 0.8 | 5 | 5 | 5 | 5 | 5 |
| 2/23/19 13:00 | 1.8 | 2.62 | 2.62 | 2.62 | 2.62 | 2.62 |
| 2/23/19 14:00 | 0.5 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 2/23/19 15:00 | 0.2 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 2/23/19 16:00 | 0.2 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 2/23/19 17:00 | 0.5 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 2/24/19 18:00 | 0.2 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 2/24/19 19:00 | 0.5 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 2/24/19 20:00 | 0.8 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 2/24/19 21:00 | 1.0 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 2/24/19 22:00 | 3.0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 2/24/19 23:00 | 3.0 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 |
| 2/24/19 0:00 | 4.0 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 |
| 2/24/19 1:00 | 4.0 | 1 | 1 | 1 | 1 | 1 |
| 2/24/19 2:00 | 4.0 | 1 | 1 | 1 | 1 | 1 |
| 2/24/19 3:00 | 4.0 | 2 | 2 | 2 | 2 | 2 |
| 2/24/19 4:00 | 4.0 | 2 | 2 | 2 | 2 | 2 |
| 2/24/19 5:00 | 4.0 | 2 | 2 | 2 | 2 | 2 |
| 2/24/19 6:00 | 10 | 2 | 2 | 2 | 2 | 2 |

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

| Forecast Hour (LST) | ASOS | W80 | P80 | HW34 | HW77 | HW33 |
|---|---|---|---|---|---|---|
| 11/25/18 1:00 | 4.0 | 5 | 5 | 5 | | |
| 11/25/18 2:00 | 6.0 | 0.5 | 0.5 | 0.5 | 5 | 5 |
| 11/25/18 3:00 | 2.0 | 0.25 | 0.25 | 0.25 | 0.25 | 0.5 |
| 11/25/18 4:00 | 2.0 | 0.5 | 0.5 | 0.5 | 0.25 | 0.25 |
| 11/25/18 5:00 | 1.2 | 0.5 | 0.5 | 0.5 | 0.25 | 0.5 |
| 11/25/18 6:00 | 0.5 | 0.5 | 0.5 | 0.5 | 0.25 | 0.37 |
| 11/25/18 7:00 | 0.8 | 0.5 | 0.5 | 0.5 | 0.25 | 0.25 |
| 11/25/18 8:00 | 0.5 | 1 | 1 | 1 | 0.25 | 0.5 |
| 11/25/18 9:00 | 0.8 | 1 | 1 | 1 | 0.5 | 0.5 |
| 11/25/18 10:00 | 10 | 1 | 1 | 1 | 0.5 | 1 |
| 11/25/18 11:00 | 10 | 1 | 1 | 1 | 1 | 1 |
| 11/25/18 12:00 | 10 | 1 | 1 | 1 | 1 | 1 |
| 11/25/18 13:00 | 10 | 1 | 1 | 1 | 1 | 1 |
| 11/25/18 14:00 | 10 | 1 | 2 | 2 | 1 | 1 |
| 11/25/18 15:00 | 10 | 2 | 2 | 2 | 2 | 2 |

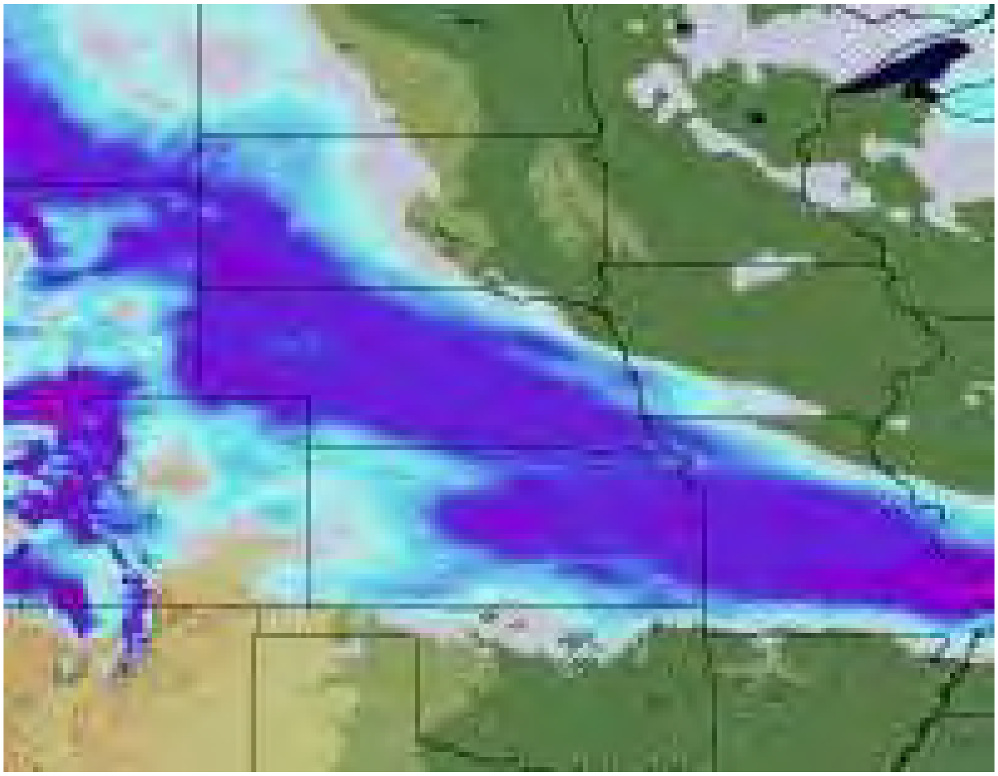

Figure 4.51: New snowfall accumulations of around 2-3 inches in central and eastern Nebraska for the 16 February event (adapted from NOHRSC 2020)

results. MDSS forecasted dewpoint temperatures throughout the entirety of snowfall event are generally too high from what is observed (Figure 4.54). For all forecast runs and all routes, there is a general increase in the dewpoint temperatures along with a general increase in temperatures over the event. When comparing the ASOS observations to the MDSS dewpoint temperature forecasts, the 12-hr forecast run has the greatest variations for all the routes (Figure 4.55). Based on higher forecasted air and dewpoint temperatures, one could draw the conclusion, that the model consistently thought more moisture would accompany the event. A common characteristic of the Clipper type system is that the low is moisture starved and would not expect the moisture content to increase so quickly.

In general, winds speed associated with Alberta Clipper type systems are usually strong (Thomas and Martin 2007). However in the case, the MDSS forecasted and ASOS observed wind speeds are slower than one might expect (Figure 4.56). Perhaps the most important analysis which was then undertaken was wind analysis. The MDSS forecasted winds are stronger at the beginning of the storm and slightly decrease towards the end of the event for Routes P80, HW33, and HW77 (figure 4.57). Wind forecasts for P80 and HW34 produce speeds that are clearly less in magnitude then the rest of the other routes.

The 15 February event saw between 2-3 inches of snowfall from the Alberta Clipper type system across the region (Figure 4.51). The snowfall accumulations from MDSS ranged from 1-3 inches (Figure 4.58). The MDSS forecasted snowfall amounts are over forecasted for the period before the snow begins. For every forecast run leading up to the start of snow, MDSS over forecasts how long the event will last for every segment (Figures 4.59, 4.60). The actual forecasted event length for all routes is nine hours. The MDSS longest period of snowfall is 18 hours, and the shortest is 11 hours. MDSS generally improves over time, as the snowfall get closer to accumulating. MDSS negative start times (Figure 4.61) also highlights the fact that each route over forecasts snow after observations stop. Perhaps this is a

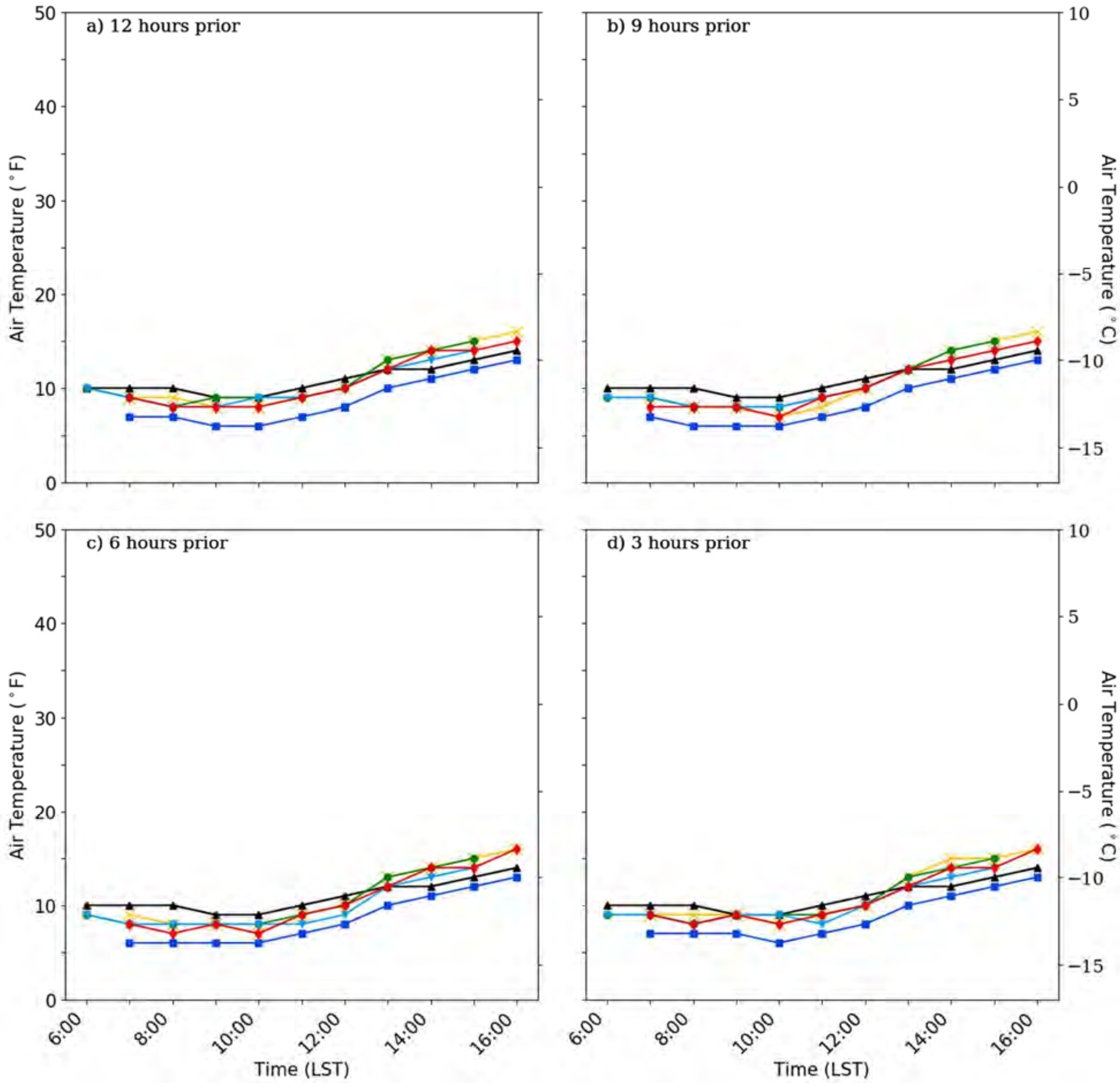


Figure 4.52: 15 February 2019 hourly temperature forecasted by NDOT-MDSS at (a) 18 LST forecast run (12-hours prior to snowfall start), (b) 21 LST forecast run (9-hours prior to snowfall start), (c) 0 LST forecast run (6-hours prior to snowfall start), and (d) 3 LST forecast run (3-hours prior to snowfall start) for W80 (yellow), P80 (blue), HW34 (red), HW33 (green), and HW77 (light blue) compared to ASOS observed (black). Date and time run from start of snowfall to end of snowfall.

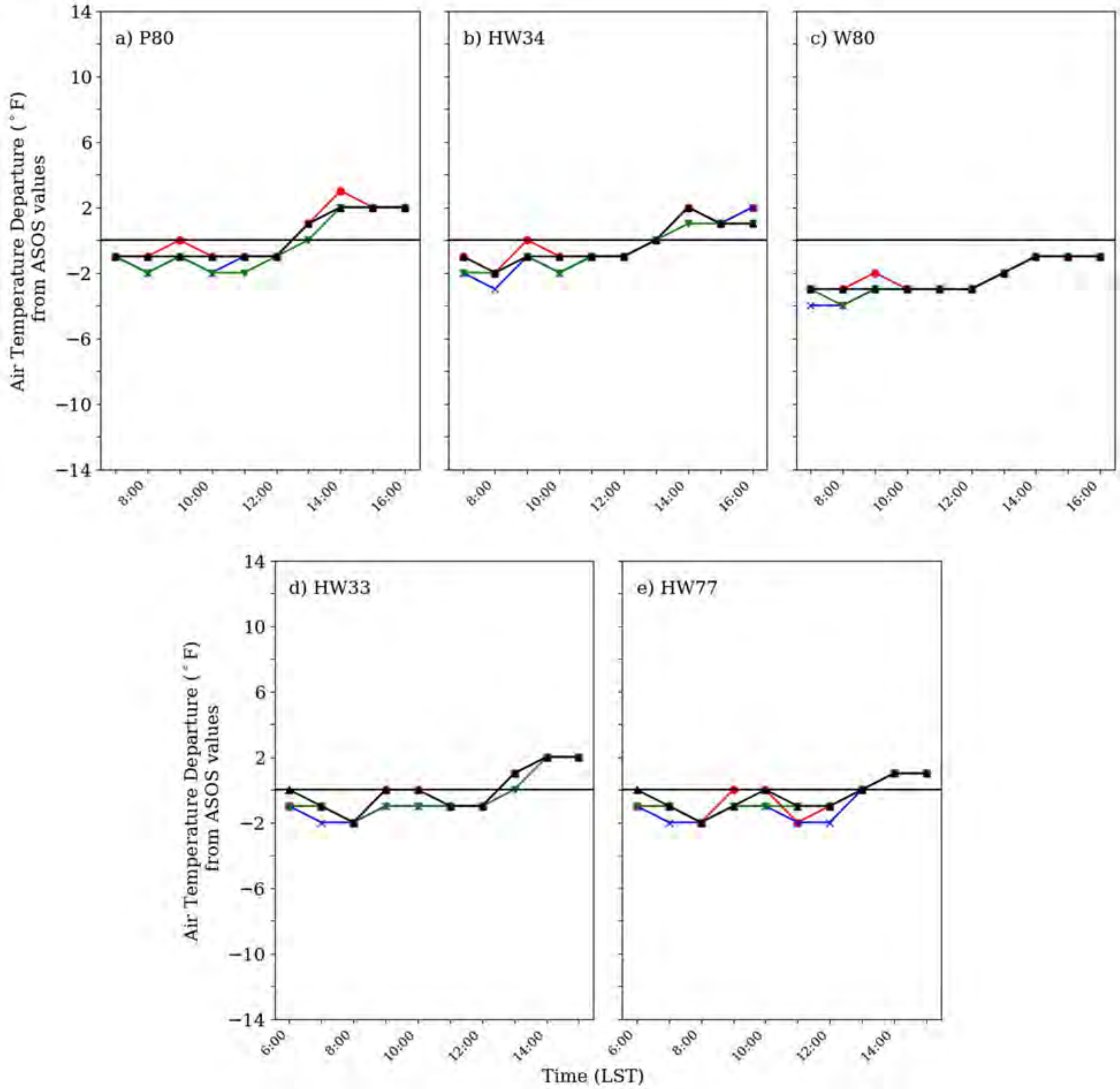


Figure 4.53: Difference graphs of the MDSS forecasted temperature departure for 15 February 2019 from the observed ASOS values at (a) W80, (b) P80, (c) HW34, (d) HW33, and (e) HW77 for 3-hours (red), 6-hours (blue), 9-hours (green), 12-hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

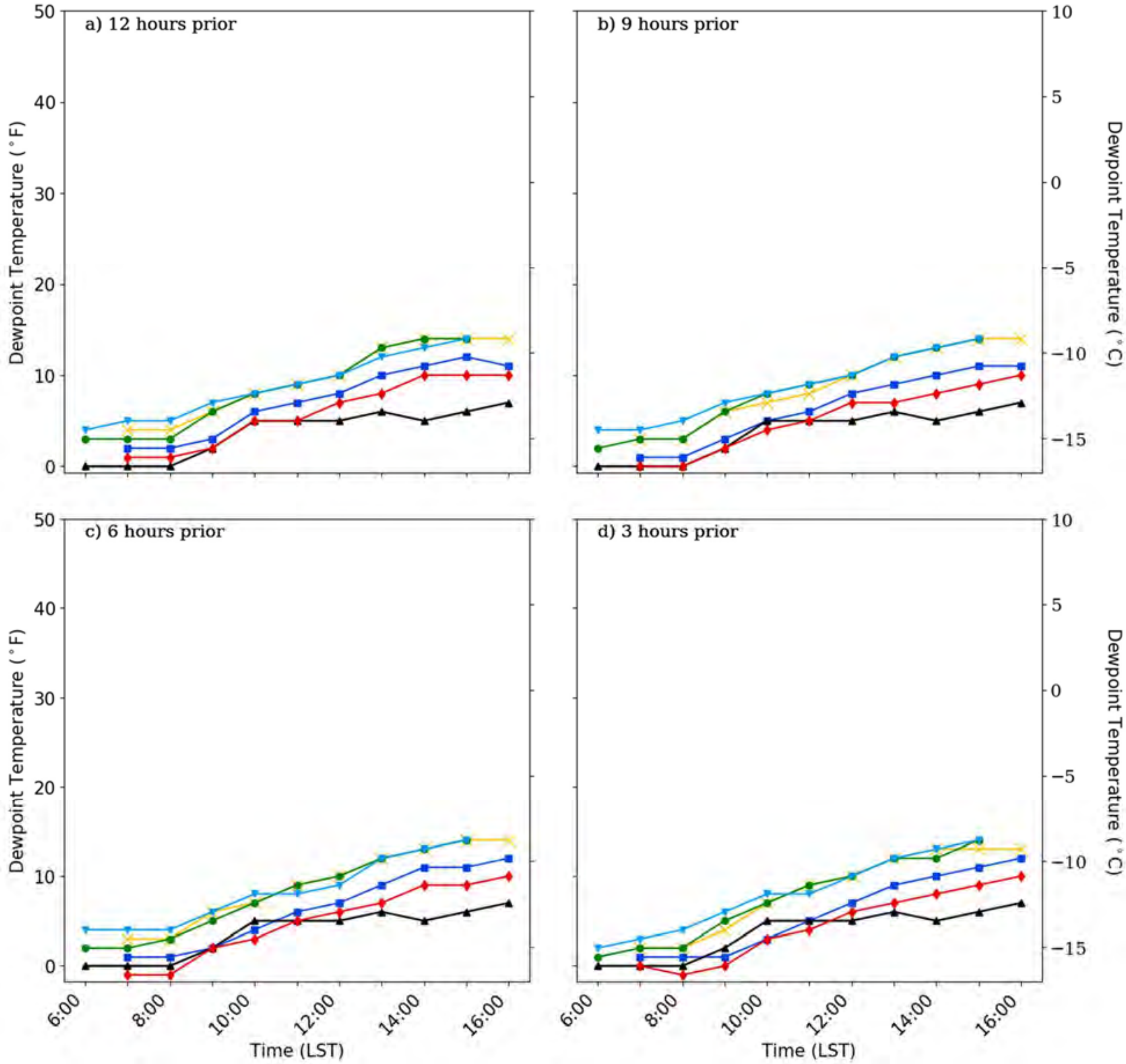


Figure 4.54: 15 February 2019 hourly dewpoint temperature forecasted by NDOT-MDSS at (a) 18 LST forecast run (12-hours prior to snowfall start), (b) 21 LST forecast run (9-hours prior to snowfall start), (c) 0 LST forecast run (6-hours prior to snowfall start), and (d) 3 LST forecast run (3-hours prior 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 start of snowfall to end of snowfall.

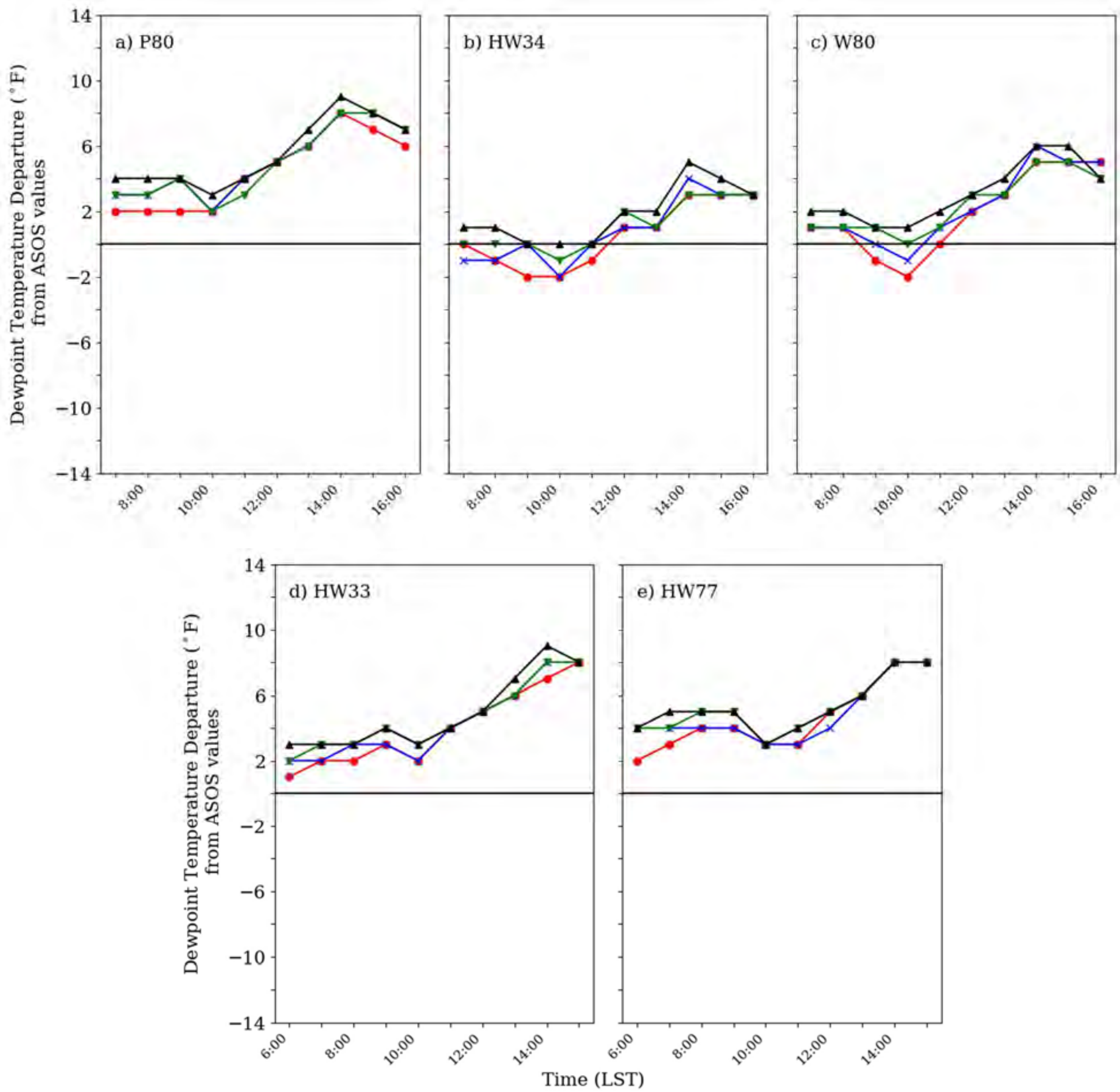


Figure 4.55: Difference graphs of the MDSS forecasted dewpoint temperature departure for 15 February 2019 from the observed ASOS values at (a) W80, (b) P80, (c) HW34, (d) HW33, and (e) HW77 for 3-hours (red), 6-hours (blue), 9-hours (green), 12-hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

case of the model being unable to forecast the speed of the faster moving clipper system. It should be noted that MDSS might be observing the next snow system, which started the following day.

MDSS snowfall accumulation forecasts are compared against NWS zone forecasts for Lancaster county and the ASOS observed snowfall for the Lincoln airport as well as the GFS, 12km NAM, 4km NAM, RAP, and their model average for KLNK at a 11:1 SLR value (figure 4.62). All numerical weather models (GFS, 12km NAM, 4km NAM, RAP) leading up to the start of snow slightly under forecasted snow amount. The NAM was closest to the actual 2.6 inches recorded with the 4km NAM being the farthest off. The NWS called for 3-4 inches of snow consistently 12 hours prior to the start of the event before calling for 2-3 inches just two hours before the start of the event. MDSS slightly over forecasted the amount of snowfall that would fall for each hour the model was ran. For W80 and HW34 for model got worst as the start time of snow started. HW33 and HW77 over forecasted snowfall throughout and remained nearly stagnant as the start of the event approached. P80 did the best of all the segments producing almost spot on snow amounts to the observed 2.6 inches four hours before the start of snow for the segment. Overall the event was pretty well handled with variations near an inch. MDSS was close to the NWS and several of the numerical weather models.

### 4.3 WMRI Analysis

Across the five selected routes within District 1 (Figure 3.4), the MDSS data showed a very broad distribution of snowfall accumulations for the 15-16 (Figure 4.58), 19-20 (Figure 4.34), and 23-24 (Figure 4.46) February 2019 case studies. There are differences in the total snowfall accumulations from MDSS and the observed ASOS snowfall accumulations for some of the routes (Figures 4.34, 4.46, 4.58). The MDSS snowfall accumulations for the 15-16 February event correspond fairly well to the WMRI snowfall accumulations (Figure 4.63) for the majority of the routes. HW77 is the exception with the

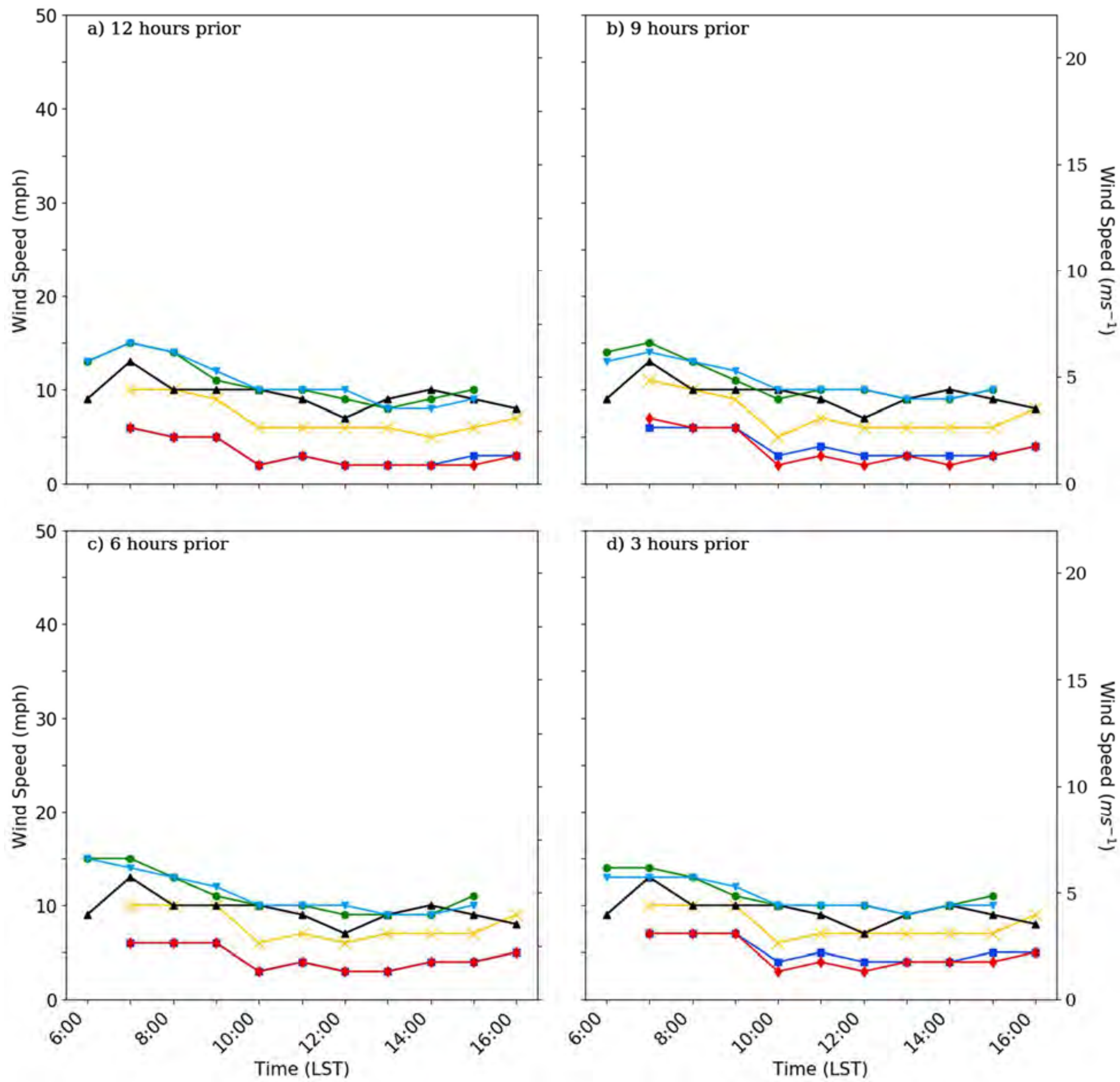


Figure 4.56: 15 February 2019 hourly wind speed forecasted by NDOT-MDSS at (a) 18 LST forecast run (12-hours prior to snowfall start), (b) 21 LST forecast run (9-hours prior to snowfall start), (c) 0 LST forecast run (6-hours prior to snowfall start), and (d) 3 LST forecast run (3-hours prior to snowfall start) for W80 (yellow), P80 (blue), HW34 (red), HW33 (green), and HW77 (light blue) compared to ASOS observed (black). Date and time run from start of snowfall to end of snowfall.

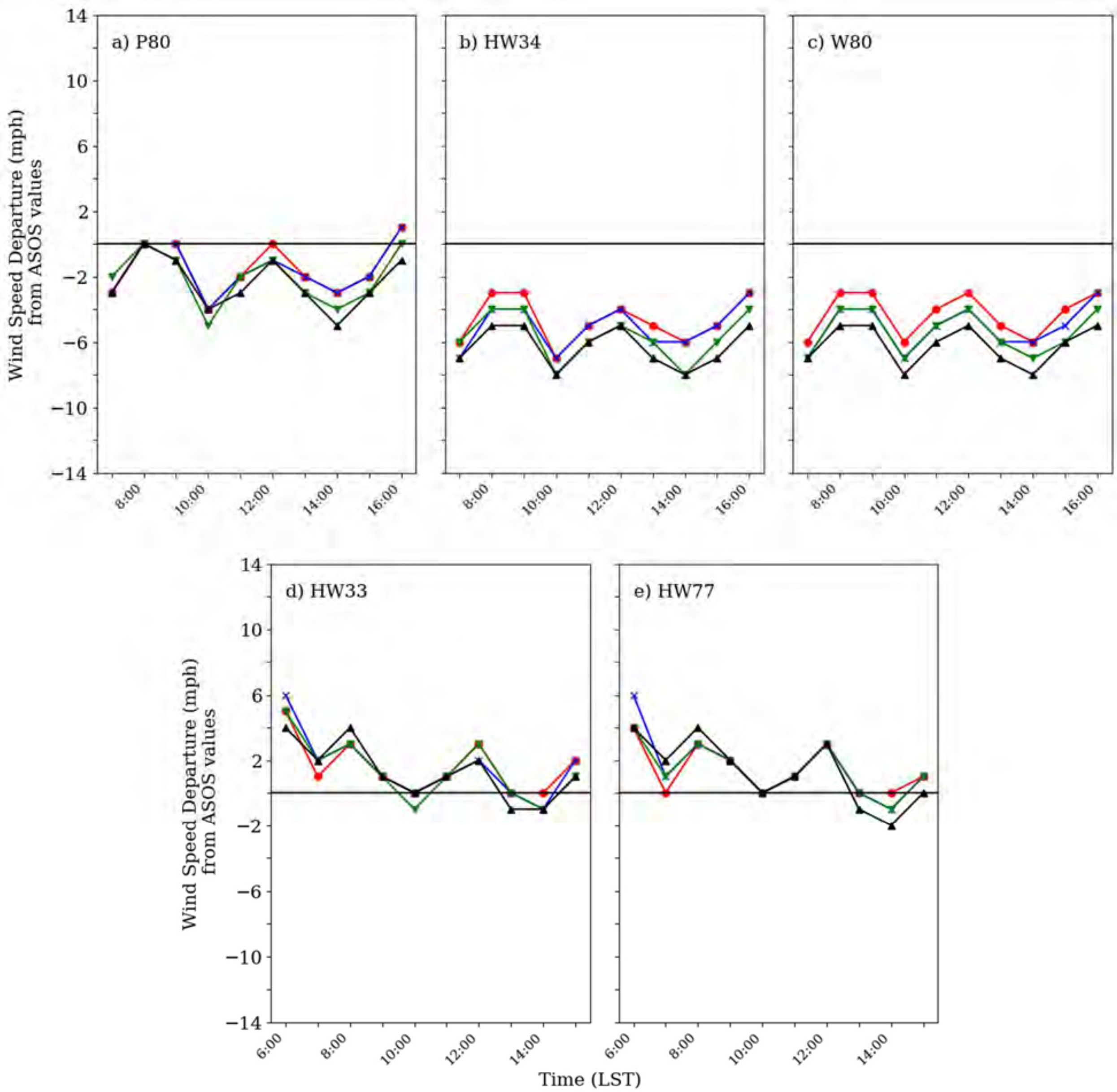


Figure 4.57: Difference graphs of the MDSS forecasted wind speed departure 15 February 2019 from the observed ASOS values at (a) W80, (b) P80, (c) HW34, (d) HW33, and (e) HW77 for 3-hours (red) for 3-hours (red), 6-hours (blue), 9-hours (green), 12-hours (black) prior to snowfall onset. The solid horizontal black line denotes zero departure from ASOS.

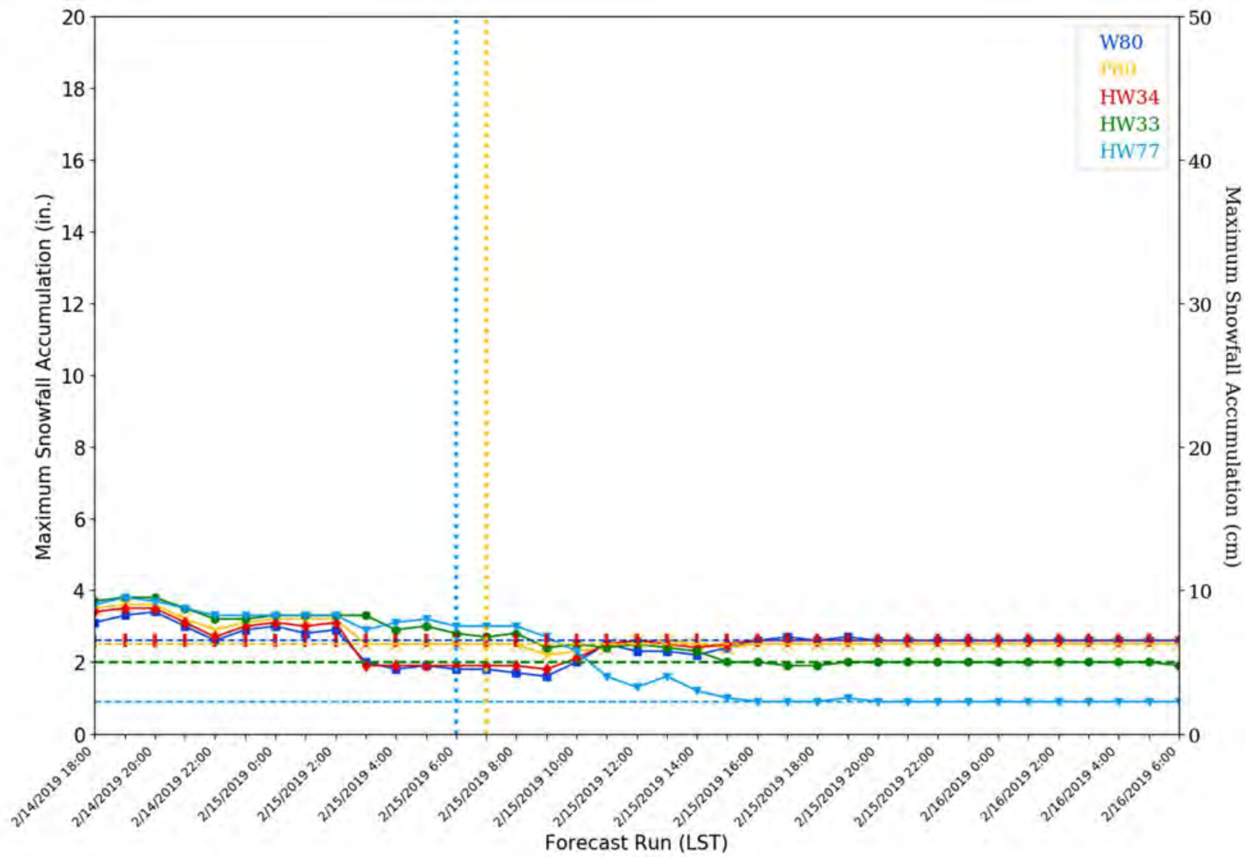


Figure 4.58: 15-16 February 2019 Maximum MDSS forecasted snowfall accumulation for the individually observed routes per forecast run. The vertical dotted line denotes snowfall start time. The color-coded horizontal lines denote the final snowfall accumulation totals recorded at the snowfall end time for their corresponding routes.

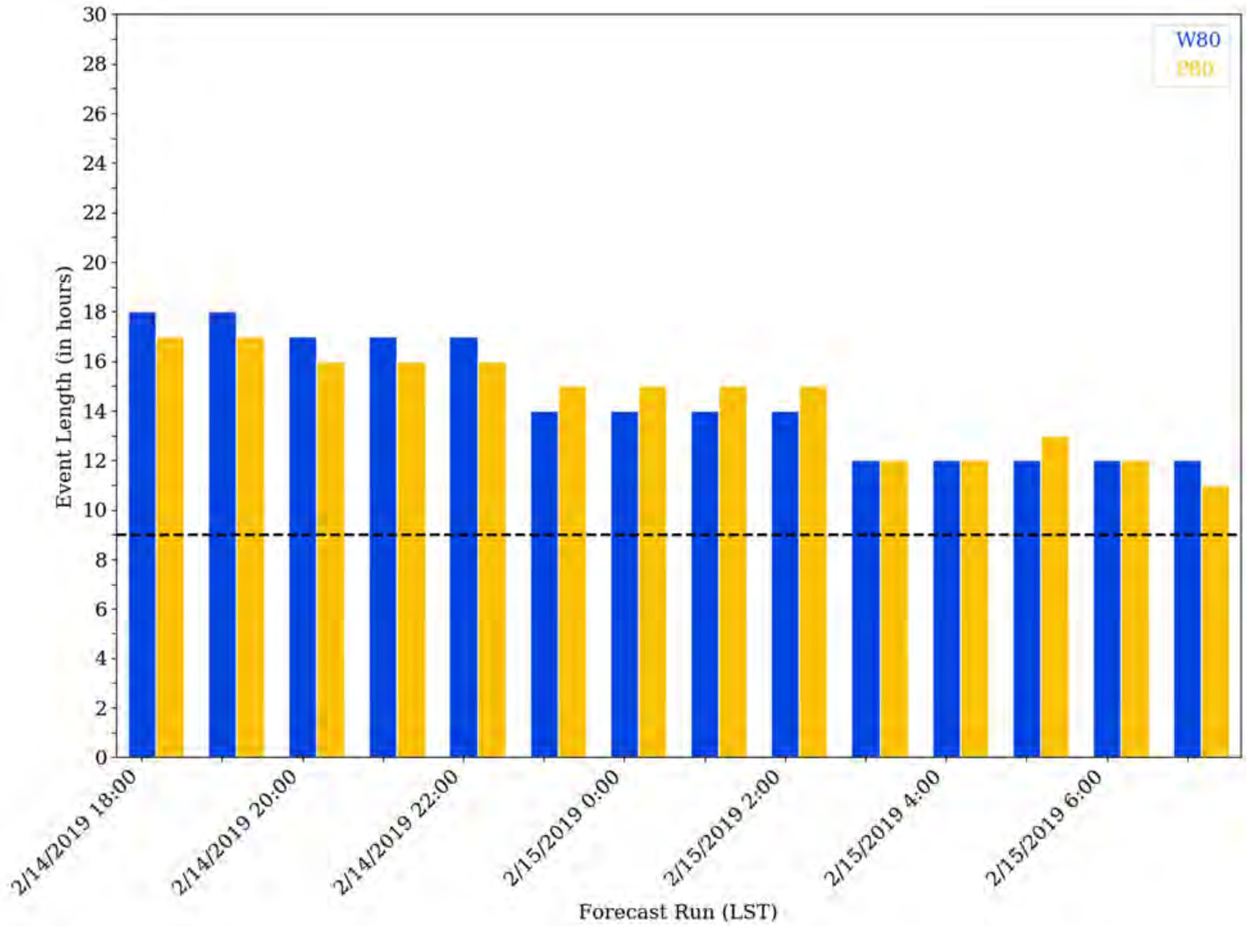


Figure 4.59: 15 February 2019 MDSS forecasted event length for the W80 (yellow) and P80 (blue) I-80 interchanges per forecast run. The color-coded horizontal lines denote the final recorded event length for the corresponding routes.

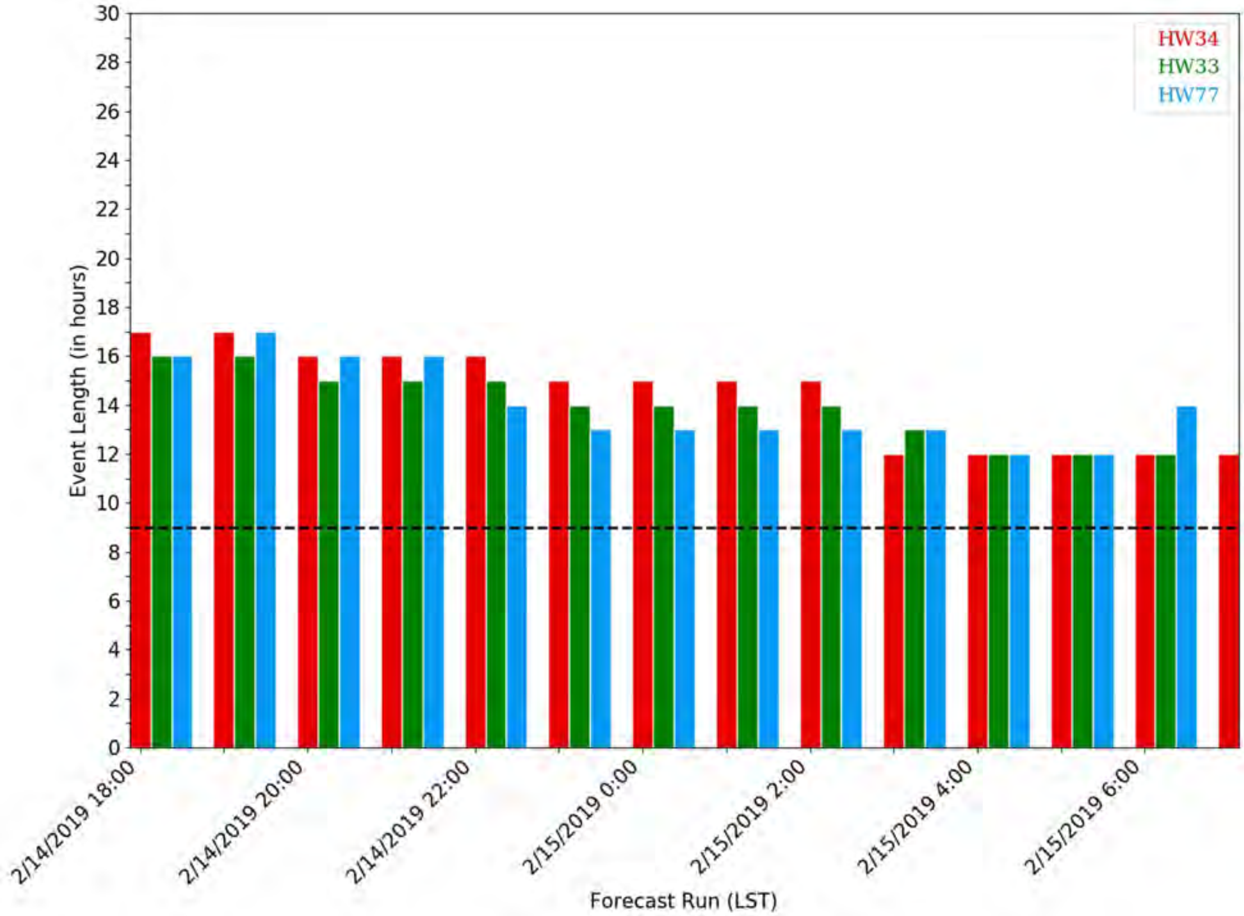


Figure 4.60: 15 February 2019 MDSS forecasted event length for HW34 (red), HW33 (green), and HW77 (light blue) per forecast run. The color-coded horizontal lines denote the final recorded event length for the corresponding routes.

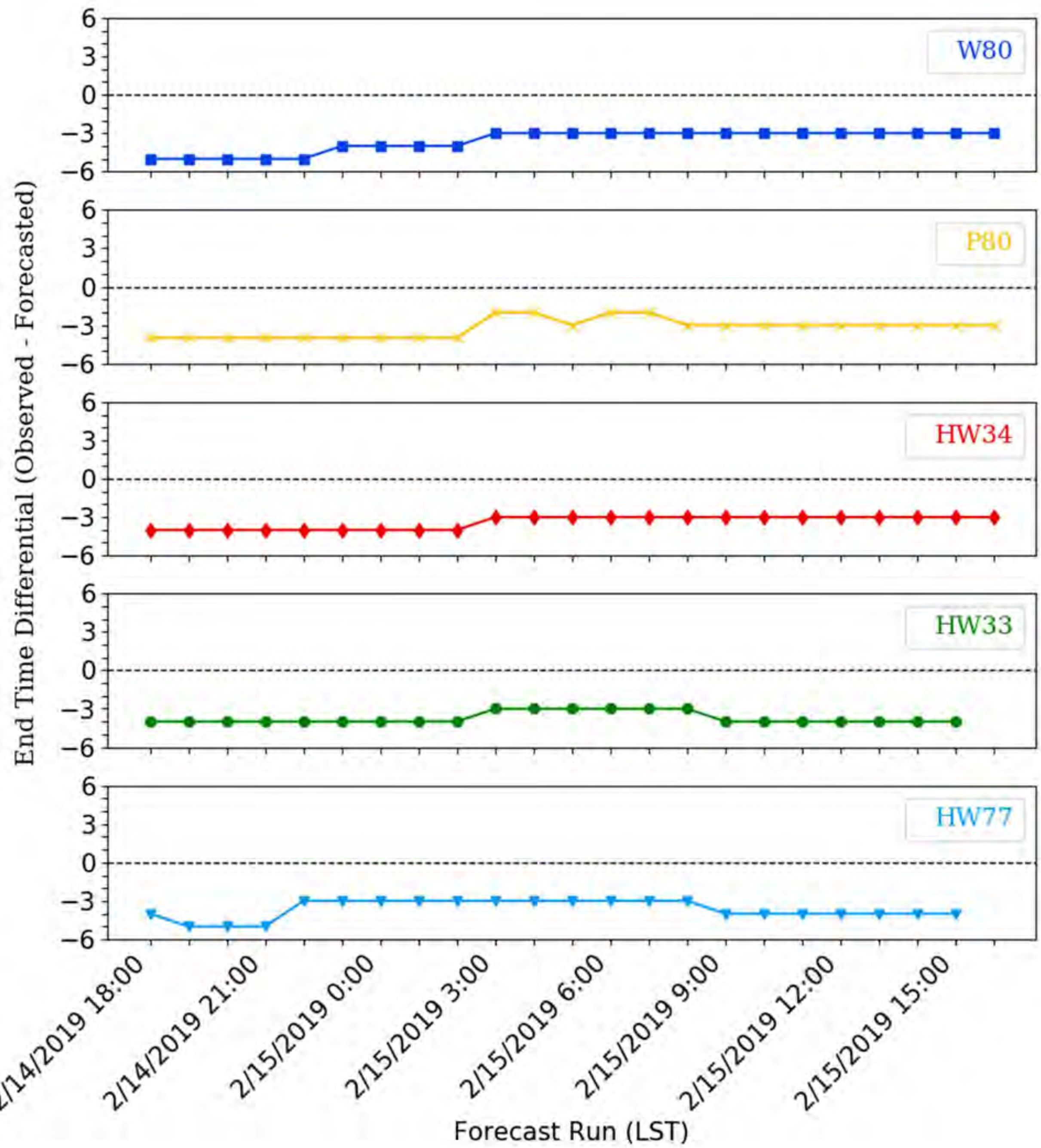


Figure 4.61: 15 February 2019 snowfall end time difference graphs for the five observed routes from the MDSS.

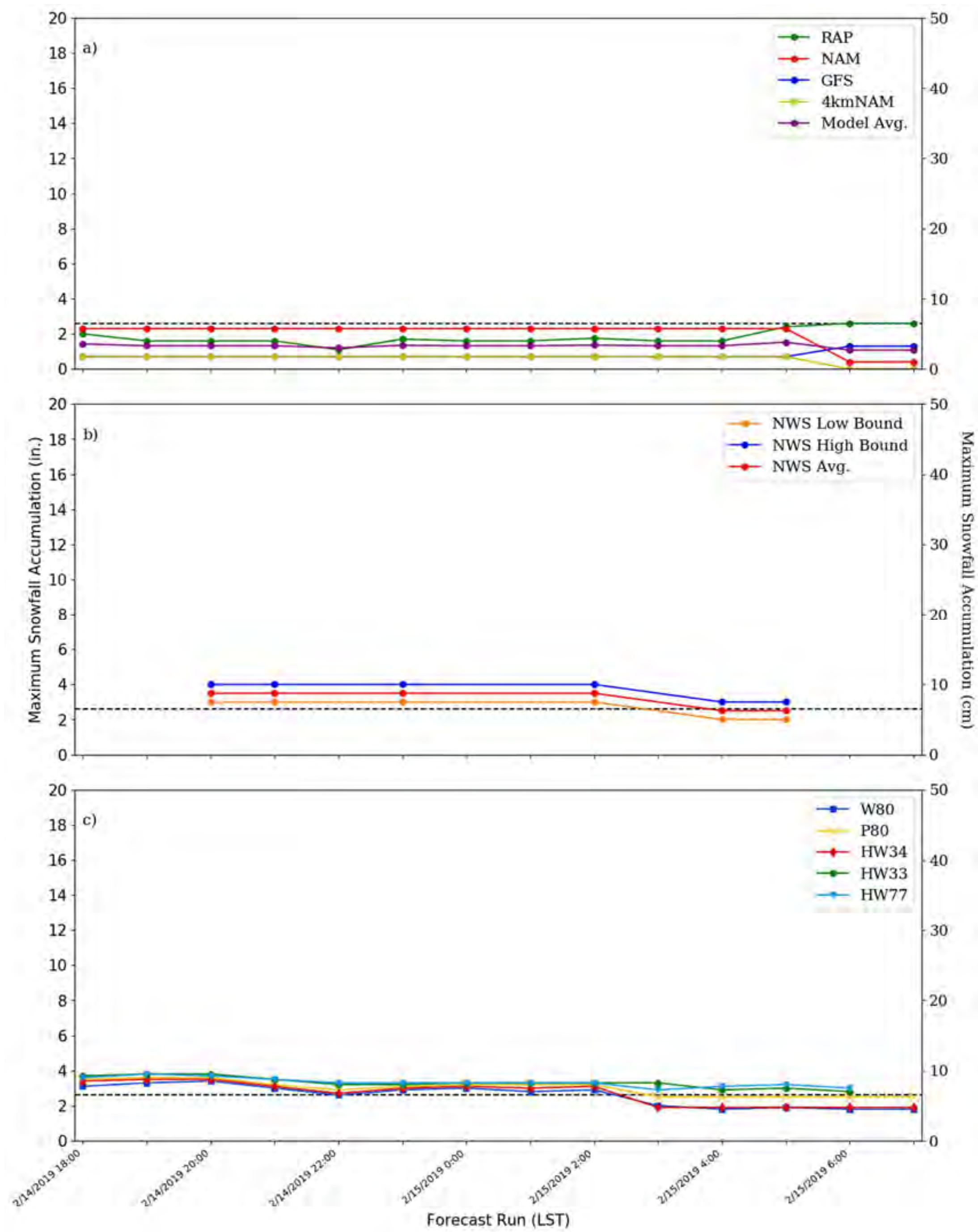


Figure 4.62: 15 February 2019 case study forecasted snowfall accumulation composite for: a) weather models (RAP, 12km NAM, GFS, 4km NAM), b) National Weather Service zone forecast product, c) the MDSS.

MDSS accumulation amount always much less than the other Routes. The rest of the MDSS and WMRI route accumulations all compare favorably to the ASOS observation. The agreement could be explained by the lower snowfall totals overall due to the Alberta Clipper nature of the system being easier to verify within the MDSS.

The cold case Colorado low system, 19-20 February, exhibits the same type of pattern as the previous event; however, the snowfall accumulations are much greater than the ASOS observed value for all of the routes (Figure 4.64). The warm case Colorado low event, 23-24 February, has very different accumulations depending of the method of determination. The MDSS accumulations for the different routes indicate a lot of variation between the routes and all are less than the ASOS observation. There is very little spread between the WMRI accumulations and the five routes. The amount from the WMRI; however, is more than the ASOS observations. The variability of the transitioning precipitation types that occurred during the 23-24 February 2019 event could be the reason why there was more variability between the WMRI and the MDSS when compared against the other two events.

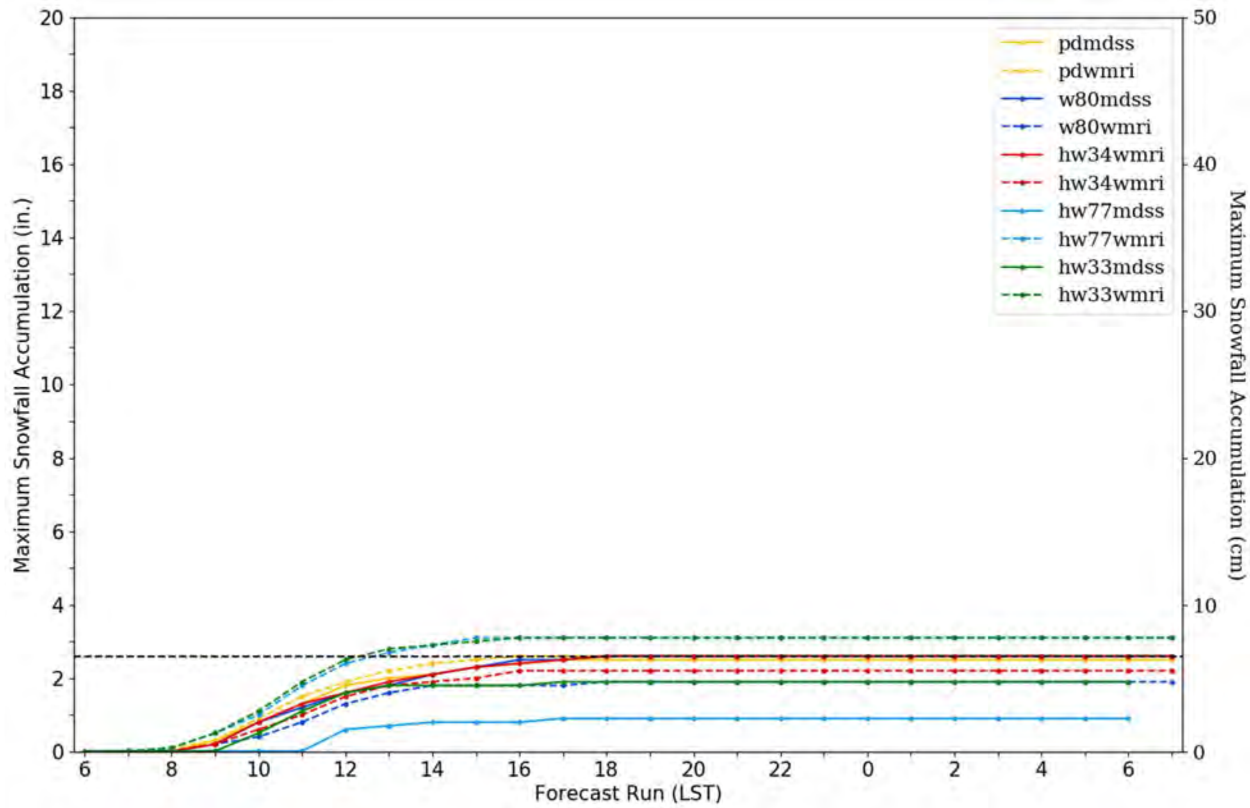


Figure 4.63: WMRI “analyzed” vs. MDSS “observed” snowfall accumulation totals for District 1 routes during the 15-16 February 2019 event. The color-coded horizontal lines denote the ASOS recorded snowfall accumulation for the corresponding routes.

The WMRI accumulations for District 7 indicate larger spreads in route accumulations throughout the district compared to the District 1 results for the same three February events. The WMRI accumulations for all events (Figures 4.66-4.68) are much less than what was observed in District 1 (Figures 4.63-4.65). For the 15-16 February event indicate great variations for the different routes though there is little different between the WMRI and MDSS accumulations (Figure 4.66). The lower snowfall accumulations are the same for the 19-20 (Figure 4.67) and the 23-24 (Figure 4.68) February events. The disparity between the MDSS and WMRI total accumulations is much less than the difference between the MDSS and WMRI in District 1. This is most likely because the total snowfall for the event in District 7 was much lower to the snowfall accumulation numbers in District 1. One difference between the WMRI in the two districts is that the WMRI snowfall period for District 7 is much longer and mirrors the MDSS event length. This may again be attributable to the lower snowfall totals which could allude to lighter snow rates that occurred over a longer period of time in District 7.

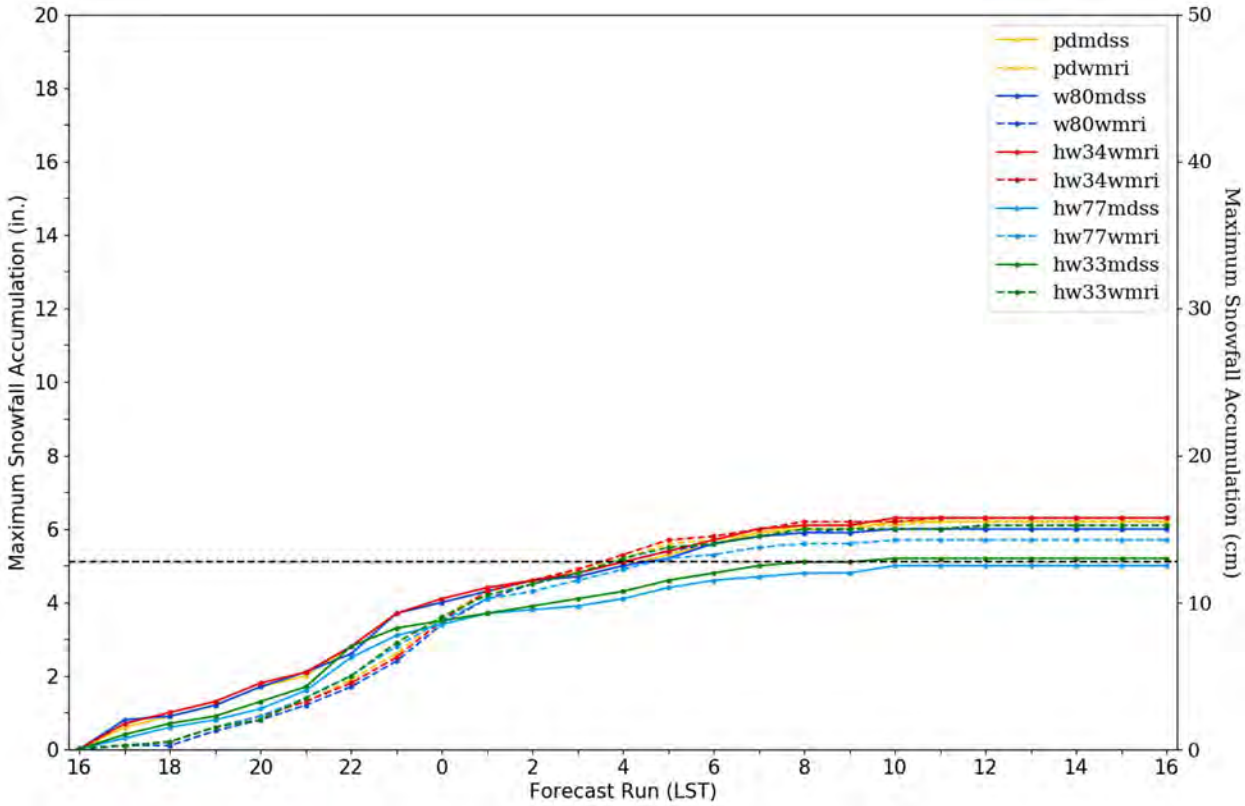


Figure 4.64: WMRI “analyzed” vs. MDSS “observed” snowfall accumulation totals for District 1 routes during the 19-20 February 2019 event. The color-coded horizontal lines denote the ASOS recorded snowfall accumulation for the corresponding routes.

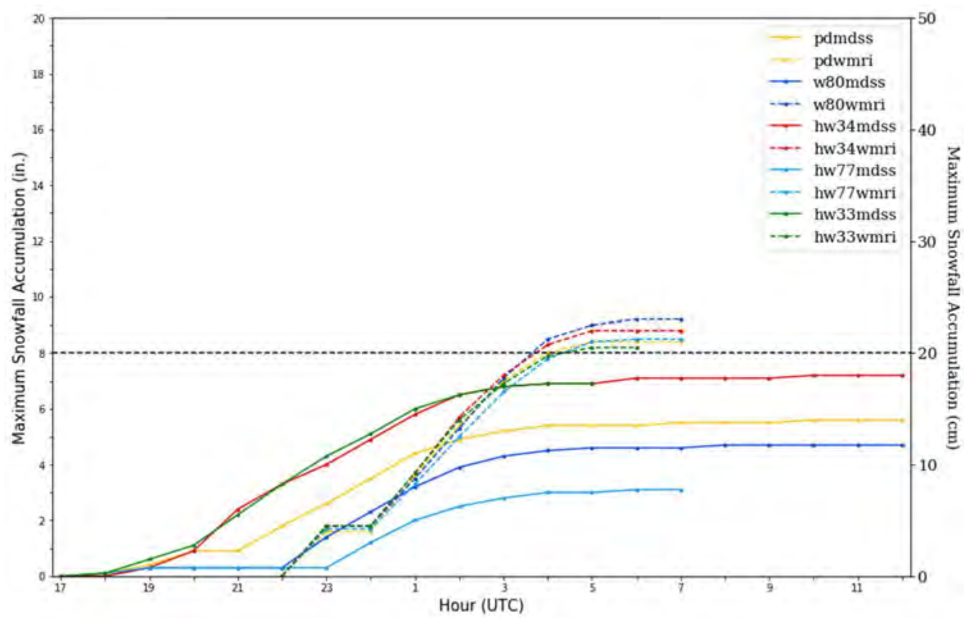


Figure 4.65: WMRI "analyzed" vs. MDSS "observed" snowfall accumulation totals for District 1 routes during the 23-24 February 2019 event. The color-coded horizontal lines denote the ASOS recorded snowfall accumulation for the corresponding routes.

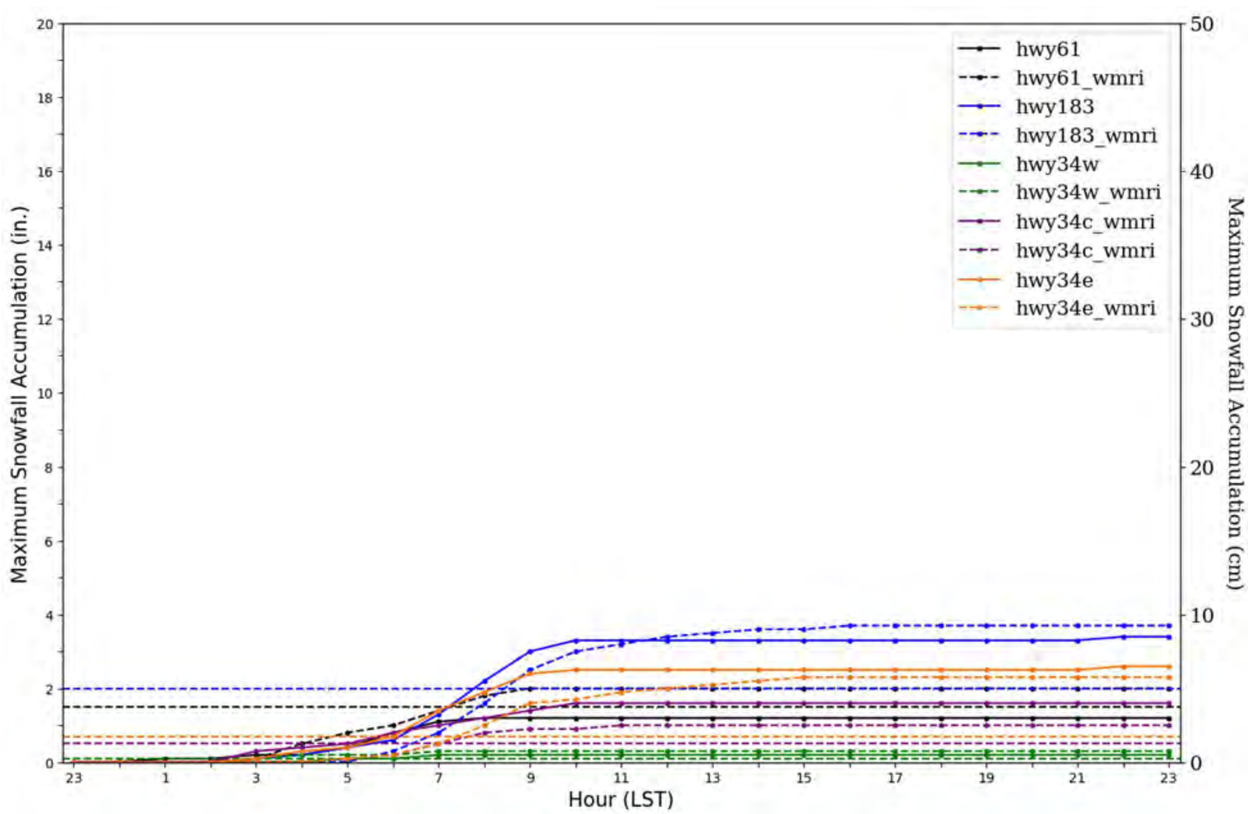


Figure 4.66: WMRI “analyzed” vs. MDSS “observed” snowfall accumulation totals for District 7 routes during the 15-16 February 2019 event. The color-coded horizontal lines denote the ASOS recorded snowfall accumulation for the corresponding routes.

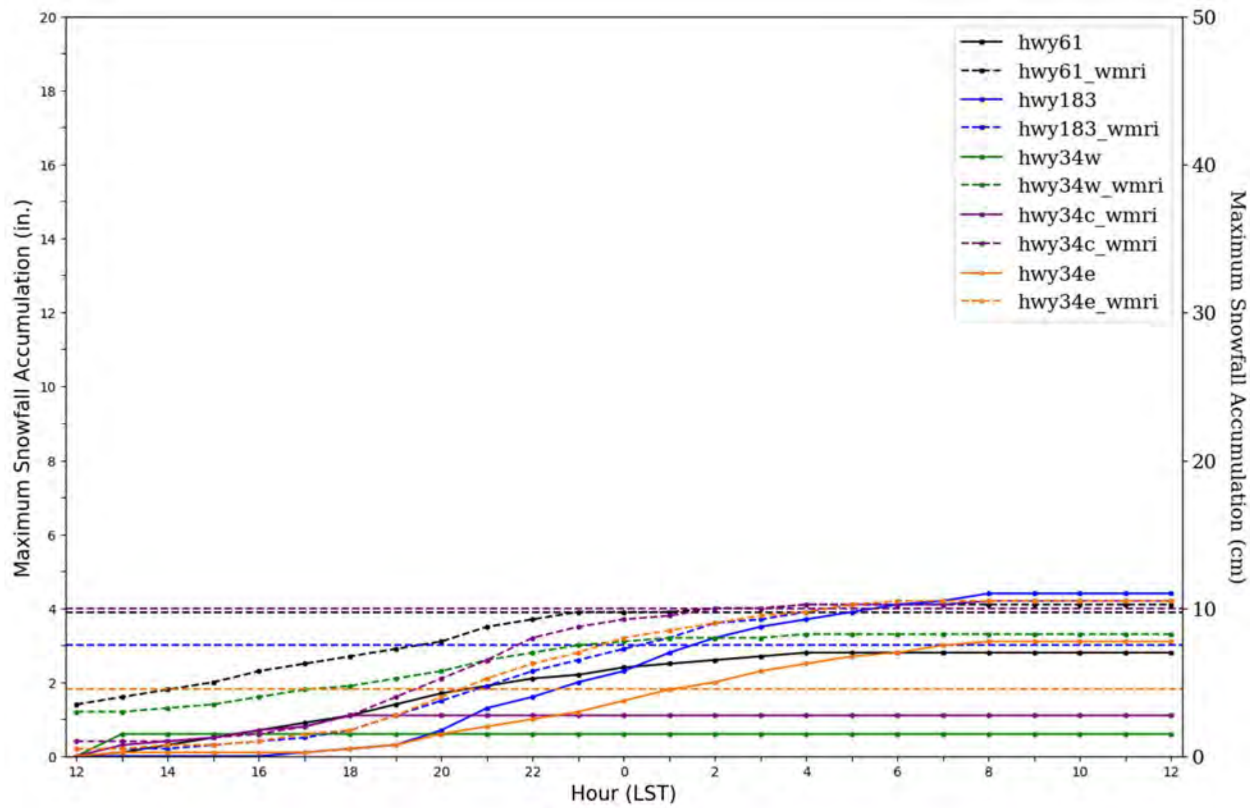


Figure 4.67: WMRI “analyzed” vs. MDSS “observed” snowfall accumulation totals for District 7 routes during the 19-20 February 2019 event. The color-coded horizontal lines denote the ASOS recorded snowfall accumulation for the corresponding routes.

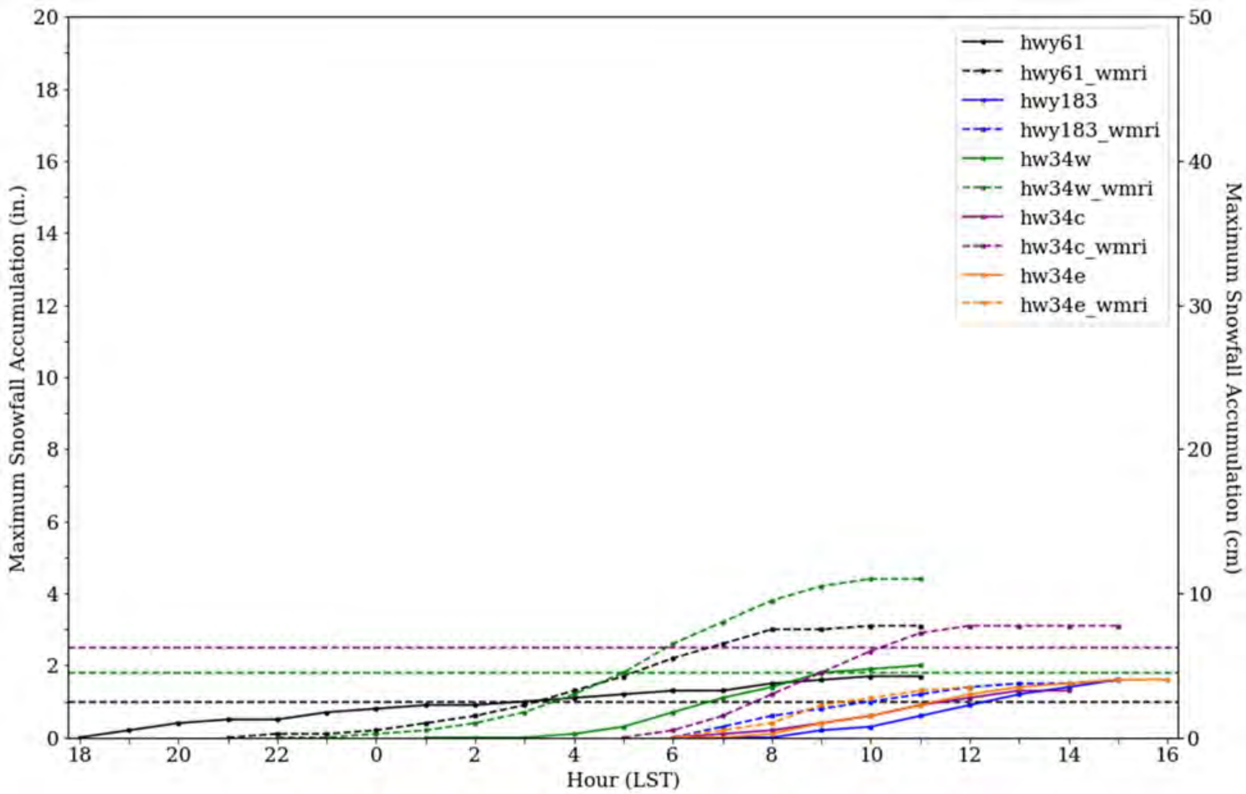


Fig 4.68: WMRI "analyzed" vs. MDSS "observed" snowfall accumulation totals for District 7 routes during the 23-24 February 2019 event. The color-coded horizontal lines denote the ASOS recorded snowfall accumulation for the corresponding routes.

## 5.0 Summary and Conclusions

After investigating many MDSS forecasts and observations across different storm types, route locations and orientations scattered around Nebraska, and varying times of the season, several concluding interpretations are presented. The results from the three objectives indicate that the MDSS system handles the different types of storms reasonably well, and the meteorological parameters within MDSS compare well with observations obtained outside of the MDSS system. It should be noted that many of these comparison data sets are also inputted to the MDSS data stream, so totally independent data comparisons are not feasible. The locations of precipitation, precipitation type and weather parameters were accurately depicted within MDSS for all storm types.

The NEWINS values for the storm events also did an excellent job of relaying the conditions and impacts associated with the storm events. The NEWINS values for the NDOT Districts were elevated over the routes when the conditions were the worst as would be expected. The NEWINS values also showed the progression of the events across the state. The first NEWINS values were usually observed in the District 5 and then NEWINS values were determined for districts to the east of District 5. On one occasion, the NEWINS District 1 value was lower than what would have been expected with the MDSS conditions reported for Lincoln. The MDSS snowfall totals for Lincoln were correct and should have been rated a higher NEWINS value; however, the NEWINS District values are for the whole district and in this case the southern portion of District 1 received much less snowfall, resulting in an appropriate lower NEWINS value than the conditions in Lincoln should have warranted.

However, the MDSS is not perfect and differences were found during the case study investigations. Some of the differences found were meteorological in nature, meaning the storm system changed path or became stronger (weaker) in intensity, which had an influence on the forecasts produced by MDSS. If the meteorological conditions are not forecasted well, especially from the numerical prediction models which are input, then MDSS, as well as the NWS forecasters, and any other weather enterprise forecasters will all have issues with the strength, timing, and location of the storm event, regardless of type of situation.  Usually, within the last 36 to 24 hours of the event taking place, the meteorological community; including MDSS, have an appropriate response for the event, though conditions will change, and updates are needed throughout the event.

There were some differences which were more systematic, or at least consistent in some of the case studies investigated. The start and ending times of the snowfall did not match up well with observations. Some of the differences might be in the meteorological conditions of the storm itself; however, some might be the result of the MDSS. For example, there was a general increase in the length of time of an event within MDSS. The change in time length appears to also have differences in the snowfall amounts. If the snow can fall over a longer period of time, it will accumulate more snowfall. Therefore, in our comparisons with the route segments studied for the few snowstorms we did investigate, it appeared that MDSS forecasted longer periods of snow and greater snowfall amounts than what occurred. It also appears that the forecasts 9-12 hours away were better than forecast made under 3-hours.

Snowfall accumulation within MDSS is calculated by taking a relationship between visibility and snowfall rate. While this is a general rule of thumb for forecasting, it may not represent the conditions occurring along a route. In several cases, snowfall amount along a route were under forecasted compared to observations. While it was beyond the scope of this project, further research is probably needed to determine if this rule of thumb holds up for Nebraska wind driven events. The accuracies of visibility measurements are also a concern, especially the further away a route segment is located compared to an ASOS observation.

Several outcomes were discovered through the case studies regarding the information obtained in MDSS, which was not necessarily meteorological in nature, though had an effect on how meteorological conditions were represented within MDSS. Probably the biggest outcome that was observed is how MDSS treats the individual route segments within the system. If you have two parallel routes or even routes that intersect, the individual route may have very different responses to the weather conditions. The different responses are caused by how the parameters are calculated within MDSS. For example, the amount of snowfall reported for a given route segment may be very different compared to a similarly located route. Meteorologically, the amounts or more generally the values would be roughly the same for the individual route segments. However, if one route segment is longer in distance or slightly orientated differently, the meteorological value can be very different. The parameter represented within MDSS is determined by averaging along the route. If there is a gradient along one route because of the length of the route, the values for that given route could be largely different. Three to five inches of snowfall difference were found along routes due to the averaging. The difference is not necessarily in the meteorological conditions, the difference is a result of the route length usually crossing a meteorological gradient. Caution has to be applied in interpreting the results for routes close to each other, especially when one of the routes is a longer distance than the other route segment, or oriented in a different cardinal direction.

A second situation which was observed with MDSS was that values of parameters could change through time within the system. Observations such as snowfall could change in the history within the MDSS archive. Several times it was observed that snowfall amounts would change in the archive when new information is incorporated into the MDSS. The MDSS saved storm archive is considered dynamic and any value within the archive is subject to change during the first 24-hours of the time period within the archive. This was explained as updates to the system made to the archive, since the archive is really an operational system, and new data can be reported within the system up to 24-hours. Therefore, caution should be used when using saved storms. For the most part this was rare and did not really change any of our findings, though it was concerning.

**References**

Andrle, S. J., Kroeger, D. A., & Sinhaa, R. (2003). *Deploying the Maintenance Decision Support System (MDSS) in Iowa* (rep.). Ames, IA: Iowa Department of Transportation.

Barnhardt, N., 2019: A case study analysis of two heavy snowfall events and road weather implications in 2018 for Nebraska. Thesis in Earth and Atmospheric Sciences, M.S. Thesis, University of Nebraska–Lincoln

Baxter, M. A., Graves, C. E., & Moore, J. T. (2005). A Climatology of Snow-to-Liquid Ratio for the Contiguous United States. *Weather and Forecasting*, **20**(5), 729–744. doi:10.1175/waf856.1

Block, C. B., Mewes, J. J., & Gaddy, S. G. (2003). Supporting Surface Transportation Weather Forecasting at Meridian Environmental Technology, Inc. In *Supporting Surface Transportation Weather Forecasting at Meridian Environmental Technology, Inc.* Meridian Environmental Technology, Inc. https://ams.confex.com/ams/annual2003/techprogram/paper_57040.htm. Accessed August 2019

Chapman, M., Linden, S., Dumont, A., Cowie, J., Craig, J., Mahoney, B., et al. (2008). *The Maintenance Decision Support System (MDSS) Project Technical Performance Assessment Report Colorado Field Demonstration Winter 2007-2008*. NCAR.

Crevier, L., and Y. Delage, 2001: METRo: A new model for road condition forecasting in Canada. *J. Appl. Meteor.*, **40**, 2026–2037, doi:10.1175/1520-0450(2001)040,2026:MANMFR.2.0.CO;2.

Federal Highway Administration, & SDDOT Department of Research. (2015). *Winter Maintenance Response Index (WMRI) Guide for Realizing the Desired Benefits*.

Frankenstein, S., & Koenig, G. G. (2004). Fast All-Season Soil Strength (FASST). *Engineer Research and Development Center (ERDC)/Cold Regions Research and Engineering Laboratory (CRREL)* . https://www.researchgate.net/publication/235157815_Fast_All-Season_Soil_STrength_FASST

Frankenstein, S. (2012, November 19). SNTHERM. *Engineer Research and Development Center Website*. https://www.erdc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/476650/sntherm/. Accessed August 2019

Frick, C., & Wernli, H. (2012). A Case Study of High-Impact Wet Snowfall in Northwest Germany (25–27 November 2005): Observations, Dynamics, and Forecast Performance. *Weather and Forecasting*, ***27*****(5)**, 1217–1234. doi:10.1175/waf-d-11-00084.1

Gray, D. M., & Male, D. H. (Eds.). (1981). *Handbook of Snow Principles, Processes, Management & Use*. Toronto: Pergamon Press.

Hallowell, R. G., and G. L. Blaisdell, (2003): Automated forecasting of road conditions and recommended road treatments for winter storms. Preprints, 19th Conf. on Interactive Information and Processing Systems, Long Beach, CA, *Amer. Meteor. Soc.*, 10.6

Hanbali, R. M. (1994). Economic Impact of Winter Road Maintenance on Road Users. Transportation Research Board, 1442, 151–161.

Henry, A., 1917: The density of snow. *Mon. Wea. Rev.*, **45**, 102– 113.

Hutchinson, T. A., 1995: An analysis of NMC's Nested Grid Model forecasts of Alberta Clippers. *Wea. Forecasting*, **10**, 632-641.

Jordan, R., 1991: A one-dimensional temperature model for a snow cover: Technical documentation for SNTHERM.89. CRREL Special Rep. SR-91-16, 61 pp.

Linden, S. K., & Petty, K. R. (2008). The Use of METRo (Model of the Environment and Temperature of the Roads) in Roadway Operation Decision Support Systems. In *The Use of METRo (Model of the Environment and Temperature of the Roads) in Roadway Operation Decision Support Systems*. Boulder, CO: National Center for Atmospheric Research. https://ams.confex.com/ams/pdfpapers/132234.pdf . Accessed September 2019

Mahoney, W. P., and Myers, W. L., 2003: Predicting Weather and Road Conditions: Integrated Decision-Support Tool for Winter Road-Maintenance Operations. *Transportation Research Record: Journal of the Transportation Research Board*, **1824**, 1, 98–105. doi:10.3141/1824-11

McClellan, T., Boone, P., & Coleman, M. A. (2009). *Maintenance Decision Support System (MDSS): Indiana Department of Transportation (INDOT) Statewide Implementation Final Report for FY09*. INDOT.

Nebraska Department of Roads (NDOR), (2010): Maintenance Manual. *Nebraska Department of Roads,* 1-224.

Petty, K. R., and Mahoney, W. P., 2008. The U.S. Federal Highway Administration winter road Maintenance Decision Support System (MDSS): Recent enhancements & refinements. *Standing International Road Weather Commission*. 12 pp, sirwec.org/wp-content/uploads/Papers/2008-Prague/D-29.pdf

Pisano, P. A., A. D. Stern, and W. P. Mahoney III, 2005: The U.S. Federal Highway Administration Winter Road Maintenance Decision Support System (MDSS) Project: Overview and results. Preprints, *21st Int. Conf. on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology,* San Diego, CA, Amer. Meteor. Soc., 6.5. [Available online at http://ams.confex.com/ams/pdfpapers/83959.pdf.]

Rick, N., 2020 (in press): A multiple case study review of the Nebraska Department of Transportation’s Maintenance Decision Support System: Colorado Lows. Thesis in Earth and Atmospheric Sciences, M.S. Thesis, University of Nebraska–Lincoln

Schwartz, R. M. and T. W. Schmidlin, 2002: Climatology of blizzards in the conterminous United States, 1959–2000. *J. Climate*, **15**, 1765–1772, doi:10.1175/1520-0442(2002)015,1765:COBITC.2.0.CO;2.

Shi, X. (2009). Winter Road Maintenance: Best Practices, Emerging Challenges and Research Needs. *Journal of Public Works and Infrastructure*, **2,** 4, 318–326.

Stewart, R. E., and and Coauthors, 1995: Winter storms over Canada. *Atmos.–Ocean*, **33,** 223–247.

Storm Prediction Center (SPC). (2019). *Image Archive.* https://www.spc.noaa.gov/obswx/maps/

Thomas, B.C. and J.E. Martin, 2007: A Synoptic Climatology and Composite Analysis of the Alberta Clipper. *Wea. Forecasting,* **22**, 315–333, https://doi.org/10.1175/WAF982.1

US Department of Commerce, & NOAA. (NWS) (2008) NOAAPort. NOAA's National Weather Service. https://www.weather.gov/noaaport/. Accessed September 2019

Walker, C. L., D. Steinkruger, P. Gholizadeh, S. Hasanzadeh, M. R. Anderson, and B. Esmaeili, 2019: Developing a Department of Transportation Winter Severity Index. Journal of Applied Meteorology and Climatology, 58, 1779-1798, doi: 10.1175/JAMC-D-18-0240.1.

Weather Prediction Center (WPC). (2019). *Image Archive.* https://www.wpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php

Weather Prediction Center. (WPCWW). (2019). *WPC Winter Weather Archive*. https://www.wpc.ncep.noaa.gov/archives/web_pages/winwx/get_winwx_images.php Accessed September 2019

WebMDSS™ (2018). Iteris. https://www.webmdss.com/#. Accessed 21 November 2018

Wunderlin, C., 2020 (in press): Case Studies of Alberta Clipper Lows and their Impact on Transportation in Nebraska. Thesis in Earth and Atmospheric Sciences, M.S. Thesis, University of Nebraska–Lincoln

Ye, Z., Strong, C., Shi, X., & Conger, S. (2009). *Analysis of Maintenance Decision Support System (MDSS) Benefits & Costs* (pp. 0–143). (SDDOT 2009)