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Development of the Nebraska Department of Transportation Winter Severity Index - Phase II

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For the Nebraska Department of Transportation (NDOT), the Nebraska Winter Severity Index (NEWINS) provided an independent framework to calculate a winter season’s severity by categorizing individual winter storms. However, one of the greatest limitations of NEWINS is that it is not predictive. Thus, this study builds on the previously developed NEWINS by creating a predictive winter storm severity index known as NEWINS-Predictive (NEWINS-P). The quantitative precipitation forecast, snow accumulation, ice accumulation, and surface wind speed parameters from the National Digital Forecast Database (NDFD) are used to develop the five components composing the NEWINS-P framework. These components consist of snow severity (NEWINS-S), precipitation type, ice likelihood, blowing snow, and drifting snow likelihood, and attempt to forecast different in-storm and post-storm winter weather hazards over a 72 hour duration at a 6-h resolution. The NEWINS-P framework is assessed through spatial forecasts across Nebraska and temporal forecasts at Nebraska airports on select Colorado Low and Alberta Clipper Systems from the 2018-19, 2021-22, and 2022-23 winter seasons. Additionally, spatial and temporal forecast trends are investigated in each system for select components to assess their degree of change. The results show that Colorado Low Systems were forecasted to have a larger areal extent and longevity of winter weather hazards than Alberta Clipper Systems. Furthermore, the Colorado Low Systems produce a higher intensity and spatial coverage of NEWINS-S, more types of precipitation, more icing concerns, and more blowing snow concerns. Post-storm impacts such as drifting snow are not forecasted in most systems as surface wind speeds decrease rapidly following the conclusion of snow accumulation. In all systems analyzed, the forecast trends reveal an increasing intensity of NEWINS-S as the system gets closer in time. Interpretations of the NEWINS-P output can be affected by a systematic artifact within the NDFD that is caused by forecast differences between weather forecast offices. In summary, NEWINS-P is a tool that supports NDOT in its winter maintenance operations for personnel and resource planning in advance of winter storms.</td></tr>
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List of Acronyms

DOT	Department of Transportation
NDOT	Nebraska Department of Transportation
NDFD	National Digital Forecast Database
NEWINS	Nebraska Winter Severity Index
NEWINS-P	NEWINS-Predictive
NEWINS-S	anticipated snowfall severity index
NWS	National Weather Service
QPF	quantitative precipitation forecast
WSI	winter severity index
WSSI	winter storm severity index

Disclaimer

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Executive Summary

The objective of this research was to translate the previously developed Nebraska Winter Severity Index (NEWINS) framework, which provided only a retrospective assessment of winter storms, to a predictive, strategic maintenance operations planning tool. Additionally, this work sought to expand the previous NEWINS framework to consider freezing rain induced ice accumulation events as well as blowing and drifting snow conditions during and after storms.

This new predictive, planning NEWINS framework, hereafter referred to as NEWINS-P, was achieved by interpolating the National Weather Service (NWS) National Digital Forecast Database (NDFD) to produce gridded forecasts. The new and expanded NEWINS-P provides spatial maps at a 6-hour resolution, up to 72 hours in advance of a winter storm. The specific NEWINS-P parameters displayed include anticipated snowfall (NEWINS-S), precipitation type, ice accumulation, blowing snow (during precipitation), and drifting snow (after precipitation). Time series for NEWINS-P can be extracted anywhere statewide and for specific corridors and road segments of interest as well as district superintendent and maintenance yard areas.

The NEWINS-P case study analysis reveals that most winter storms across Nebraska result in a more intense impact than what was indicated in the preceding 72-hour forecasts. This upward trend in impacts is noteworthy for NDOT's planning and personnel scheduling activities leading up to a storm. It is important to highlight that NEWINS-P is developed and tuned uniquely for Nebraska and NDOT maintenance operations. Other indices, such as the NWS Winter Storm Severity Index (WSSI), provide a nationwide assessment of impending winter storms at a much coarser temporal resolution and not geared to Nebraska conditions. An important limitation of NEWINS-P is its inability to predict post-storm drifting snow events beyond 72 hours after the conclusion of a winter storm.

Recommendations for NDOT's use of the NEWINS-P include an awareness of the expected storm type (i.e., Colorado Low System versus Alberta Clipper System), which implicates potential impacts across the state. A Colorado Low System is a storm moving from the west/southwest that brings abundant moisture from the Gulf of Mexico, strong winds, and greater snowfall, resulting in more significant impacts across the whole state compared to an Alberta Clipper System, depending on the storm track. In this study, Colorado Low Systems were found to have the greatest increase in intensity from 72 h before the event to the actual time of the event by three or more impact categories. An Alberta Clipper System, on the other hand, is a storm system that moves into the region from the north/northwest, has less moisture, colder temperatures, strong winds, and greater temperature decreases after the passage of the storm system, which can still be impactful to the state. The colder, drier snow may be more susceptible to blowing and drifting impacts, though this is offset by the relatively lower snowfall accumulations. Storm track and intensity of either storm type may also produce changes in NEWINS-P.

NEWINS-P offers a new lens for winter severity indices by considering weather hazards beyond the period of precipitation and assessment of weather forecast model changes over time. The spatial and temporal capabilities of NEWINS-P provide great benefit to NDOT's winter maintenance operations and decision support services. Moreover, NEWINS-P is complementary to both ongoing investments in maintenance decision support systems (MDSS) as well as ongoing Federal Highway Administration/National Weather Service (FHWA/NWS) efforts such as Pathfinder.

Chapter 1 Introduction and Background

Winter storms induce substantial societal disruptions and costs including billions of dollars in congestion delays, insurance liability and property damage payments, and transportation agency winter maintenance snow and ice control operations budgets; millions of vehicular crashes, and thousands of fatalities each year in the United States (Black and Mote 2015a, b; Blincoe et al. 2015; Steiner et al. 2015; Bentley et al. 2019; Tobin et al. 2019, 2021, 2022; Lazo et al. 2020). In addition to snow and mixed precipitation, winter storms are often accompanied by strong winds which can induce blizzard conditions well after precipitation has ended. Many studies have considered the climatology of winter storms (e.g., Boatman and Reinking 1984; Horel and Gibson 1994; Hirsch et al. 2001; Hoskins and Hodges 2002; Bentley et al. 2019; Feser et al. 2021), particularly those occurring across the Great Plains (e.g., Dunn 1987; Bannon 1992; Mahoney et al. 1995; Davis 1997; Winters and Walker 2022). Two main winter storm types cause notable disruptions to transportation across the Great Plains: Colorado Low and Alberta Clipper Systems. Colorado Low Systems are low-pressure systems that form on the lee side of the Rocky Mountains, typically near Colorado, and track across the Great Plains, producing widespread impactful winter weather such as heavy snowfall, freezing rain, and blizzard conditions (Figure 1.1). Alberta Clipper Systems are fast-moving low-pressure systems that typically originate from the Canadian province of Alberta and track across the Northern Plains, Midwest, and Great Lakes regions (Figure 1.2). Due to the fast progression speed and less available moisture, Alberta Clipper Systems generally produce much less snowfall than Colorado Low Systems. However, following the passage of these systems, strong northwesterly winds can cause blizzard conditions and intense drops in temperature resulting in flash freezing conditions. Ongoing efforts to better quantify and relay the impacts of these types of systems have led to the

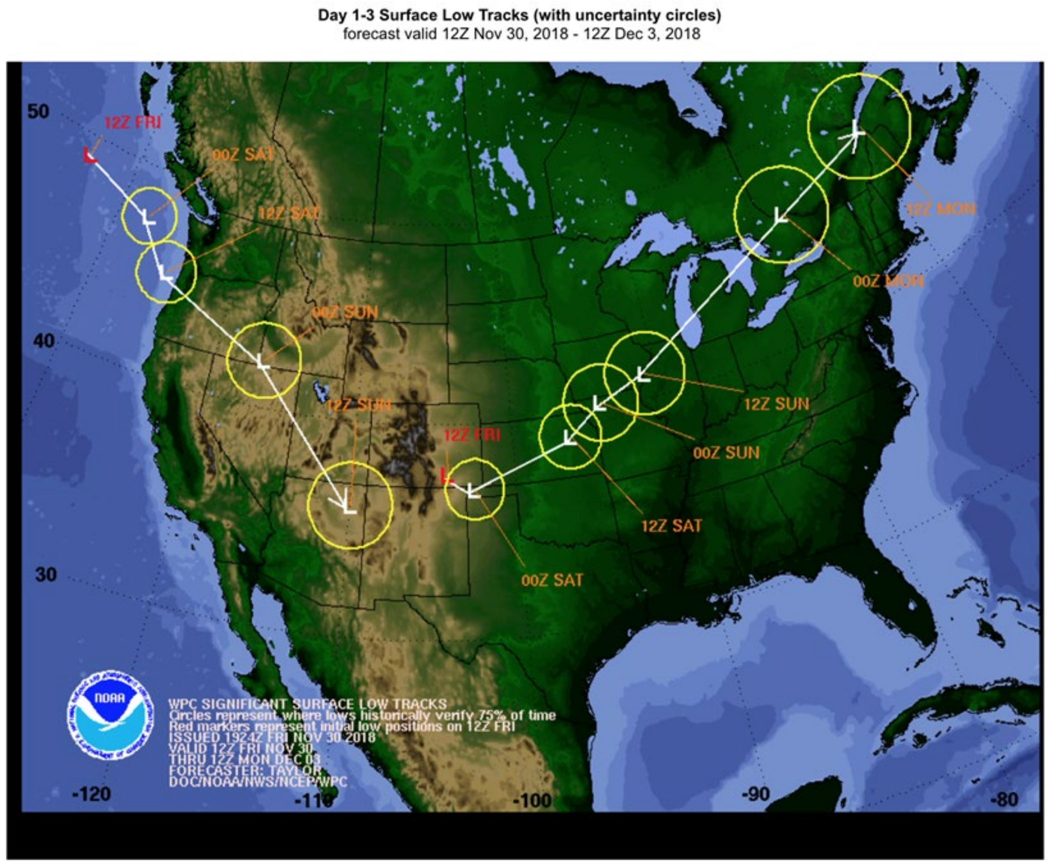

Figure 1.1 Typical storm track of a Colorado Low System (obtained from WPC 2018)

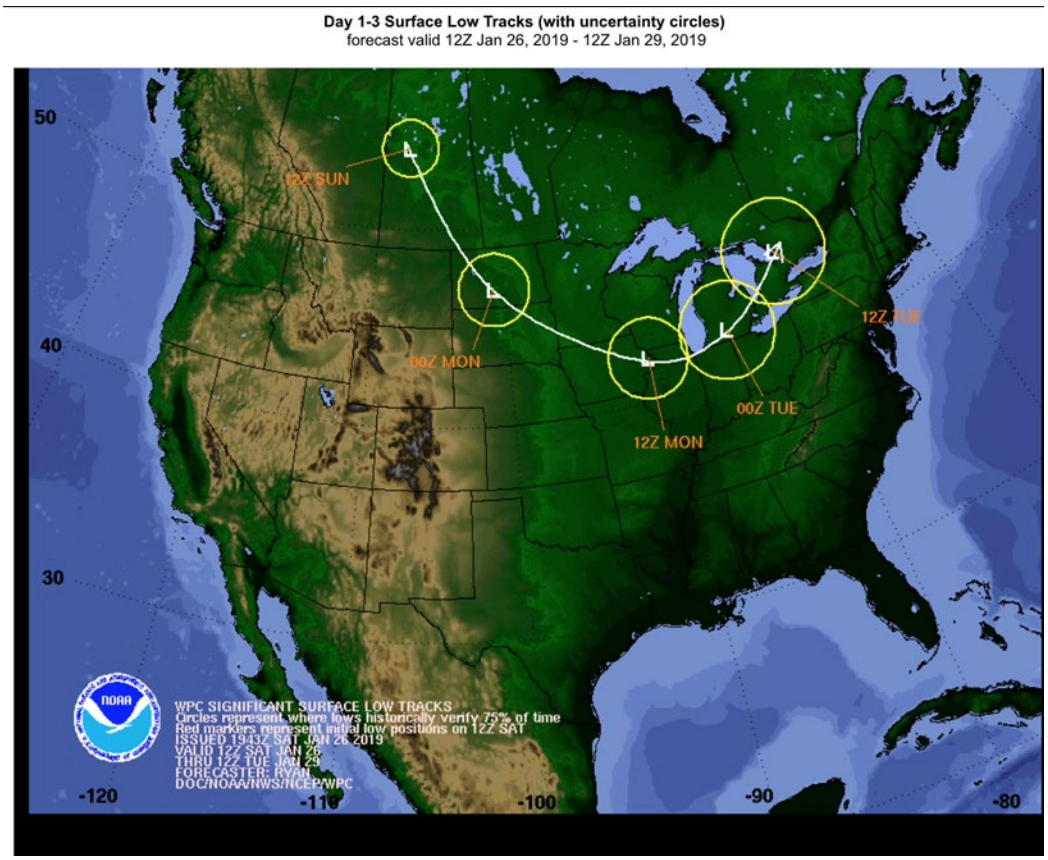

Figure 1.2 Typical surface low track of an Alberta Clipper System (obtained from WPC 2018)

development of winter storm severity indices (Boustead et al. 2015; Matthews et al. 2017; Walker et al. 2019a; NWS 2024).

At least 19 state Departments of Transportation (DOTs) have adopted winter severity indices (WSIs) to historically measure the severity of a winter season on spatial and temporal scales (Walker et al. 2019a). Most of these DOT-developed WSIs develop statistical relationships from atmospheric data over a winter season to gauge the severity of a weather season. An exception is the well-documented Iowa WSI which evaluates winter seasons based on weather hazards associated with individual winter storms (Carmichael et al. 2004; Strong and Shvetsov 2005). The desire to evaluate a winter season based on individual winter storms motivated Walker et al. (2019b) to develop the Nebraska Winter Severity Index (NEWINS). For the Nebraska Department of Transportation (NDOT), NEWINS provided a 10-year climatology of winter severity for the state of Nebraska by categorizing winter storms to gauge road impacts, which proved beneficial to NDOT (Figure 1.3). Among NEWINS and most DOT-developed WSIs, one of the greatest limitations is that they are not predictive (Villwock-Witte et al. 2021). Translating the NEWINS categorial framework to be predictive would provide immense value for NDOT. Additionally, expanding NEWINS to include other in-storm weather hazards, such as freezing rain and blowing snow, and post-storm hazards like drifting snow, would provide further benefit to NDOT.

This study expands on the previously developed NEWINS (Walker et al. 2019b) by developing a predictive winter severity index utilizing forecast data from the National Digital Forecast Database (NDFD). The NDFD is provided by the National Weather Service (NWS) and uses a combination of numerical weather prediction and human inputs to provide forecasts across the United States and is considered a premier forecasting product (Glahn and Ruth 2003). The

Parameter	Category					
	Trace (1)	Marginal (2)	Slight (3)	Enhanced (4)	Moderate (5)	High (6)
Road Access	No Impact	No Impact	Minimal road closures	Occasional road closures	Numerous Road Closures	Significant Road Closures
Road Conditions	Wet Roads	Wet Roads	Spotty snow and ice covered roads, otherwise wet	Roads partially covered with snow and ice	Roads completely covered with snow and ice	Impassable Roads Covered with snow and ice
Traffic Speeds	No Impact	No Impact	Minimal speed reductions	Considerable speed reduction	Significant speed reduction	Significant speed reduction
Treatment Operations	No Deployment	Minimal Deployment	Partial Deployment	Full Deployment	Full Deployment	Full Deployment with Possible Operation Suspension
Winter Maintenance Performance Objective	Met	Met	Likely Met	Unlikely Met	Not Met	Not Met
Storm Classification Road Impacts						

Figure 1.3 Nebraska winter severity index (NEWINS) categorical road and maintenance operations impacts (modified from Walker et al. 2019b).

NDFD has been used in several different applications in the field of meteorology (Hilliker et al. 2010; Page et al. 2018; Tobin et al. 2020). One of the most recent applications is an impacts-based predictive winter storm severity index (WSSI) developed by the NWS (Weather Prediction Center 2024; Tobin et al. 2024). While the NWS WSSI provides helpful forecasts of different winter weather hazards, the index is influenced by population and outputs at a 24-h temporal resolution. This study complements ongoing NWS efforts to modify the WSSI by developing an impacts-based predictive winter severity index, hereafter referred to as NEWINS-Predictive (NEWINS-P). Moreover, the NEWINS-P is developed specifically for use by NDOT whereas the NWS WSSI is for a broader group of NWS partners and stakeholders (e.g., emergency management, school officials, transportation personnel, farmers and ranchers, general public, aviation industry). Atmospheric parameters are collected from the NDFD to develop the multi-component NEWINS-P framework. The NEWINS-P framework is assessed through spatial and temporal forecasts on select Colorado Low and Alberta Clipper Systems from different winter seasons, with particular emphasis on Colorado Low Systems since these systems are more deadly and cause more vehicular crashes (Cecava et al. 2021; Walker et al. 2024).

Chapter 2 Methodology

The study region for the development and testing of the NEWINS-P framework is the state of Nebraska and the eight different NDOT maintenance districts (Figure 2.1). NDFD data from the six NWS weather forecast offices serving Nebraska (Figure 2.1) are collected from the National Centers for Environmental Information (NCEI) archive (NCEI 2024a) on six Colorado Low Systems and three Alberta Clipper Systems from the 2018-19, 2021-22, and 2022-23 winter seasons (Table 2.1). These case studies are chosen because of the significant impacts they caused across the state. Although the case studies are not a complete database of all systems during the study period, they represent known impact situations. For each case study, an NDFD run is chosen to best represent the forecasted conditions, hereafter referred to as the representative NDFD run (Table 2.1). The representative NDFD run for a case study is subjectively determined as the 6:00 pm CST NDFD run on the day that the first instance of snowfall occurs across the state from the National Operational Hydrologic Remote Sensing Center (NOHRSC) 6-h gridded snowfall analysis (NOHRSC 2023). It should be noted that all times given in this report are CST. If the 6:00 pm NDFD run is unavailable, the preceding day’s 6:00 pm NDFD run is used instead. The 6:00 pm NDFD runs are chosen since they provide a 72-h forecast duration for all Colorado Low and Alberta Clipper Systems. Within each representative run, NDFD runs are chosen since these runs provide a 72-h forecast duration for all Colorado Low and Alberta Clipper Systems. Within each representative run, NDFD parameters such as quantitative precipitation forecast (QPF), snow accumulation, ice accumulation, and wind speed parameters are obtained from the contiguous United States sector (Table 2.2) since these data provide the highest spatial and temporal resolution for each of the parameters (NWS 2023a, personal communication; NCEI 2023, personal communication).

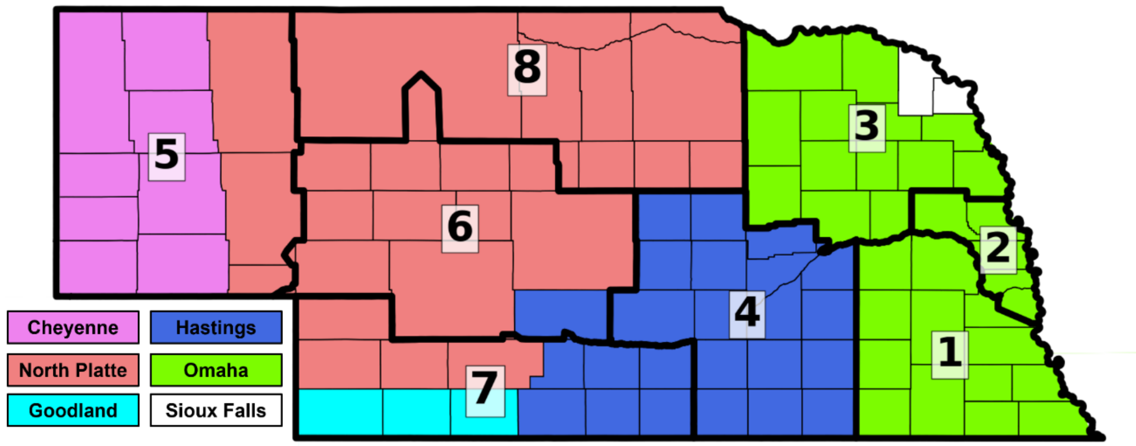

Figure 2.1 The eight NDOT maintenance districts overlaid onto the color-coded county warning areas for NWS Weather Forecast Offices serving Nebraska.

Table 2.1 Selected case studies from the 2018-19 through 2022-23 winter seasons. Each case study's storm type, NDFD representative run, storm period, and maximum snow accumulation coverage are assigned.

Case Study	**System Type**	**NDFD Representative Run**	**Snow Accumulation Period**
13-17 December 2022	Colorado Low	6:00 pm 12 December 2022	6:00 pm 12 December to 6:00 pm 15 December
2-3 January 2023	Colorado Low	6:00 pm 1 January 2023	6:00 pm 1 January to 6:00 pm 3 January
18-19 January 2023	Colorado Low	6:00 pm 17 January 2023	6:00 pm 17 January to 6:00 am 19 January
5-6 February 2021	Clipper	6:00 pm 5 February 2021	6:00 pm 5 February to 6:00 pm 6 February
7-8 February 2021	Clipper	6:00 pm 5 February 2021	6:00 pm 6 February to 6:00 pm 7 February
24-25 November 2018	Colorado Low	6:00 pm 23 November 2018	midnight 24 November to 6:00 pm 25 November
1-2 December 2018	Colorado Low	6:00 pm 30 November 2018	6:00 pm 30 November to noon 4 December
15 February 2019	Clipper	6:00 pm 14 February 2019	midnight 15 February to 6:00 pm 15 February
16-17 February 2019	Colorado Low	6:00 pm 15 February 2019	6:00 am 16 February to 6:00 pm 17 February

Table 2.2 Selected NDFD Parameters and Temporal Resolutions

Meteorological Parameters	**Temporal Resolution Available**		**Temporal Resolution Used**	**Aggregate Method**
	1 to 36 hours	**36 to 72 hours**	**1 to 72 hours**	**--**
Snow Accumulation	6 hours	6 hours	6 hours	N/A
QPF	6 hours	6 hours	6 hours	N/A
Ice Accumulation	6 hours	6 hours	6 hours	N/A
Surface Wind Speed	1 hour	3 hours	6 hours	Average

2.1 Defining a Grid

The NDFD data contain points spanning across the contiguous United States at a 1.6 mile resolution. Since the NEWINS-P framework is designed for Nebraska, only the NDFD data points within the state are considered. To attain a grid containing these points, hereafter referred to as the NEWINS-P grid, a necessary first step is to extract the NDFD data points within Nebraska. To extract these NDFD data points, the NDFD data are compared to an NDOT grid (Table 2.3; NDOT 2023b, personal communication) containing a collection of Nebraska coordinates at approximately a 1.5-mile resolution. The coordinates within the NDFD data that are nearest to the NDOT grid coordinates are then used to derive the NEWINS-P grid. From the NEWINS-P grid, the locations of Nebraska airports from the original NEWINS framework (Walker et al. 2019b) are also identified.

2.2 NEWINS-P Components

The NEWINS-P framework consists of five components (NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood) that are developed from the NDFD parameters to assess different forecasted winter weather hazards spatially and temporally across the case studies (Figure 2.2). Utilizing NDFD data for developing the NEWINS-P framework results in a notable increase in the spatial and temporal resolution across the state of Nebraska compared to the NEWINS framework (Walker et al. 2019b). In other words, the NEWINS-P framework allows for the evaluation of winter storms in a way the original NEWINS could not achieve. Since the NEWINS-P graphical framework uses multiple color scales, a color-blind vision simulator (Pilestone 2023) is used to ensure the analyses are readable and accessible to all audiences. The color scales are run through simulated color deficiencies and blindness tests and

Table 2.3 Number of grid points, spatial areas, and average distance per gird point across the NDOT Districts and the total number of grid points, total spatial area, and average distance per gird point across the state.

NDOT Districts	Number of Grid Points	Spatial Area (x 10^3 mi^2)	Average Distance per Grid Point (mi^2/grid point)
1	3262	7.94	2.30
2	779	1.78	2.26
3	3868	8.80	2.27
4	4246	9.73	2.30
5	6250	14.17	2.27
6	5500	12.59	2.29
7	4012	9.27	2.31
8	5992	13.51	2.25
State	33909	77.79	2.28

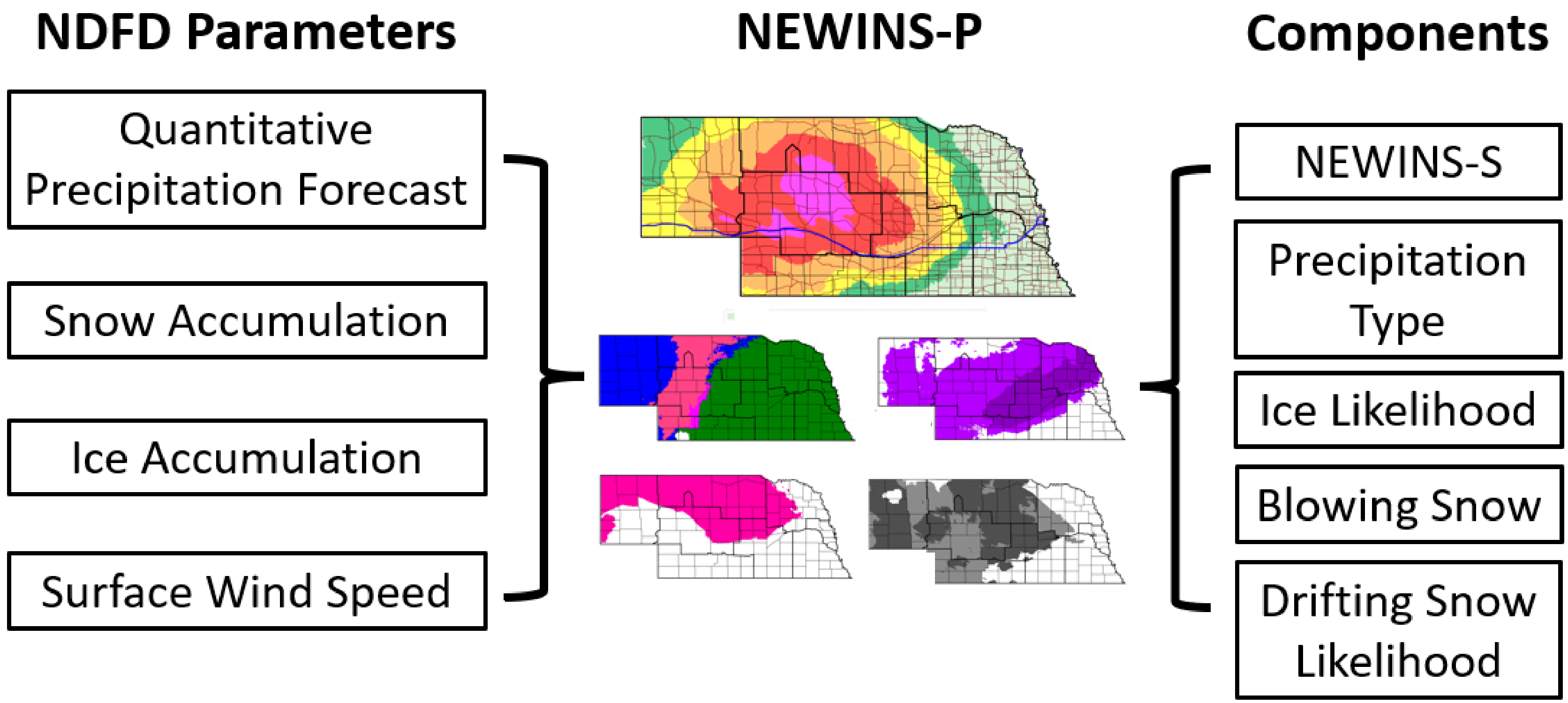

Figure 2.2 Schematic of the multi-component NEWINS-P framework. The NDFD parameters are used to derive the five NEWINS-P components. The graphic is not a real forecast and is meant to showcase a sample NEWINS-P forecast: a) NEWINS-S with NDOT districts and highways (brown lines) and interstates (blue lines) overlaid, b) precipitation type, c) ice likelihood, blowing snow, and drifting snow likelihood. The color scales represented are the scales used throughout the study.

are adjusted as necessary to make sure the colors do not blend in with surrounding colors (Figures 2.3 to 2.5).

2.2.1 NEWINS-S

The NDFD data do not contain identical parameters used to derive the original NEWINS. Therefore, the NEWINS-S component strictly uses the snow accumulation parameter, since NEWINS is weighted 80% by snowfall. NEWINS-S uses the NEWINS snowfall thresholds (Walker et al. 2019b) to output categorical snow accumulation (Figure 2.6). Initially, the NEWINS snow thresholds were divided into four equal periods due to the temporal resolution changing from 24-h to 6-h. However, applying the divided thresholds to the case studies shows that too many locations are assigned NEWINS-S Category 6 and the snow accumulation patterns do not match (Figure 2.7). Using the NEWINS snowfall thresholds improved alignment between the categories and snow accumulation patterns.

To further support the justification, an analysis is conducted on snow accumulation duration and 6-h snow accumulation in a representative sample of Colorado Low and Alberta Clipper Systems from the case study database, which includes the 18-19 January 2023, 2-3 January 2023, and 24-25 November 2018 Colorado Low Systems, and the 5-6 February 2021, 7-8 February 2021, and 15 February 2019 Alberta Clipper Systems. The analysis is conducted inside each case study's system period (Table 2.4) to prevent another system's snow accumulation from being considered. The system period for each case study is based on a subjective assessment of snow accumulation from their representative NDFD run and synoptic conditions to determine the start and end times of snow accumulation across the state. The snow accumulation duration for each location is calculated by summing the total occurrences of 6-h snow accumulation within the system period. The distributions are grouped by system type to

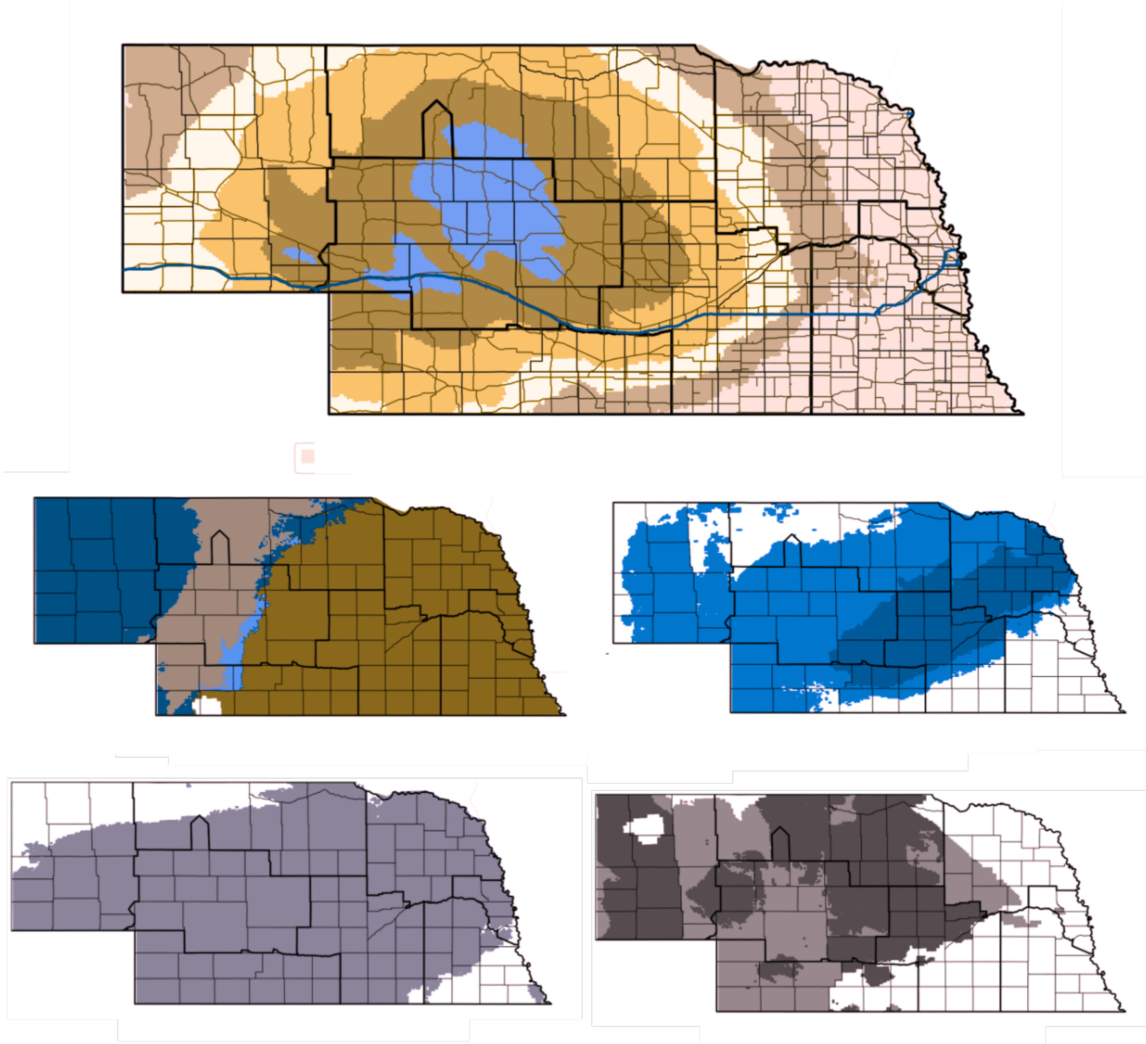

Figure 2.3 Sample NEWINS-P forecast with simulated green color blindness.

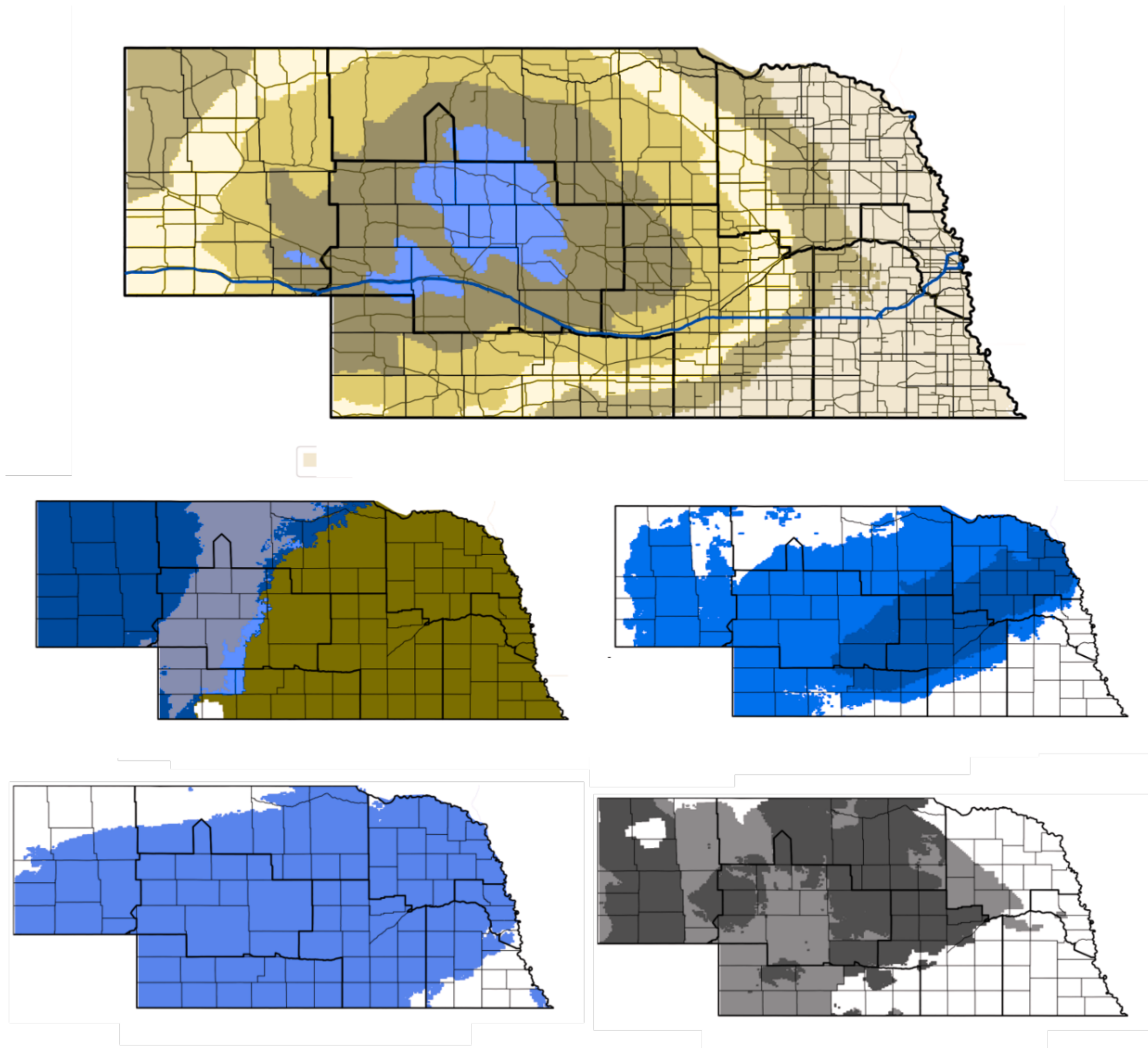

Figure 2.4 Sample NEWINS-P forecast with simulated red color blindness.

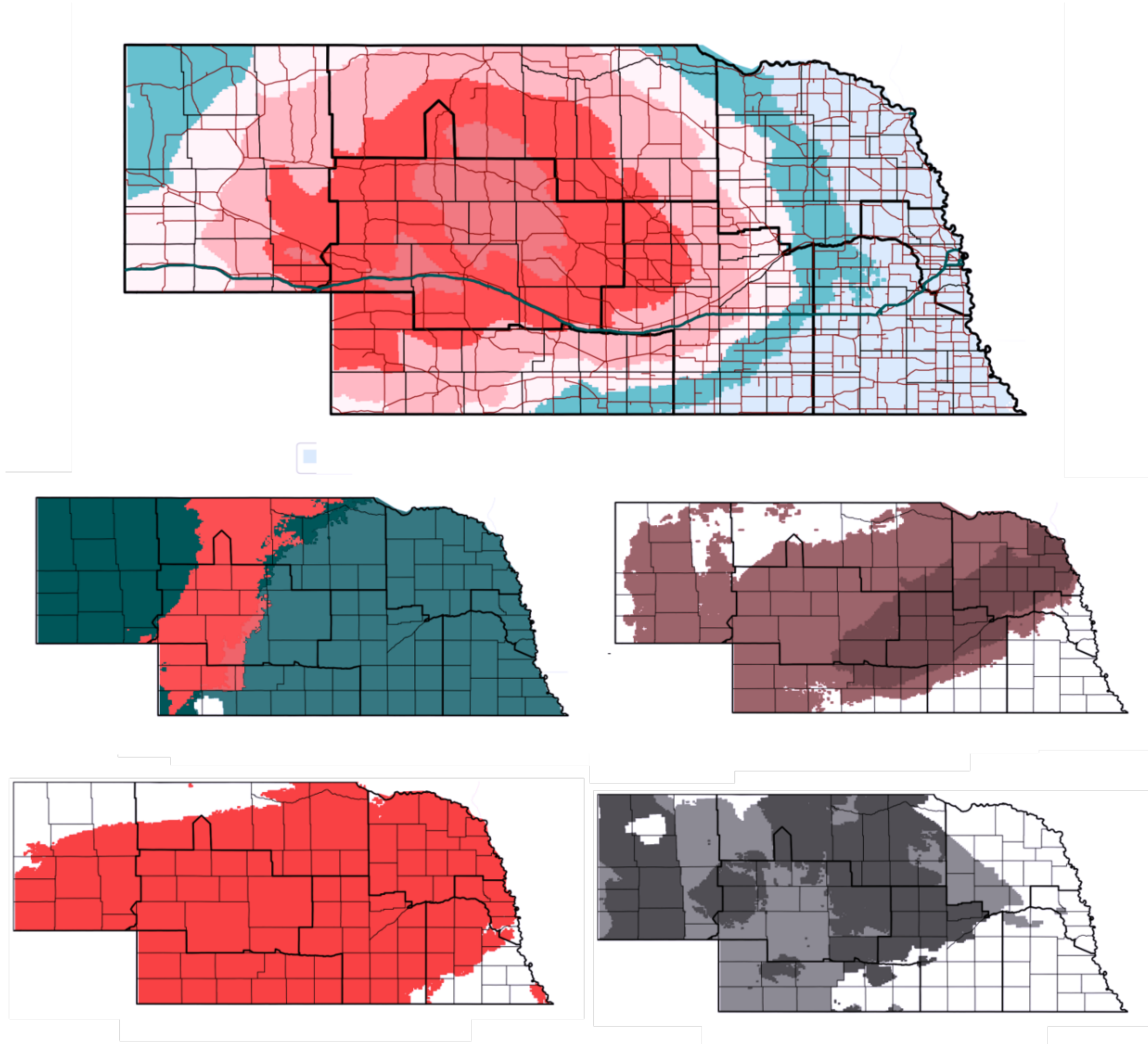

Figure 2.5 Sample NEWINS-P forecast with simulated blue color blindness.

<u>Parameter</u>	**NEWINS-S Category**					
	1	**2**	**3**	**4**	**5**	**6**
Snow Accumulation (inches)	0.1-0.9	1.0-1.9	2.0-2.9	3.0-3.9	4.0-6.9	≥ 7.0

Figure 2.6 Categorical thresholds and color palette for the NEWINS-S components.

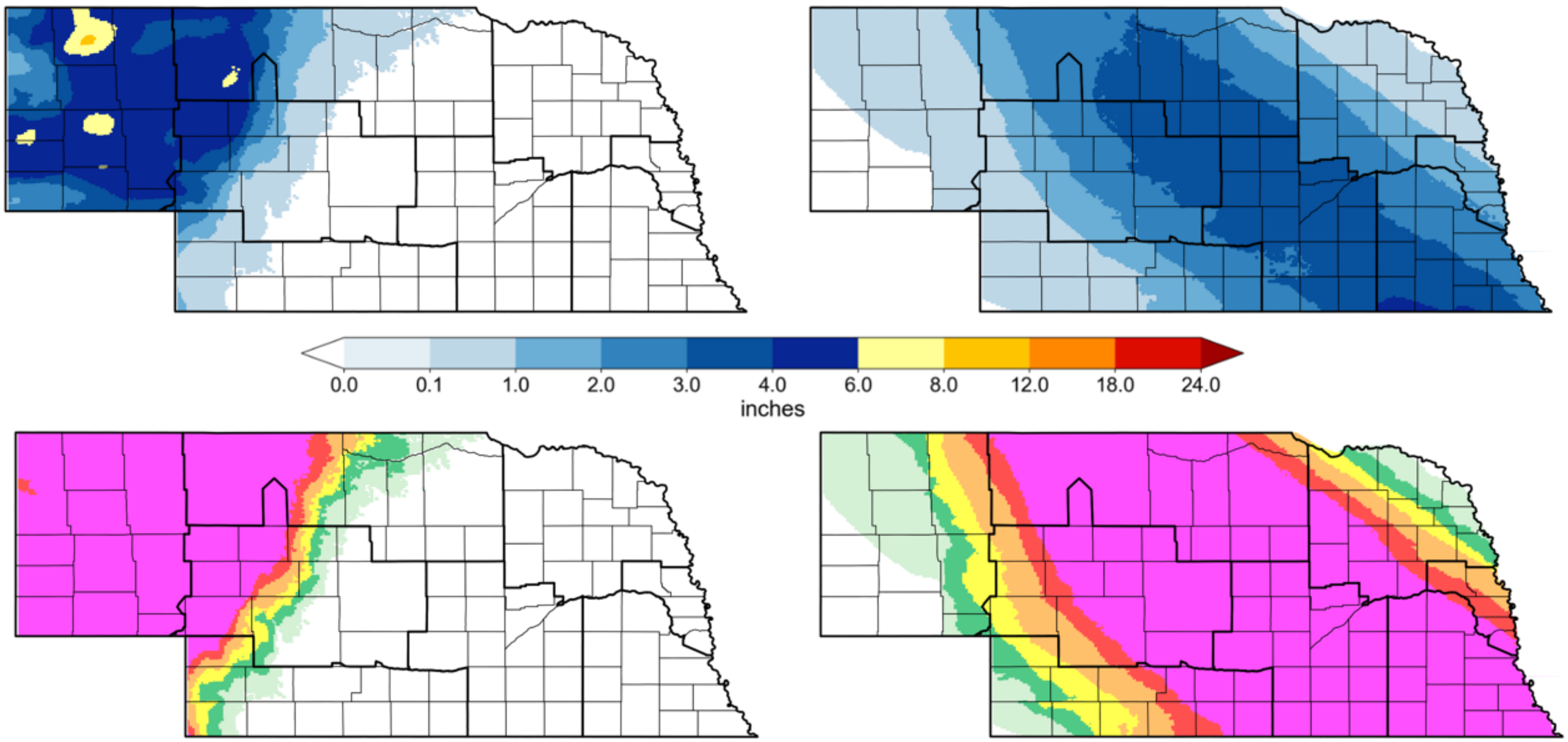

Figure 2.7 Example 6-h snow accumulations from the a) 13-17 December 2022 Colorado Low and b) 15 February 2019 Alberta Clipper Systems and resulting NEWINS-S with divided snow accumulation thresholds applied for the c) 13-17 December 2022 Colorado Low and d) 15 February 2019 Alberta Clipper Systems.

Table 2.4 Analyzed periods and NDFD runs for verification analysis.

Case Studies	**Analyzed Period**	**NDFD Run for Day 1 Forecast**	**NDFD Run for Day 2 Forecast**
24-25 November 2018	6:00 am 24 November to 6:00 am 25 November	6:00 am 24 November	6:00 am 23 November
1-2 December 2018	6:00 am 1 December to 6:00 am 2 December	6:00 am 1 December	6:00 am 30 November
15 February 2019	6:00 am 15 February to 6:00 am 16 February	6:00 am 15 February	6:00 am 14 February
16-18 February 2019	6:00 am 16 February to 6:00 am 17 February	6:00 am 16 February	6:00 am 15 February

showcase the differences in Colorado Low and Alberta Clipper Systems and then combined. Statistics from the combined 6-h snow accumulation distributions are also calculated to complement the analysis. The snow accumulation duration distributions show a longer duration of snow accumulation occurring in Colorado Low Systems than Alberta Clipper Systems (Figure 2.8) with over 50% of the combined distribution below 24 h. The 6-h snow accumulation distributions show a greater 6-h snow accumulation and variability in Colorado Low Systems than Alberta Clipper Systems. The statistics show that the median and percentiles (Table 2.5) scale well with the NEWINS-S thresholds (Figure 2.9) and underscore the importance of using these thresholds since the higher-end categories should only be reserved for high-end, relatively rare 6-h snow accumulations.

A comparison of NEWINS and a 24-h version of NEWINS-S, hereafter referred to as 24-h NEWINS-S, is conducted for the 2018-19 case studies (Table 2.1) to evaluate NDFD forecast performance and show the validity of NEWINS-S. This analysis uses previously computed NEWINS observational data (Walker 2023, personal communication) and forecast data at the airport locations from the 6:00 am NDFD runs within predetermined NEWINS analysis periods (Table 2.5). Since NEWINS abides by a 24-h predetermined window, four 6-h snow accumulation forecasts are summed for valid times within the analysis periods and given a category based on the NEWINS-S thresholds to generate the Day 1 and Day 2 forecasts of 24-h NEWINS-S at each airport location. The 24-h NEWINS-S at the airport locations within each district are averaged and multiplied by the derived district area. The derived district area is calculated by dividing the number of airport locations with non-zero categories in each district by the total number of airport locations in each district. After this process, the district-averaged

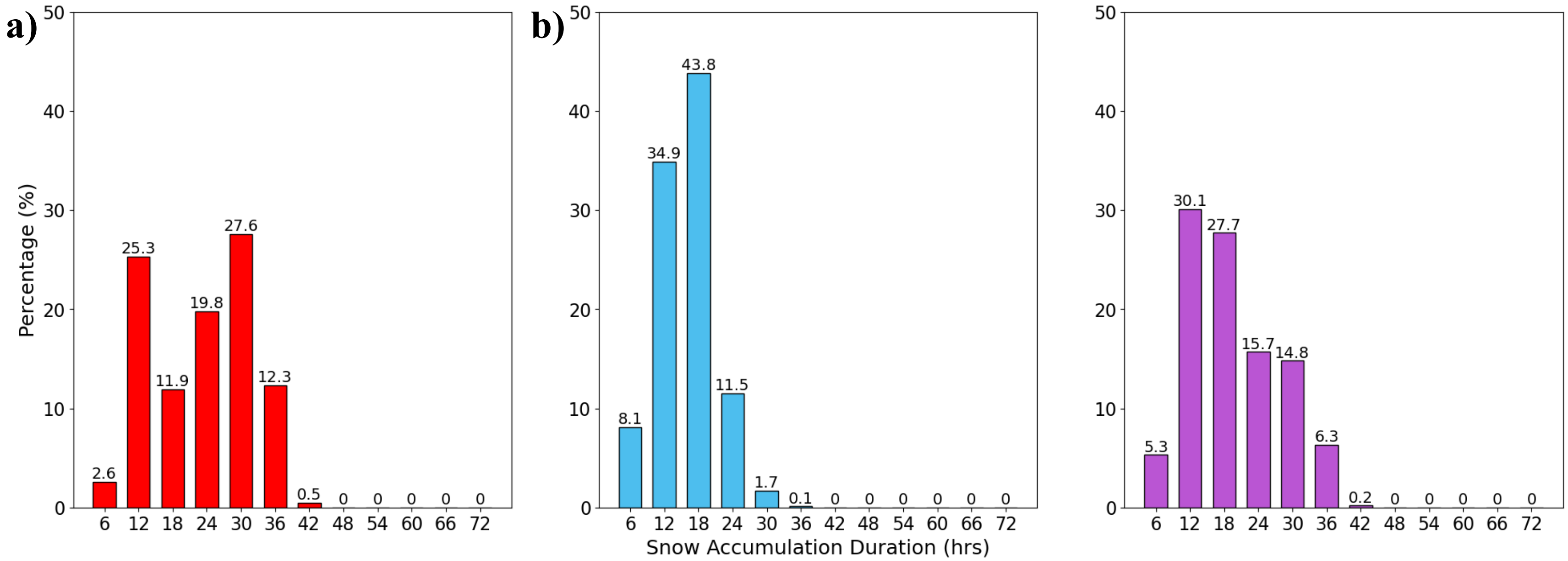

Figure 2.8 Percent distribution of snow accumulation duration for a) both Colorado Low Systems, b) Alberta Clipper Systems, and c) both Colorado Low and Alberta Clipper Systems.

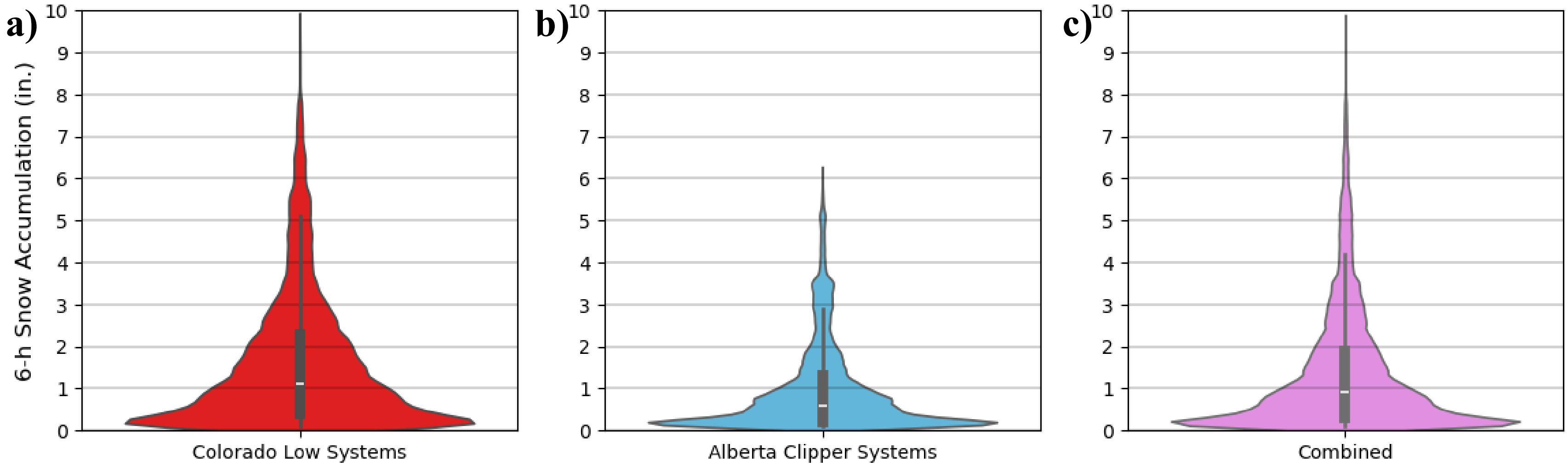

Figure 2.9 Violin plots showing frequency distribution of 6-h snow accumulation for a) both Colorado Low Systems, b) Alberta Clipper Systems, and c) both Colorado Low and Alberta Clipper Systems.

Table 2.5 Statistical parameters from combining 6-h snow accumulations from the 24-25 November 2018, 15 February 2019, 6 February 2021, 7-8 February 2021, 2-3 January 2023, and 18-19 January 2023 case study events.

Statistical Parameters	**Snow Accumulation (in.)**
Mean	1.38
Median	0.91
Standard Deviation	1.46
75th Percentile	1.89
90th Percentile	3.39
95th Percentile	4.69
99th Percentile	6.50

24-h NEWINS-S at each district is rounded. Finally, the difference between 24-h NEWINS-S and NEWINS at each district is taken to calculate the forecast performance for each district.

The four 2018-19 cases exhibit varying levels of Day 1 and Day 2 NDFD performances across the NDOT districts (Figures 2.10 to 2.13). The Day 1 and Day 2 forecasts for the 24-25 November 2018 Colorado Low System (Figure 2.10) show 24-h NEWINS-S only under/over-forecast by two or fewer categories for most of the districts, except for District 1. An under/over-forecast of one or two categories is considered a success, especially since categories are rounded. However, a difference of three categories or more is considered a miss. The 1-2 December 2018 Colorado Low System has more varying NDFD performances across the districts (Figure 2.11). The 24-h NEWINS-S is under/over-forecast by two or less categories in four out of the eight districts (Districts 1, 3, 7, and 8) in the Day 1 and Day 2 forecasts, with an under-forecast as high as four categories in District 2. The pattern of the highest 24-h NEWINS-S is adequate; however, the over-forecast in categories is problematic. The 15 February 2019 Alberta Clipper System reveals that 24-h NEWINS-S is well-forecasted across most districts in the Day 1 and Day 2 forecasts, except for District 3 (Figure 2.12). Surprisingly, the 24-h NEWINS-S is better forecasted for District 3 in the Day 2 forecast than the Day 1 forecast, where the 24-h NEWINS-S goes from under-forecasted by one category to three categories. The 16-17 February 2019 Colorado Low System features well-forecasted 24-h NEWINS-S, with either an under/over-forecast of two or less categories across the districts (Figure 2.13). Combining all the NDFD performances across the districts from the different systems shows that the Day 1 and Day 2 forecasts tend to perform equally (Figure 2.14). While the 24-h NEWINS-S cannot be used as a one-to-one comparison to NEWINS, this verification analysis still provides valuable information regarding forecast verification of NDFD data.

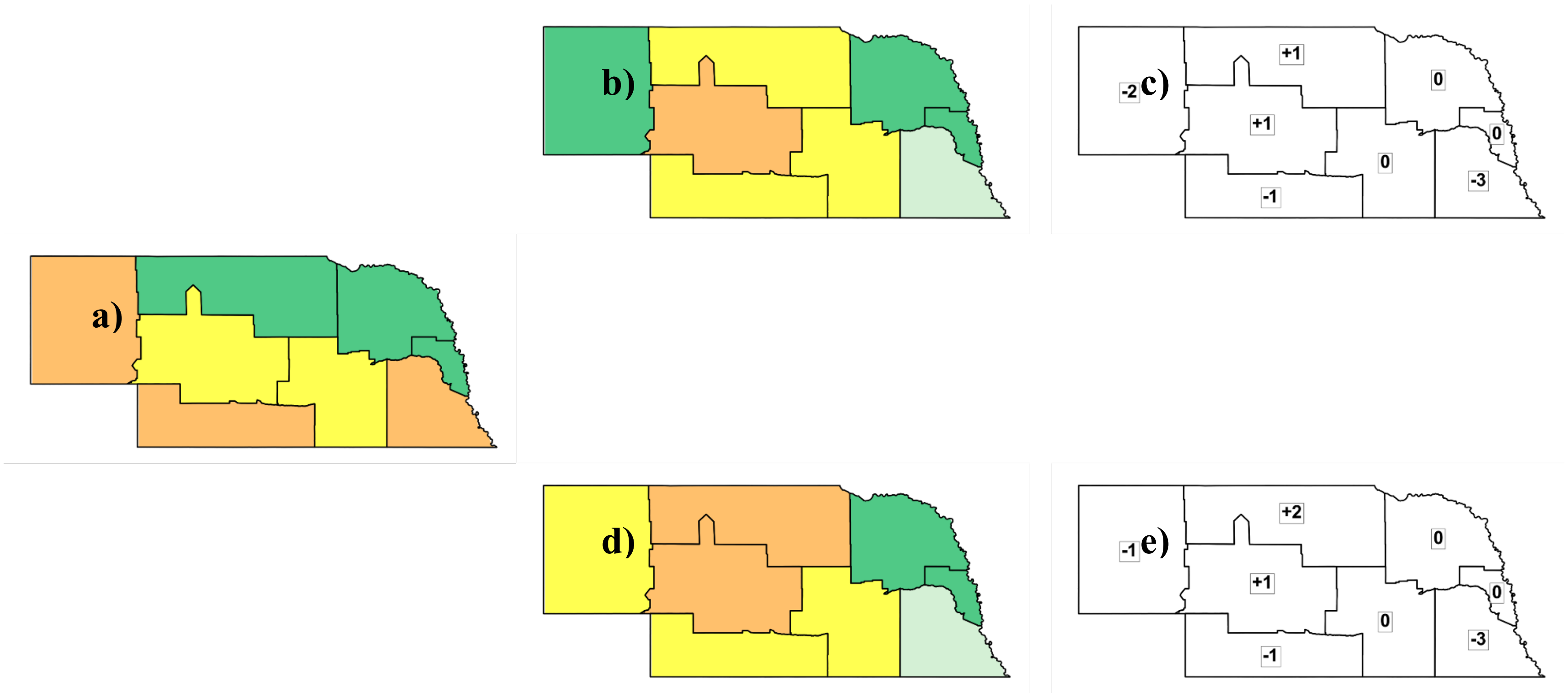

Figure 2.10 Day 1 and Day 2 forecast performances of the 24-25 November 2018 Colorado Low System for the NDOT districts within the 6:00 am 24 November to 6:00 am 25 November analyzed period. a) NEWINS, b) Day 1 24-h NEWINS-S from the 6:00 am 24 November NDFD run, c) departures between NEWINS and Day 1 24-h NEWINS-S, d) Day 2 24-h NEWINS-S from the 6:00 am 23 November NDFD run, and (e) departures between NEWINS and the Day 2 24-h NEWINS-S.

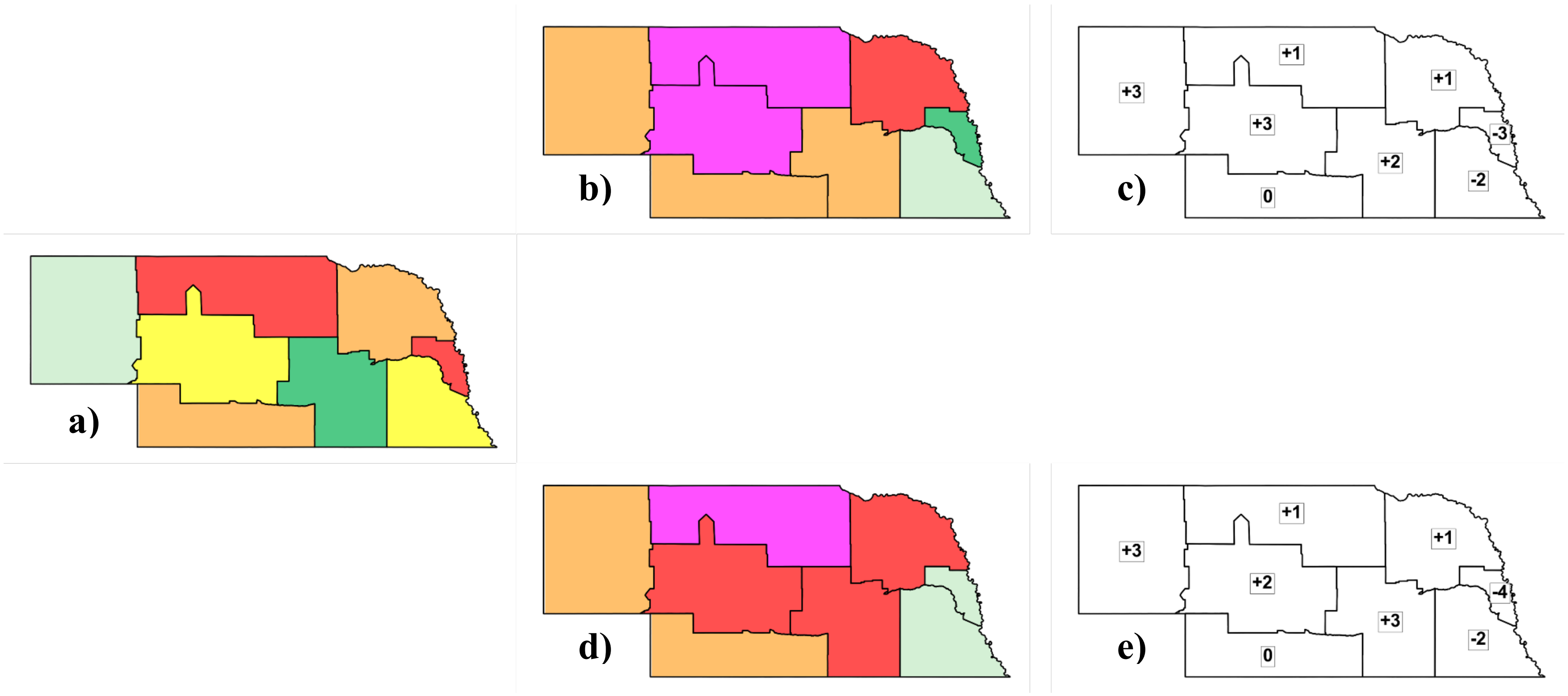

Figure 2.11 Day 1 and Day 2 forecast performance of the 1-2 December 2018 Colorado Low System for the NDOT districts within the 6:00 am 1 December to 6:00 am 2 December analyzed period. a) NEWINS, b) Day 1 24-h NEWINS-S from the 6:00 am 1 December NDFD run, c) departures between NEWINS and the Day 1 24-h NEWINS-S, d) Day 2 24-h NEWINS-S from the 6:00 am 30 November NDFD run, and e) departures between NEWINS and the Day 2 24-h NEWINS-S.

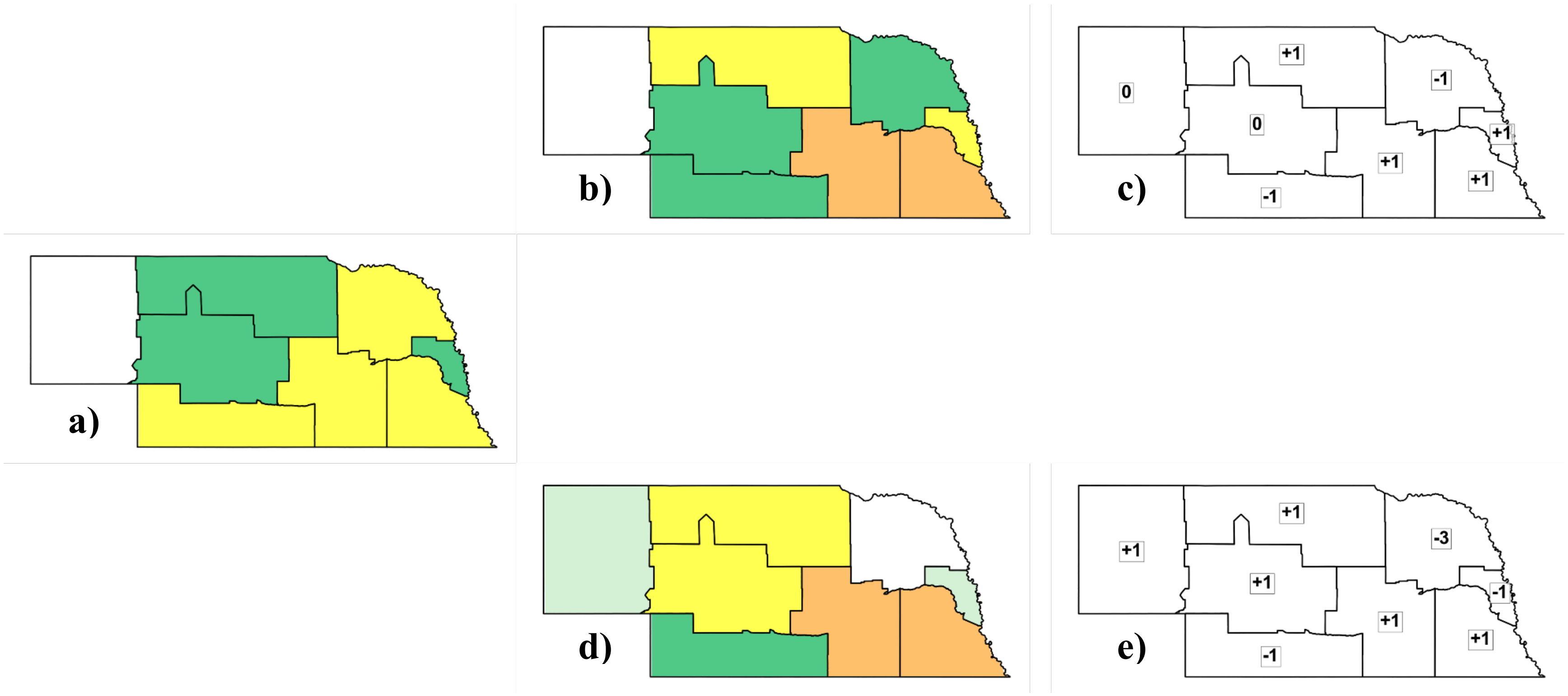

Figure 2.12 Day 1 and Day 2 forecast performances of the 15 February 2019 Alberta Clipper System for the NDOT districts within the 6:00 am 15 February to 6:00 am 16 February analyzed period. (a) NEWINS, (b) Day 1 24-h NEWINS-S from the 6:00 am 15 February NDFD run, (c) departures between NEWINS and the Day 1 24-h NEWINS-S, (d) Day 2 24-h NEWINS-S from the 6:00 am 14 February NDFD run, and (e) departures between NEWINS and the Day 2 24-h NEWINS-S.

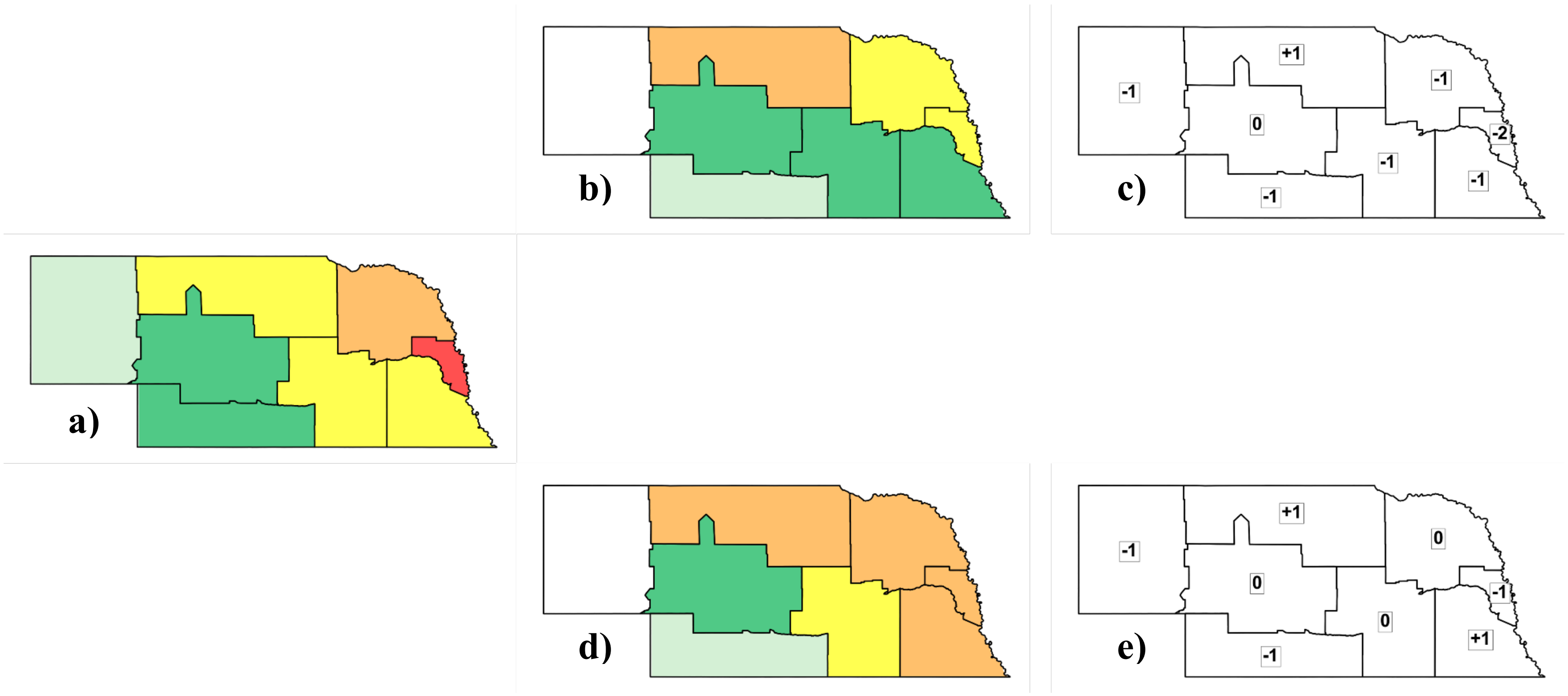

Figure 2.13 Forecast performance of the 16-17 February 2019 Colorado Low System across the NDOT districts within the 6:00 am 16 February to 6:00 am 17 February analyzed period. (a) NEWINS, (b) Day 1 24-h NEWINS-S from the 6:00 am 16 February NDFD run, (c) departures between NEWINS and Day 1 NEWINS-S, (d) Day 2 NEWINS-S from the 6:00 am 15 February NDFD run, and (e) departures between NEWINS and Day 2 24-h NEWINS-S.

Therefore, since minor differences could be from the human factor or numerical weather prediction, the 24-h NEWINS-S is close enough to continue with the snow accumulation criteria used in NEWINS-S to investigate the case studies.

2.2.2 Precipitation Type and Ice Likelihood

The precipitation type component classifies four different types of precipitation using the QPF and ice accumulation parameters as well as the NEWINS-S component for snow accumulation information (Figure 2.15). QPF is used as a baseline for identifying precipitation. If QPF is forecasted, the precipitation type can either be classified as either snow, a mixture of ice and snow, ice, or rain. The precipitation type is classified as snow if NEWINS-S is forecasted without any ice accumulation. However, if ice accumulation and NEWINS-S are concurrently forecasted, then the precipitation type is classified as a mixture of ice and snow. If there is ice accumulation and no NEWINS-S concurrently forecasted, then the precipitation type is classified as ice. Since there is no rain parameter, the precipitation type is determined to be rain if there is no NEWINS-S nor ice accumulation. The ice likelihood component strictly uses the ice accumulation parameter and considers a 0.06 inch threshold to discriminate between different likelihoods of icing (Figure 2.16). Icing is considered possible if ice accumulation is forecasted to be greater than 0.0 inches and less than 0.06 inches, while icing is considered likely if ice accumulation is forecasted to be greater than 0.06 inches. The threshold was obtained in consultation with NDOT and by accumulating 0.01 inches, the minimum accumulation possible within an hour, for a 6-h period, noting that ice accumulation is given in a 6-h temporal resolution. While the precipitation type component showcases the general locations of icing, the ice likelihood component can be used to identify regions of increased ice likelihood which can

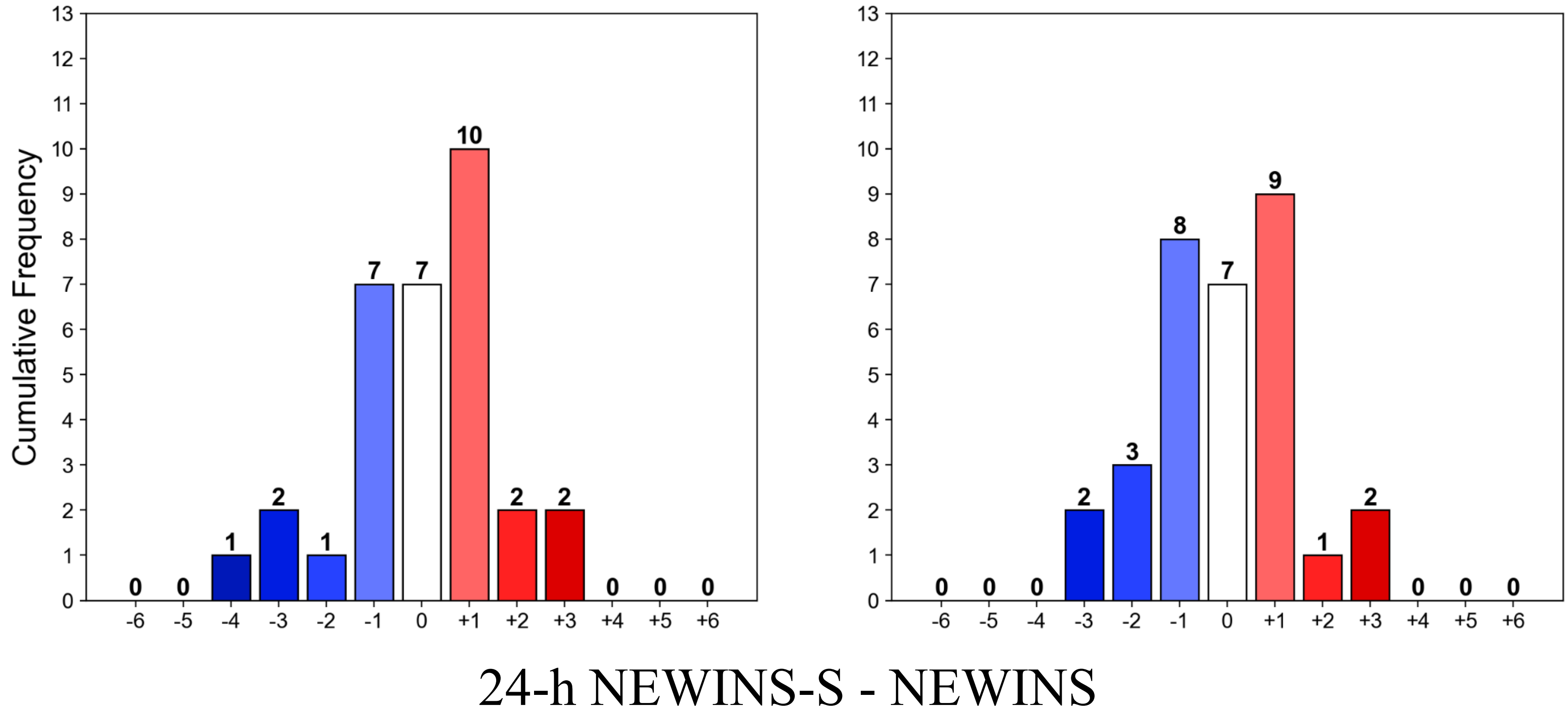

Figure 2.14 Distributions of a) Day 1 and b) Day 2 forecast performances across the NDOT districts from the 24-25 November 2018, 1-2 December 2018, 16-17 February 2019 Colorado Low Systems, and 15 February 2019 Alberta Clipper System. Positive departures represent an over forecast of 24-h NEWINS-S, negative departures represent an under forecast of 24-h NEWINS-S.

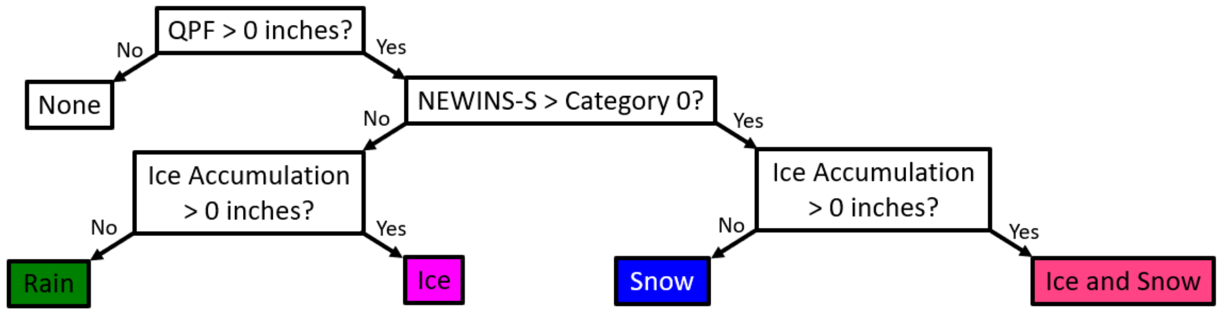

Figure 2.15 Schematic of the workflow, classifications, and color palette for the precipitation type component.

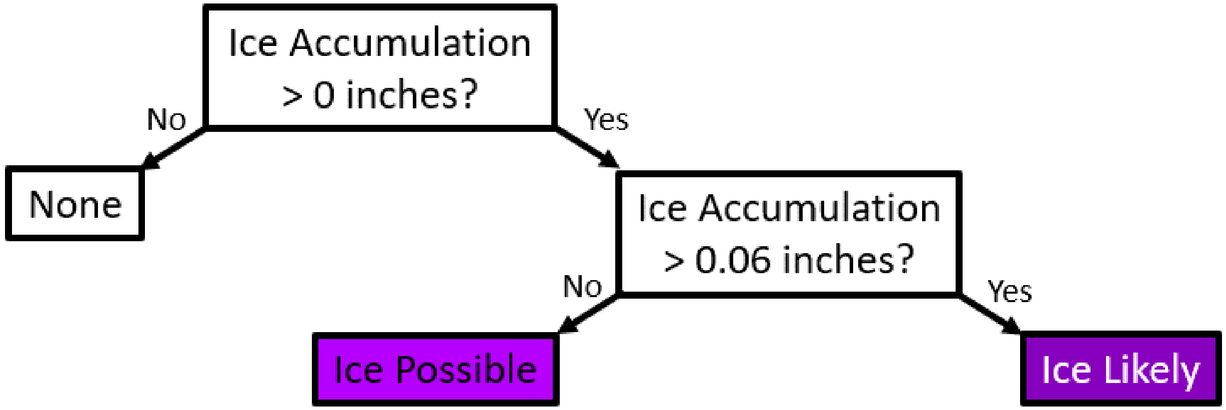

Figure 2.16 Schematic of the workflow, classifications, and color palette for the ice likelihood component

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be used as a proxy for ice severity, something that the precipitation type component fails to detect.

2.2.3 Blowing/Drifting Snow

Blowing snow is defined as concurrently forecasted NEWINS-S and high surface wind speeds, while drifting snow is defined as high surface wind speeds occurring after NEWINS-S was forecasted. In other words, blowing snow occurs during the period of precipitation (in-storm impact), while drifting snow occurs after the precipitation has concluded (post-storm impact). As such, the NEWINS-S component and surface wind speed parameter are used to develop the blowing snow and drifting snow likelihood components. The NEWINS-S component provides data at a 6-h temporal resolution and as an accumulation whereas the surface wind speed parameter is provided at a sub 6-h temporal resolution and as instantaneous values (Table 2.2). These temporal differences result in the NEWINS-S component and surface wind speed parameter not being temporally aligned. To temporally align them, 6-h surface wind speed averages are computed for each 6-h period. The surface wind speed thresholds for the blowing snow and drifting snow likelihood components are developed from a combination of previous literature on critical thresholds for blowing and drifting snow (Li and Pomeroy 1997; Baggaley and Hanesiak 2005) and in consultation with NDOT (NDOT 2023b, personal communication). The blowing snow component considers a forecast for NEWINS-S in concurrence with a surface wind speed greater than or equal to 15 mph (Figure 2.17). The drifting snow likelihood component utilizes higher surface wind speed thresholds and considers currently forecasted NEWINS-S and uses previously forecasted NEWINS-S as an indicator to determine if snow accumulation is no longer occurring. The indicator is triggered if no NEWINS-S is currently forecasted yet there was NEWINS-S previously forecasted $(\text{NEWINS-S})_p$ at any time within the same run. In other words, the algorithm assesses if snow is accumulating and on the ground. From there, the surface wind speeds are used to flag for drifting snow potential. Drifting snow is possible if the surface wind speed is greater than or equal to 20 mph and less than 25 mph, while drifting snow is likely if the surface wind speed is greater than or equal to 25 mph. Two important limitations are that 1) data cannot be calculated at the first 6-h period since there is nothing to compare to, and 2) the component cannot forecast ongoing drifting snow across multiple NDFD runs following the departure of the system.

2.3 Case Study Analysis

To provide context for the case studies, the 24-, 48-, and 72-h NOHRSC snowfall products and NWS local storm reports from the Iowa Environmental Mesonet (IEM 2024) are used to provide snowfall and icing summaries for each event, respectively. In addition, 6-h NOHRSC snowfall products are used to provide useful information such as snowfall timing and intensity.

2.3.1 NEWINS-P Forecasts and NDFD Evolution

The representative NDFD run (Table 2.1) from each case study is used to showcase spatial and temporal forecasts of the NEWINS-P components for a maximum duration of 72 h.

The spatial forecasts examine the components across Nebraska, while the temporal forecasts examine the components at select airport locations in the form of meteogram forecasts, hereafter referred to as Ngram forecasts. The airport locations chosen for Ngram forecasts are subjectively chosen to best represent the highest impact local forecast conditions for each case study. Since the NEWINS-P forecasts provide only one solution to the forecast conditions, 6:00 am and 6:00 pm NDFD runs prior to and following each representative run are gathered to assess

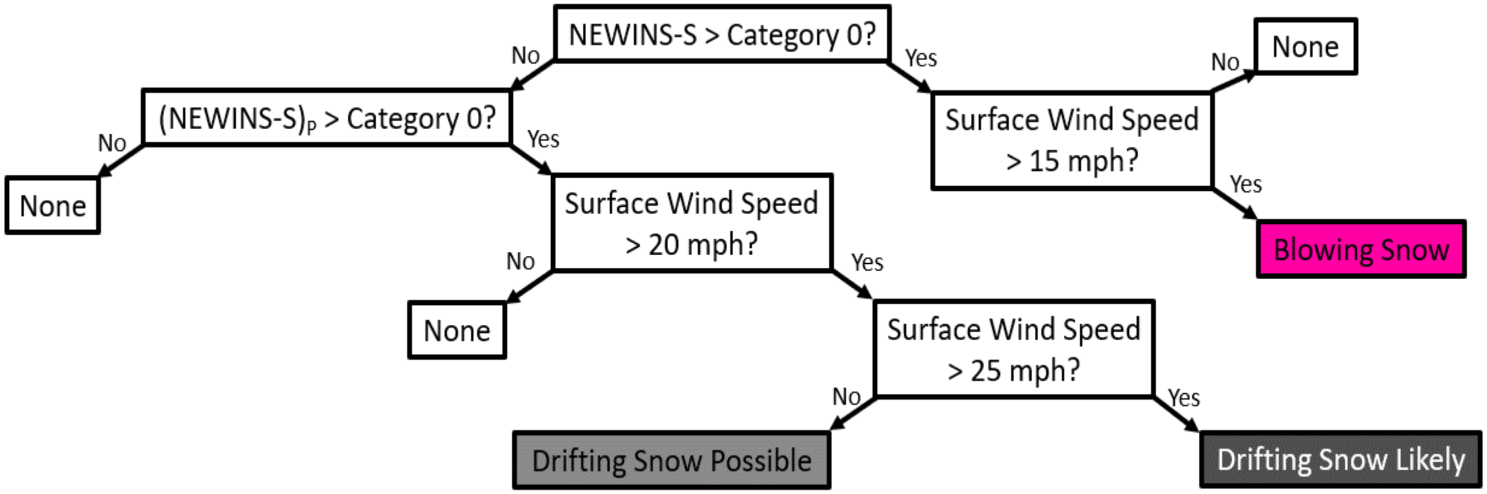

Figure 2.17 Schematic of the workflow, classifications, and color palette for the blowing snow and drifting snow likelihood components. Drifting snow results if there is no concurrent NEWINS-S and there is preceding NEWINS-S (NEWINS-S)

the spatial and temporal evolution in select components such as the NEWINS-S, precipitation type, and ice likelihood components. The number of components evaluated in each case study is dependent on meteorological conditions. The blowing snow and drifting snow likelihood components are not considered in the evolution for each case study. Spatial evolution considers meteorologically significant valid times within each case study to highlight statewide changes in select components through the comparison of forecasts. The temporal evolution is investigated in the form of a time series to offer a comparison of forecasts for multiple valid times at a location. The time series assesses the changes in select components at the airport locations chosen for Ngram forecasts or another airport location that is chosen to best represent the evolution. For each time series, the number of NDFD runs used is dependent on the period of impacts of the analyzed component within the systems period (Table 2.1) in the selected location's Ngram forecast. NDFD runs that contain valid periods within each component's impact period are considered.

Chapter 3 Case Study Results

The case studies are examined in reverse chronological order by winter season and chronological order within each winter season. Analysis begins with the 2022-23 winter season and ends with the 2018-19 winter season due to NDFD data quality improvements and increased use which poses the possibility that more recent NDFD data are better than older data. The first two case studies are evaluated and discussed to highlight the type of system (Colorado Low or Alberta Clipper) as well as other weather features associated with the event. NEWINS-P spatial and temporal forecasts are shown from the case study's representative NDFD run, as well as the spatial and temporal evolution of select components from multiple NDFD runs where applicable.

The remaining case studies are condensed to reduce space and readability (Sections 3.3-3.8). These cases are examined in full detail and the complete investigation for each case is available in Kauzlarich (2024). In this chapter, each of the remaining cases will be presented to illustrate the application of NDFD runs to forecast events and how well the case is represented by NEWINS-S categories. The snowfall observations are presented for the event, followed by spatial maps displaying NEWINS-S categories during the evolution of the event. Lastly, NEWINS-S category histograms are generated to show changes in categories during the event.

3.1 Case Study: 13-17 December 2022 Colorado Low System

The 13-17 December 2022 case study event is a Colorado Low System that impacts western Nebraska with over 12 inches of snowfall (Figure 3.1). A combination of strong winds and cold temperatures slows abilities to treat snowfall during and several days after precipitation ends, causing severe impacts from blowing and drifting snow (Figure 3.2). As a result, whiteout conditions and numerous road closures were reported across western Nebraska due to drifting snow (Figure 3.3 to Figure 3.5).

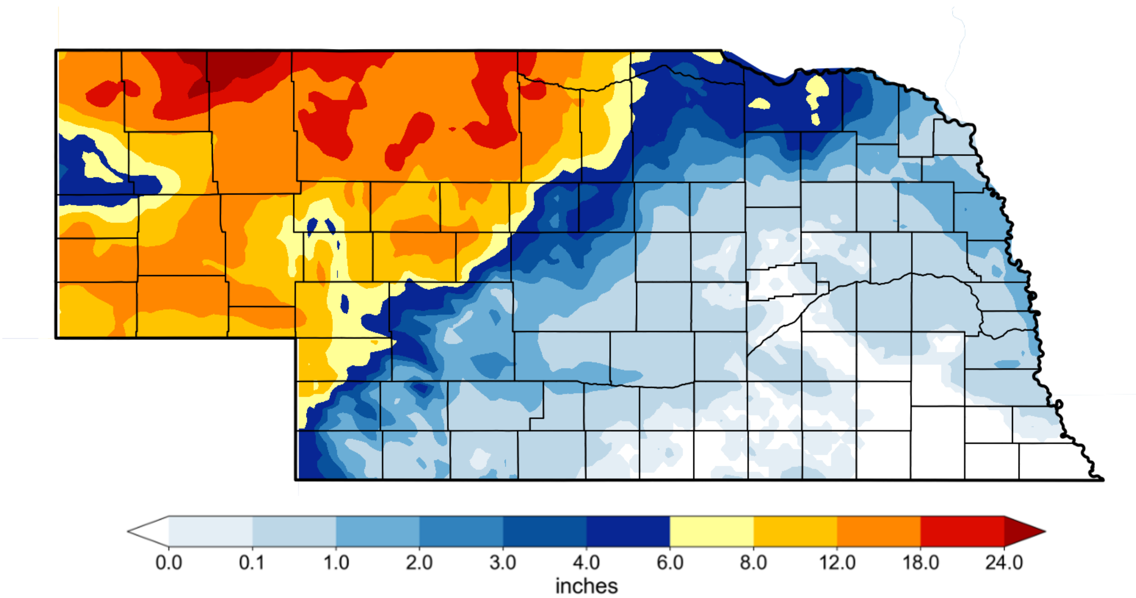

Figure 3.1 NOHRSC 72-h accumulated snowfall (inches) starting at 6:00 pm 12 December 2022 and ending at 6:00 pm 15 December (adapted from NOHRSC 2023).

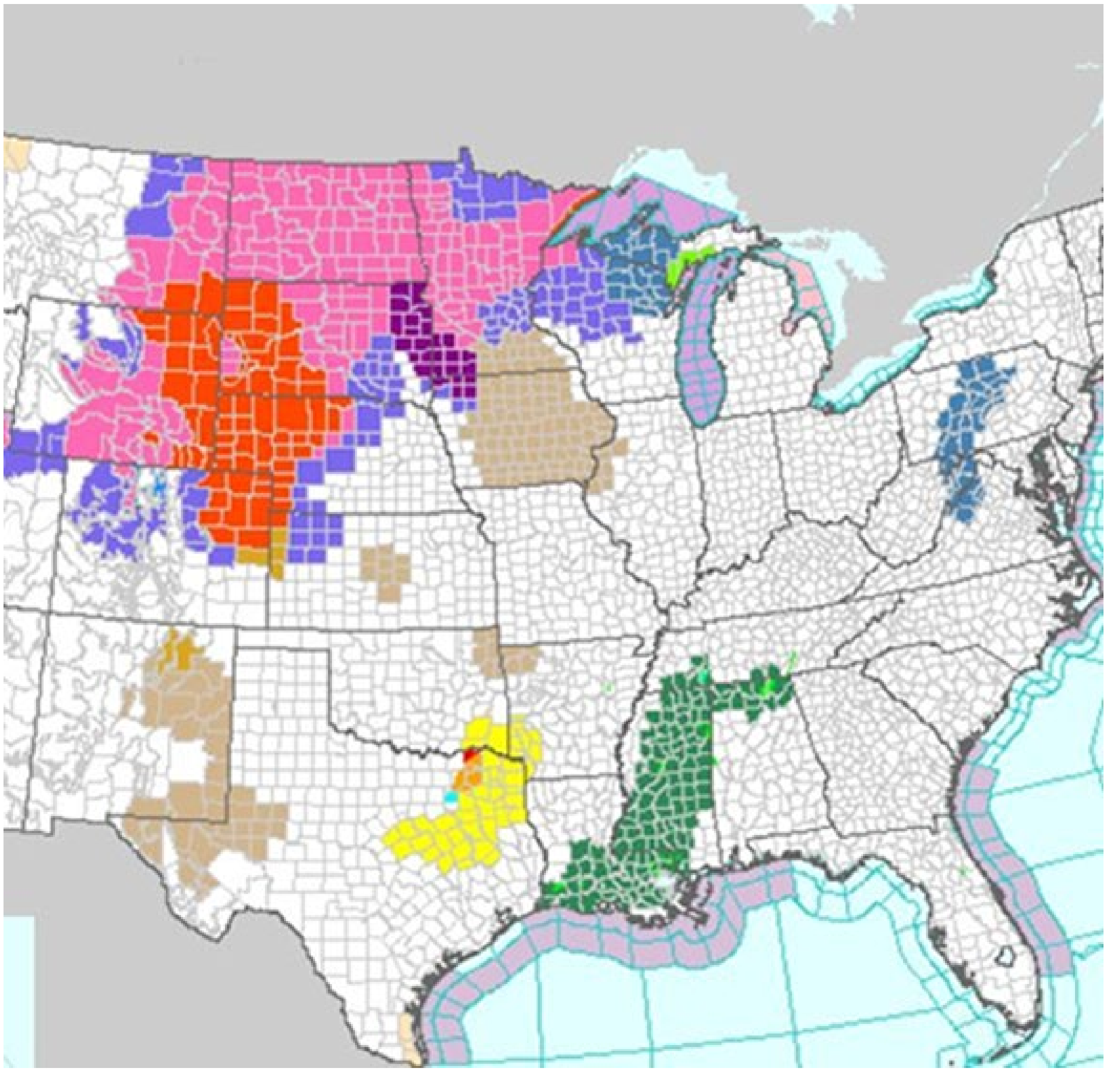

Figure 3.2 NWS watches, warnings, and advisories valid for 11:03 am 13 December 2022 (obtained from NWS 2022).

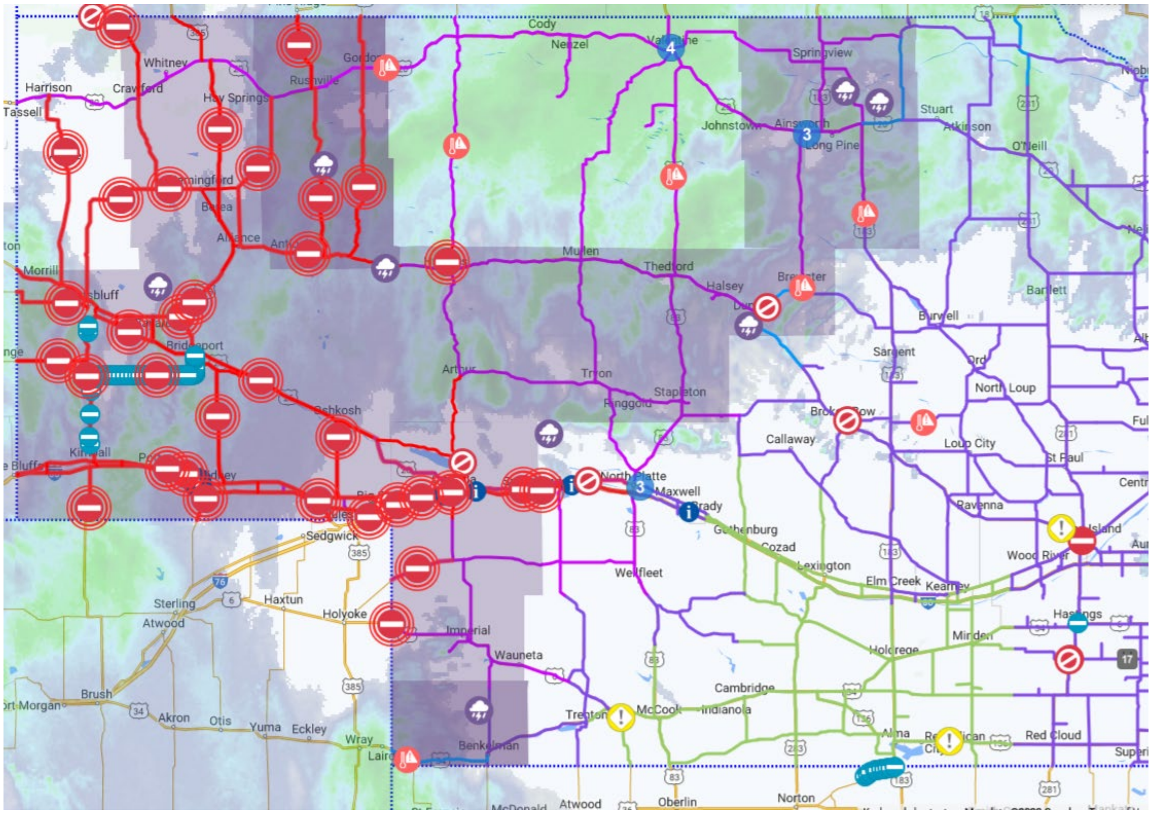

Figure 3.3 NDOT Nebraska 511 Travel Information screenshot valid for 11:43 am 13 December 2022. Red lines denote road closures. (obtained from NDOT 2023)

Figure 3.4 NDOT traffic camera screenshots valid for 7:24 am 16 December 2022 at I-80 mile marker 95 (obtained from NDOT 2023).

Figure 3.5 NDOT traffic camera screenshot valid for 7:45 am 16 December 2022 at I-80 and I-76 interchange mile marker 102 (obtained from NDOT 2023).

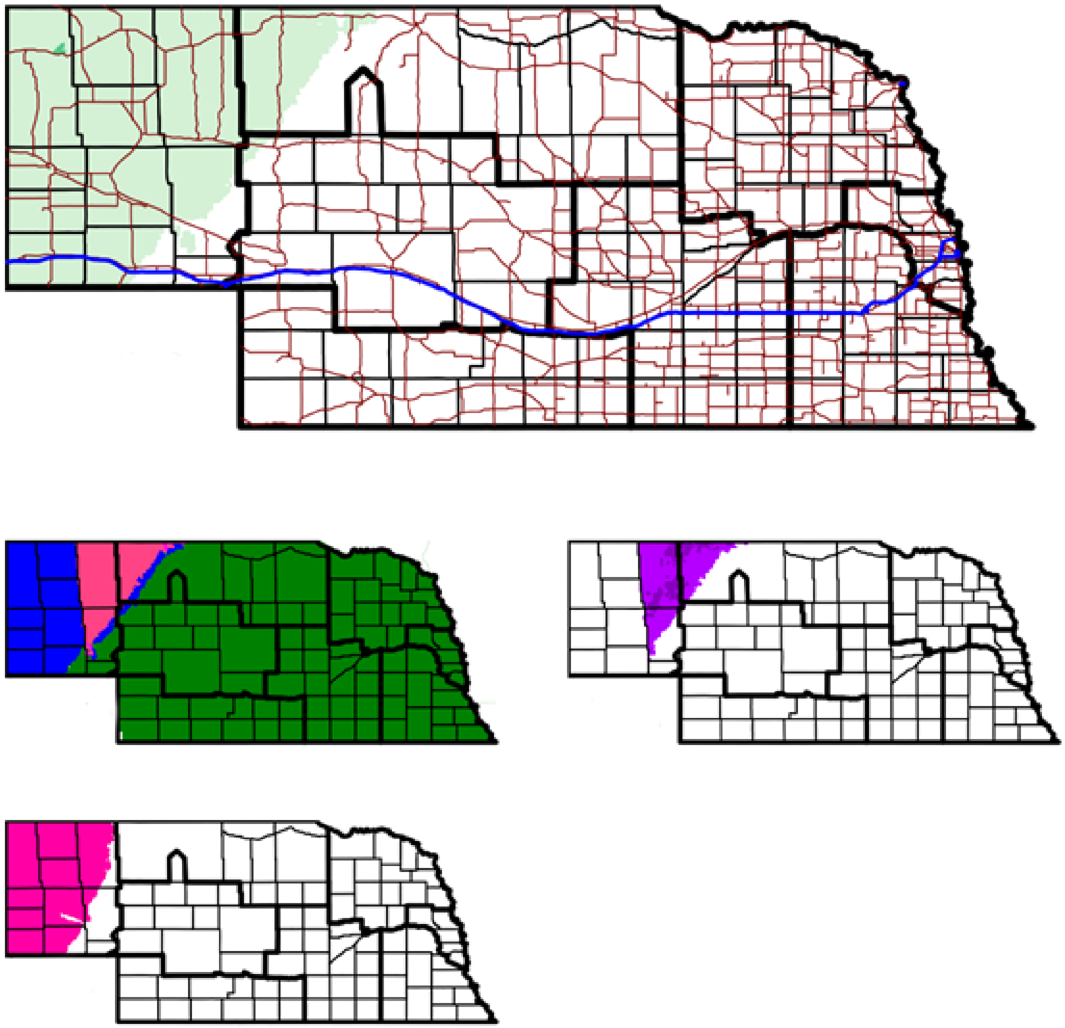

Figure 3.6 The 6-h NEWINS-P forecast from the 6:00 pm 12 December 2022 NDFD run valid for midnight 13 December comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

3.1.1 NEWINS-P Forecasts: 13-17 December 2022

The NEWINS-P forecasts from the representative NDFD run (Table 2.1) highlight the NEWINS-S categories and multi-day blowing/drifting snow concerns associated with the Colorado Low System (Figures 3.6 to 3.31). The 6-h forecast (Figure 3.6) marks the onset of the system across western Nebraska with forecasted NEWINS-S Category 1 and blowing snow. Across portions of Districts 5 and 8, mixed precipitation is anticipated along the transition zone with accompanying low ice likelihood. The coverage and intensity of these winter weather hazards expands eastward in the 12-h forecast (Figure 3.7), with NEWINS-S Categories 2 to 4 forecasted across District 5 and mixed precipitation expanding to include western portions of Districts 6 and 7. The 18-h forecast (Figure 3.8) marks the peak of the event with NEWINS-S Categories 3 to 6 across most of District 5. For districts further east, NEWINS-S expands eastward, and mixed precipitation begins to affect central portions of Districts 6 and 8 and western portions of District 7. Within the mixed precipitation, there is a forecast of ice likelihood across portions of Districts 6 and 8. The mixed precipitation changes to all snow by the 24-h forecast (Figure 3.9). Further west, the highest NEWINS-S categories become confined to northern Nebraska as the heaviest precipitation begins to move out of the state. The highest NEWINS-S categories continue to move northward for the 30-h forecast (Figure 3.10) with blowing snow coverage increasing to include most of Districts 5, 6, and 8. By the 36-h forecast (Figure 3.11), NEWINS-S categories decrease to 0 across south-central Nebraska; however, drifting snow is forecasted across the area due to continued elevated wind speeds. The 42-h to 72-h forecasts (Figures 3.12 to 3.17) feature the expansion of drifting snow risk northward as NEWINS-S categories depart.

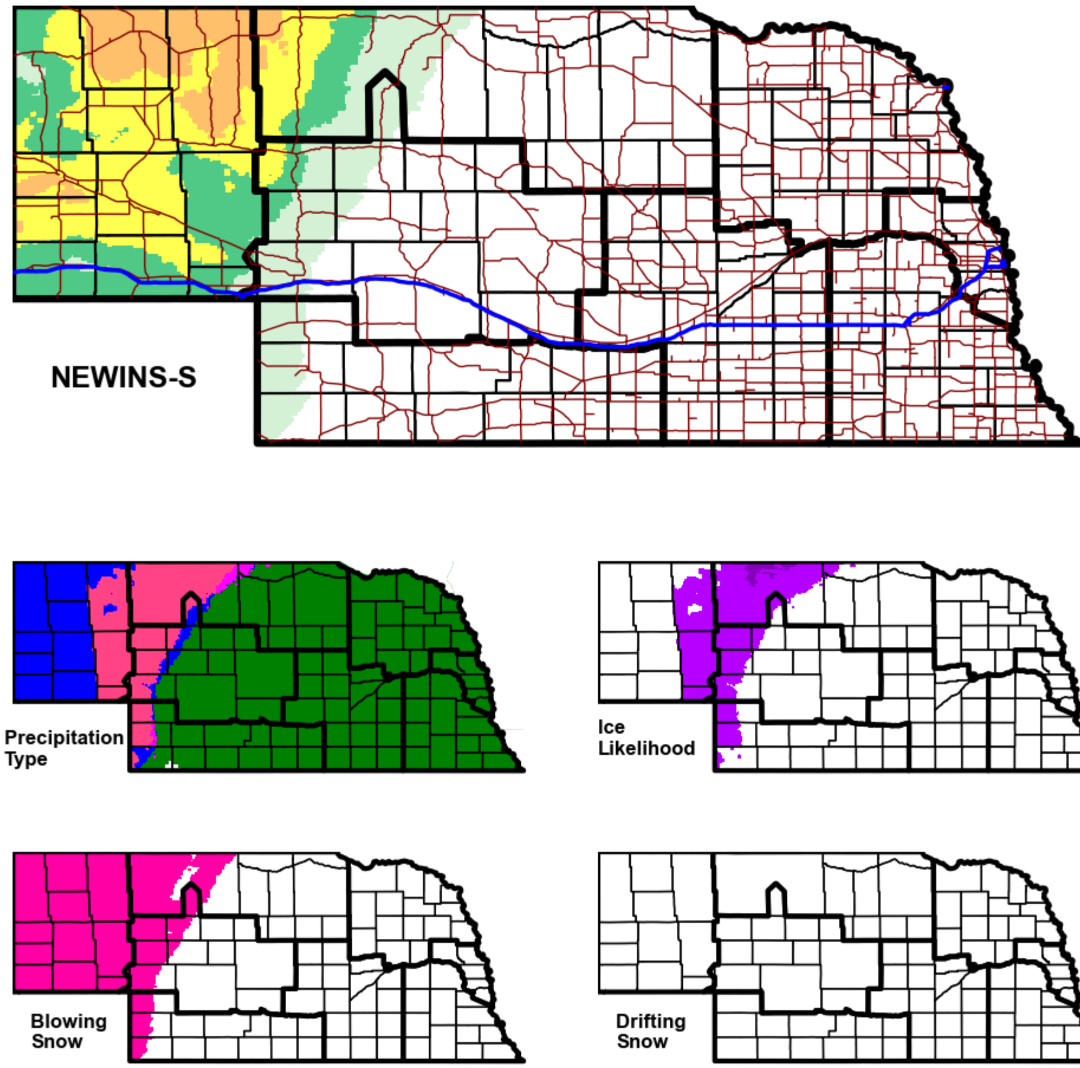

Figure 3.7 The 12-h NEWINS-P forecast from the 6:00 pm 12 December 2022 NDFD run valid for 6:00 am 13 December comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

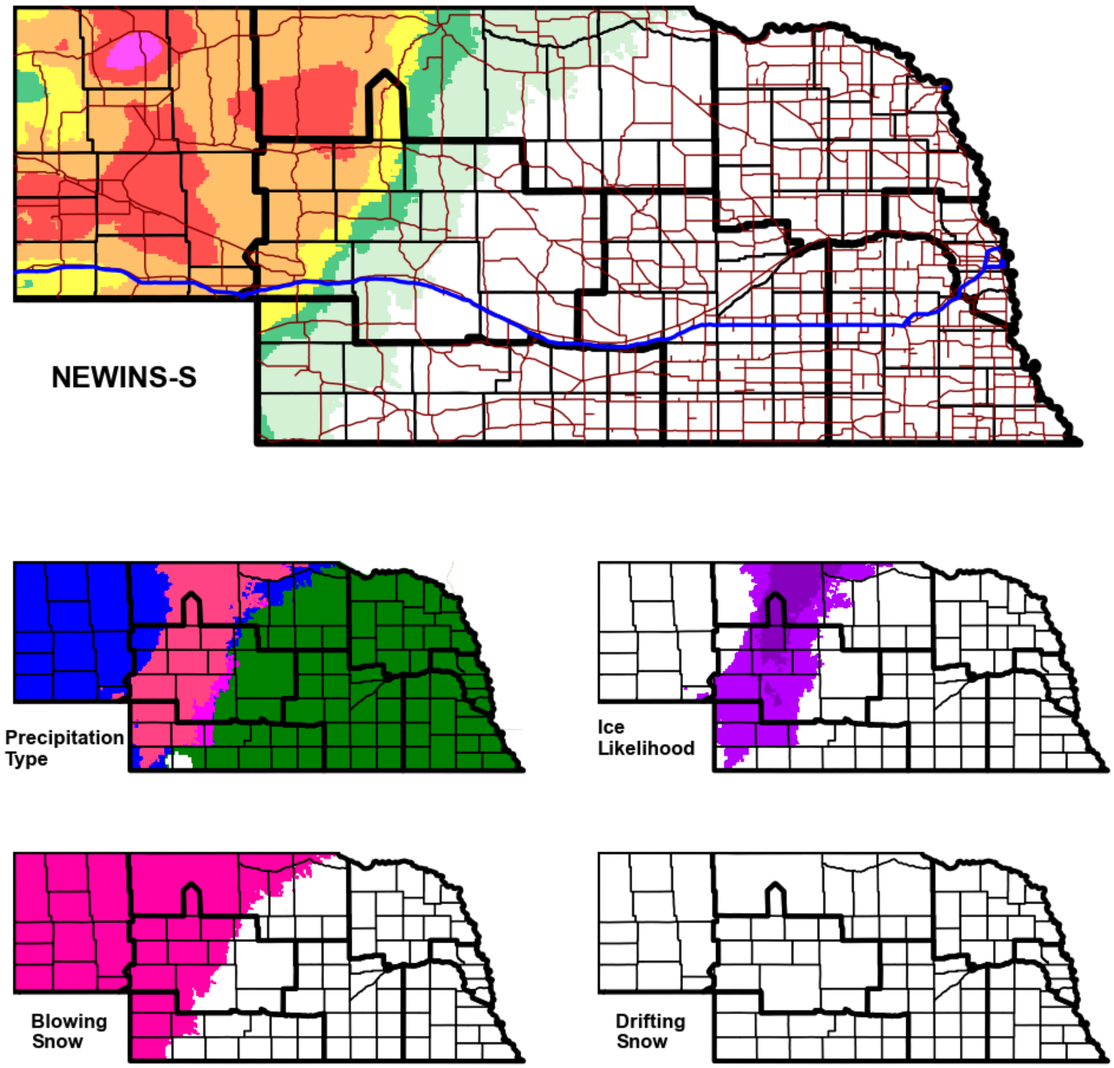

Figure 3.8 The 18-h NEWINS-P forecast from the 6:00 pm 12 December 2022 NDFD run valid for noon 13 December comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

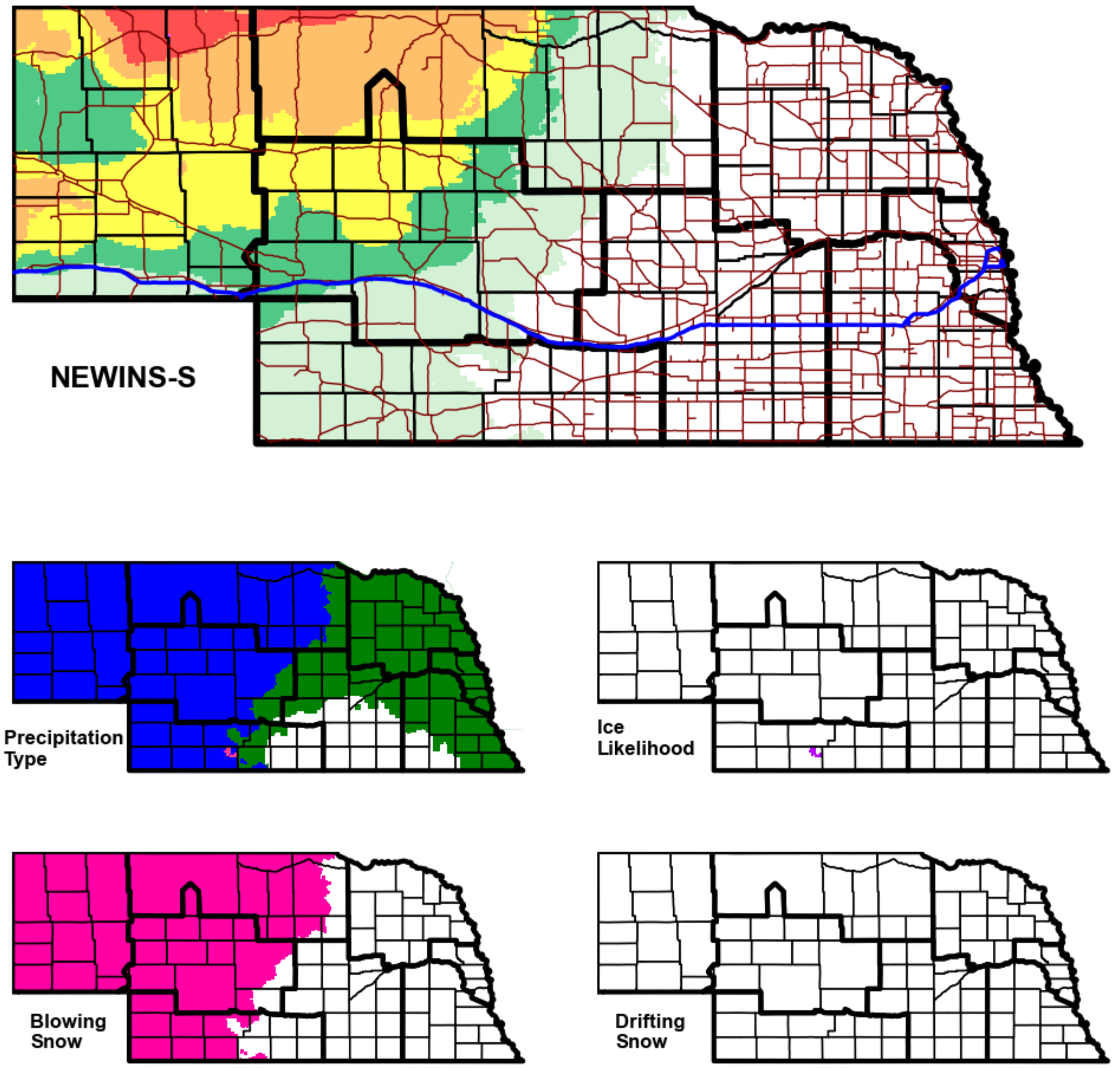

Figure 3.9 The 24-h NEWINS-P forecast from the 6:00 pm 12 December 2022 NDFD run valid for 6:00 pm 13 December comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

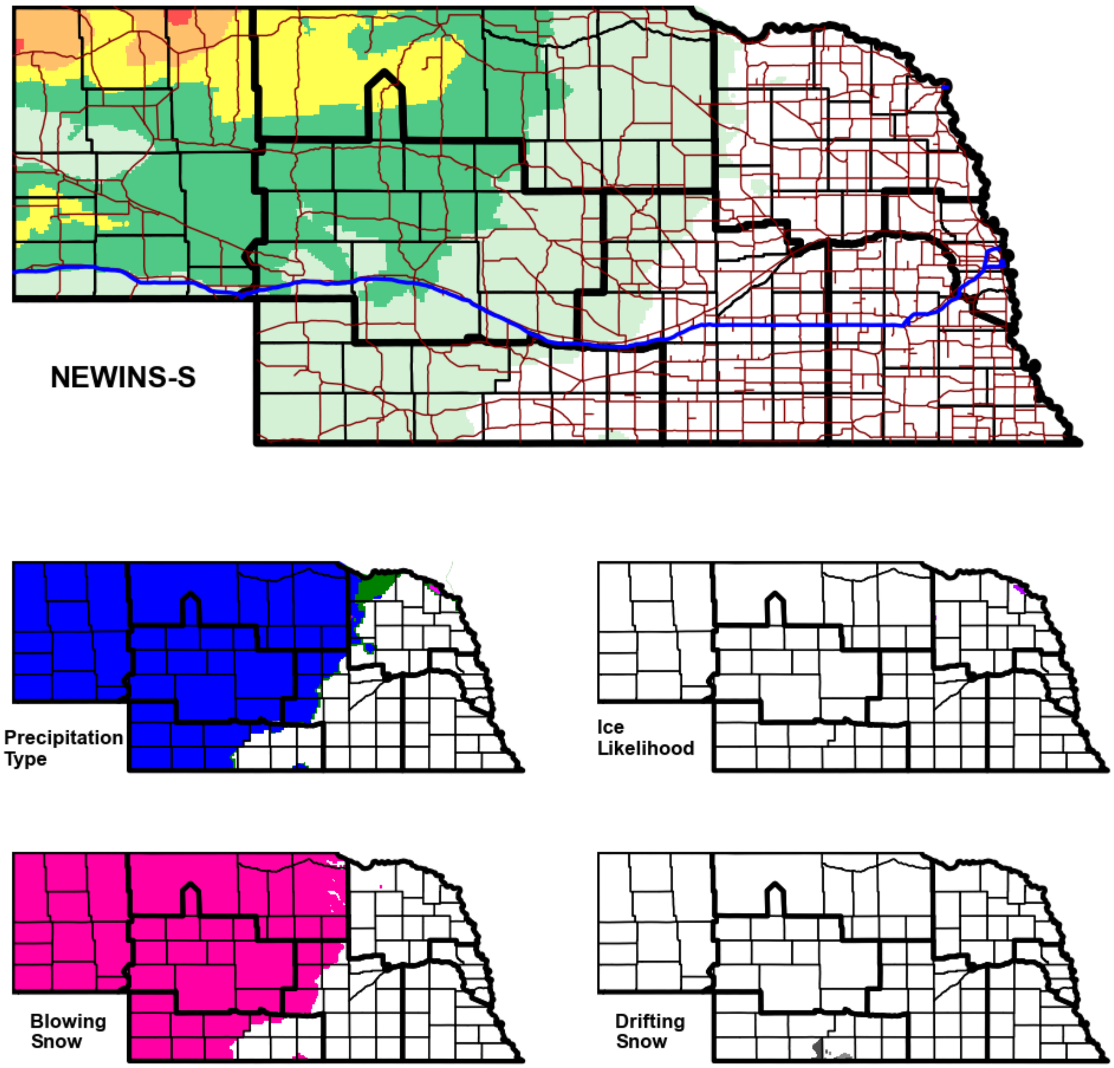

Figure 3.10 The 30-h NEWINS-P forecast from the 6:00 pm 12 December 2022 NDFD run valid for midnight 14 December comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

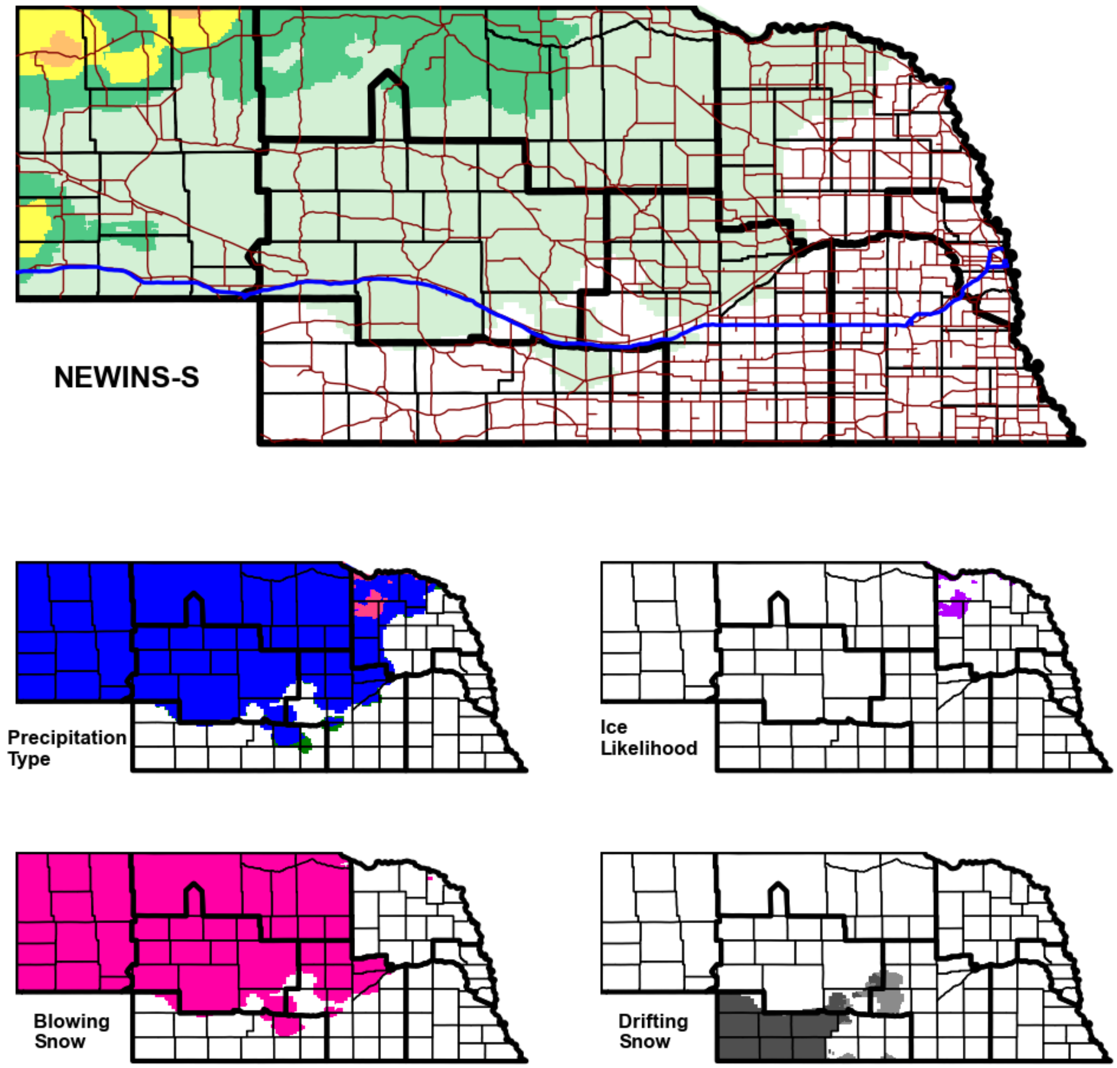

Figure 3.11 The 36-h NEWINS-P forecast from the 6:00 pm 12 December 2022 NDFD run valid for 6:00 am 14 December comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

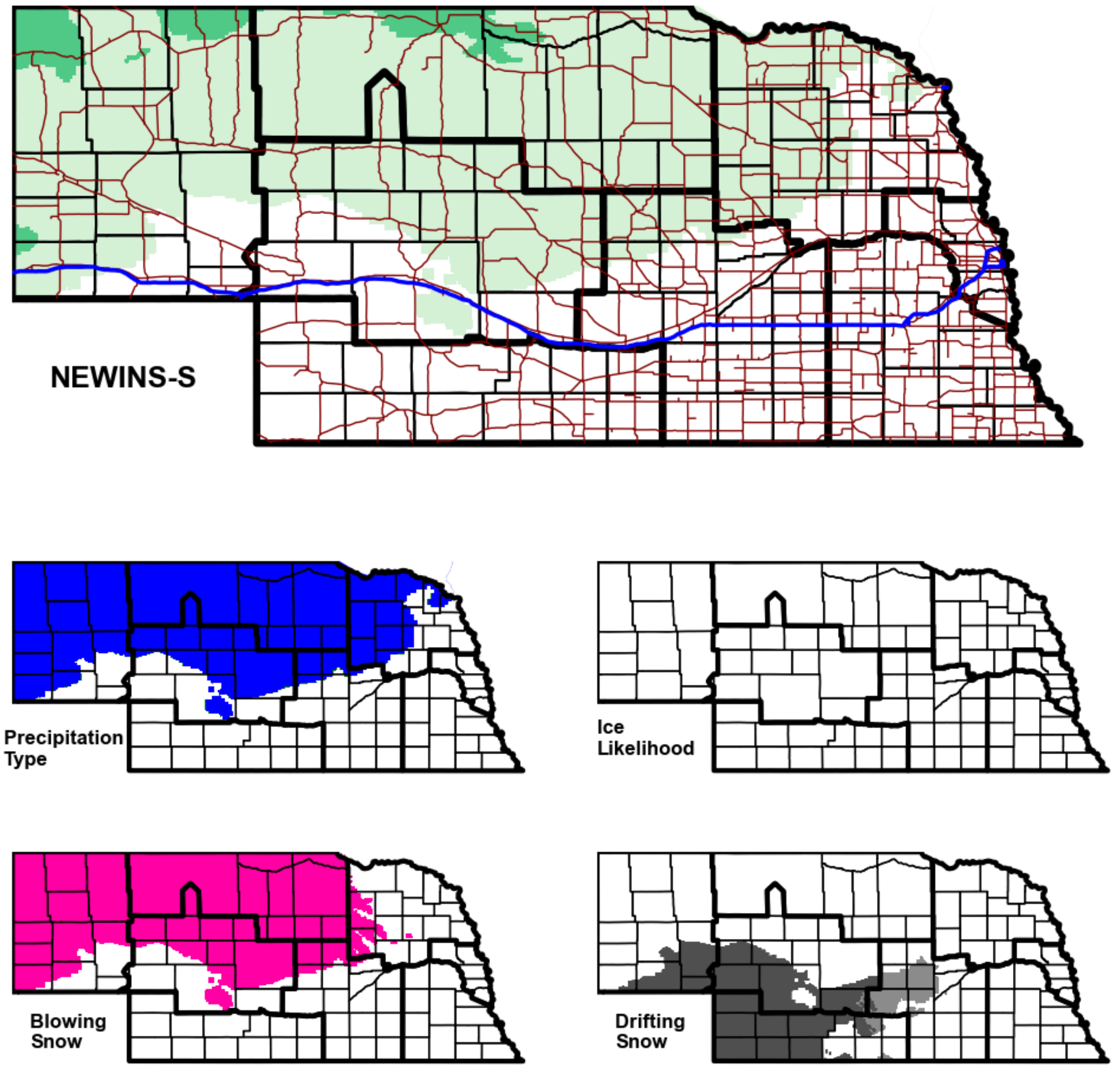

Figure 3.12 The 42-h NEWINS-P forecast from the 6:00 pm 12 December 2022 NDFD run valid for noon 14 December comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

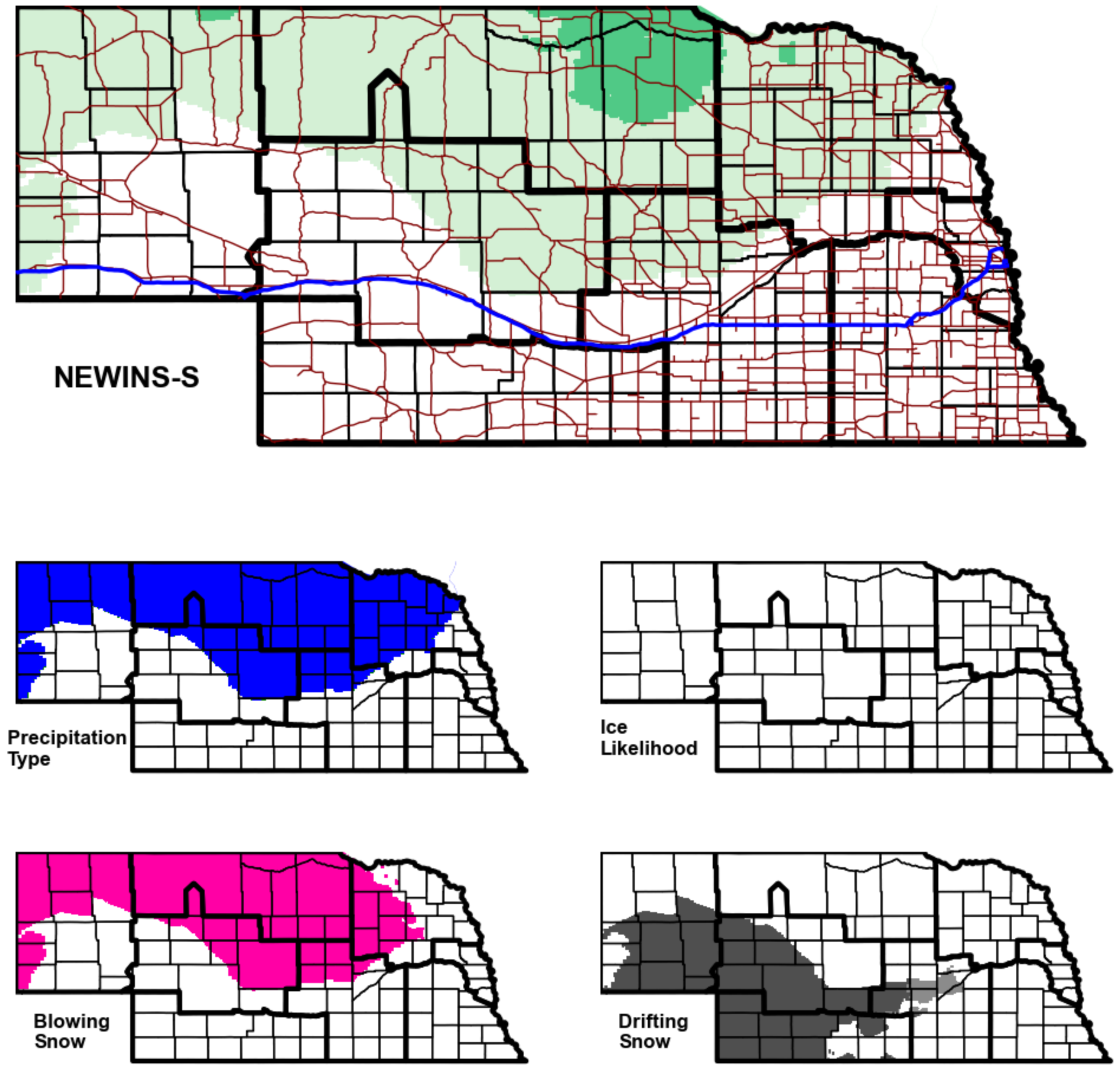

Figure 3.13 The 48-h NEWINS-P forecast from the 6:00 pm 12 December 2022 NDFD run valid for 6:00 pm 14 December comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

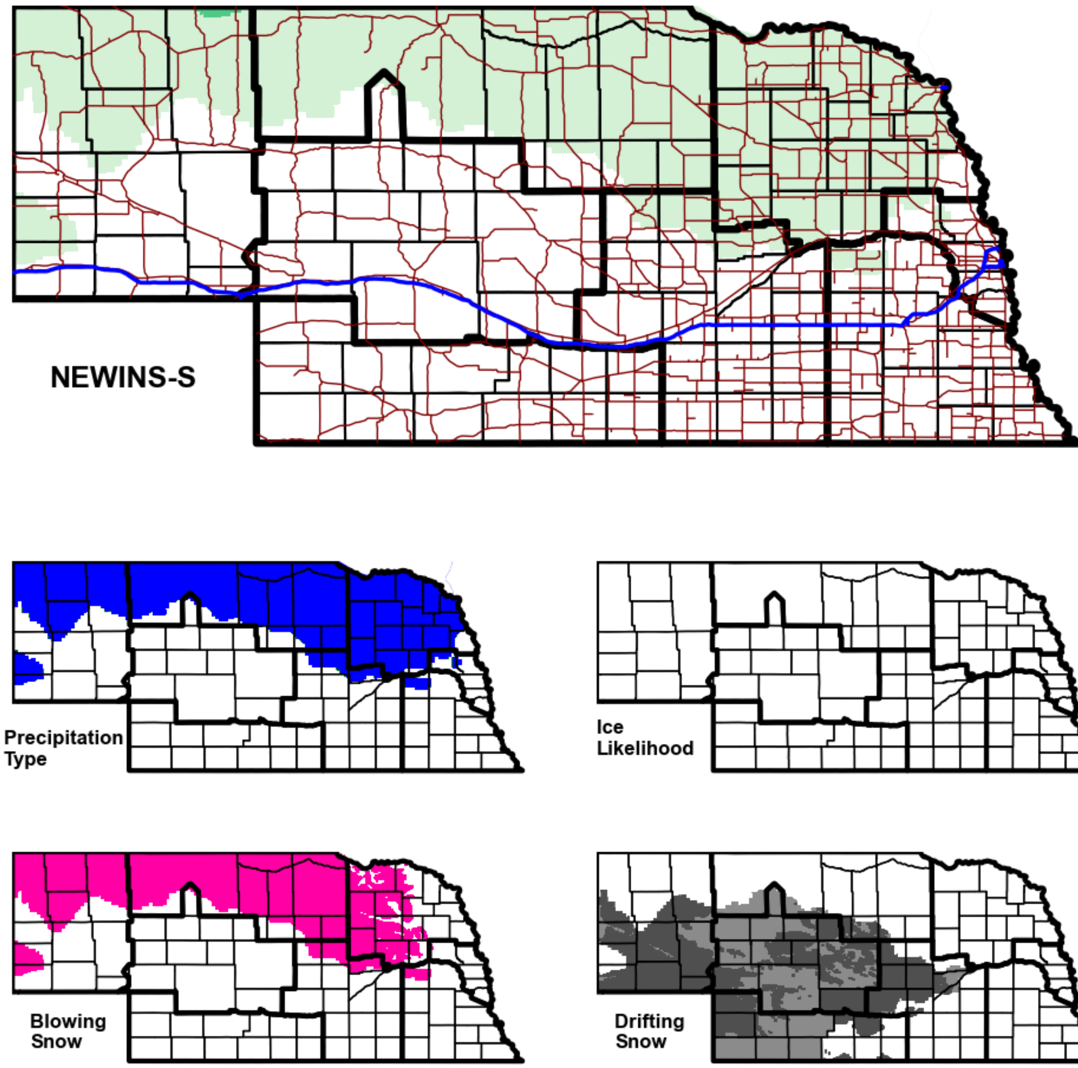

Figure 3.14 The 54-h NEWINS-P forecast from the 6:00 pm 12 December 2022 NDFD run valid for midnight 15 December comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

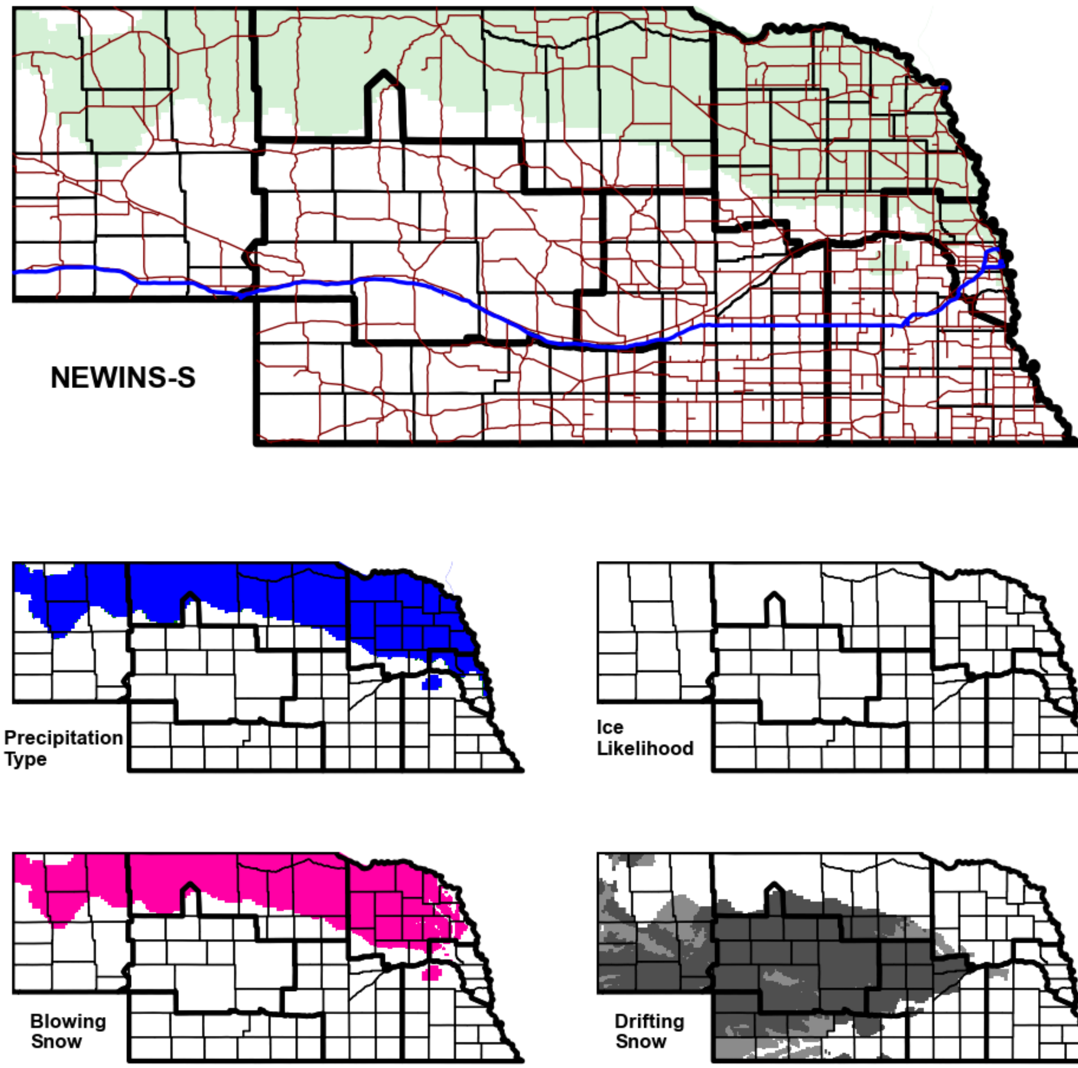

Figure 3.15 The 60-h NEWINS-P forecast from the 6:00 pm 12 December 2022 NDFD run valid for 6:00 am 15 December comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

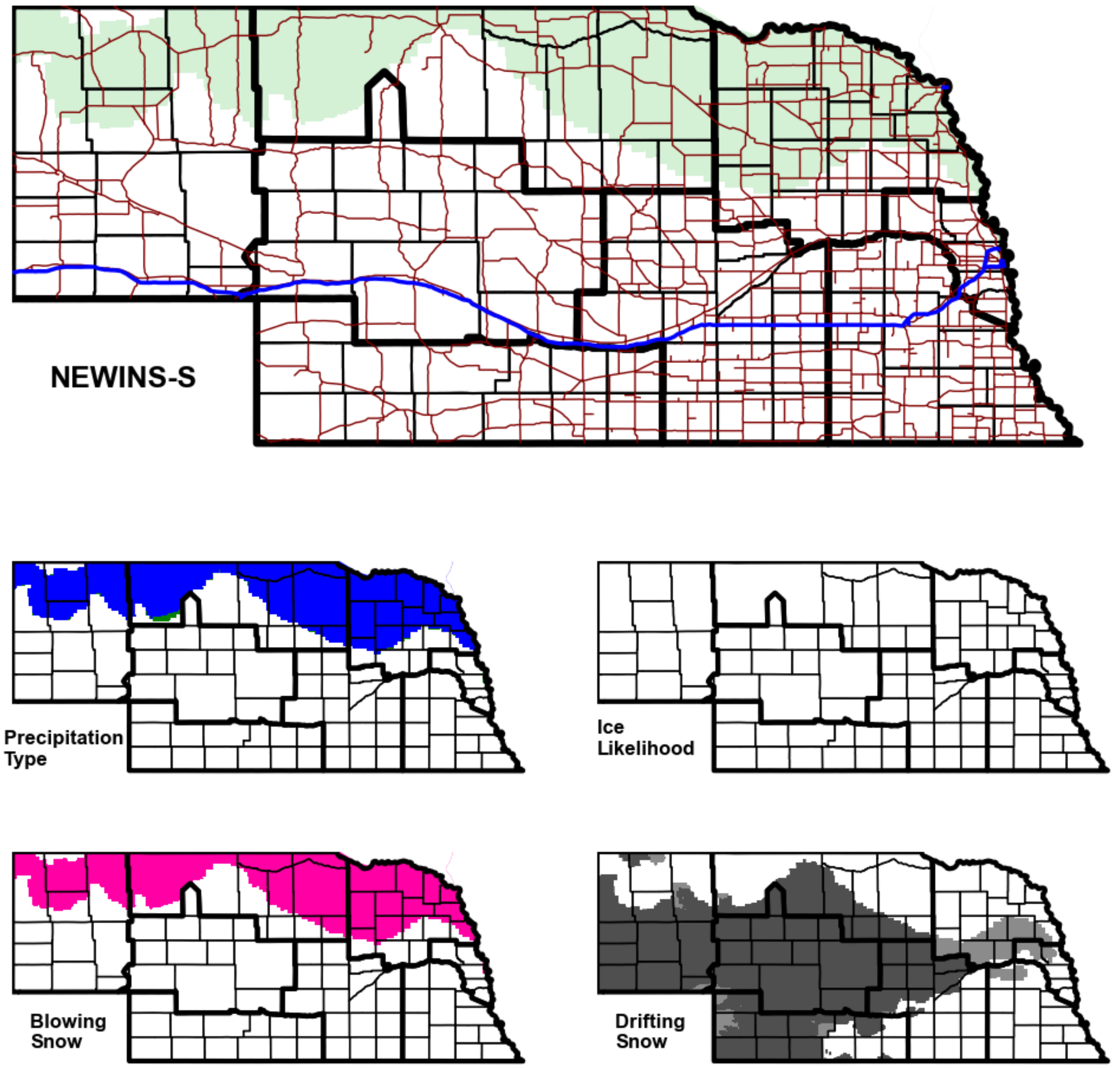

Figure 3.16 The 66-h NEWINS-P forecast from the 6:00 pm 12 December 2022 NDFD run valid for noon 15 December comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

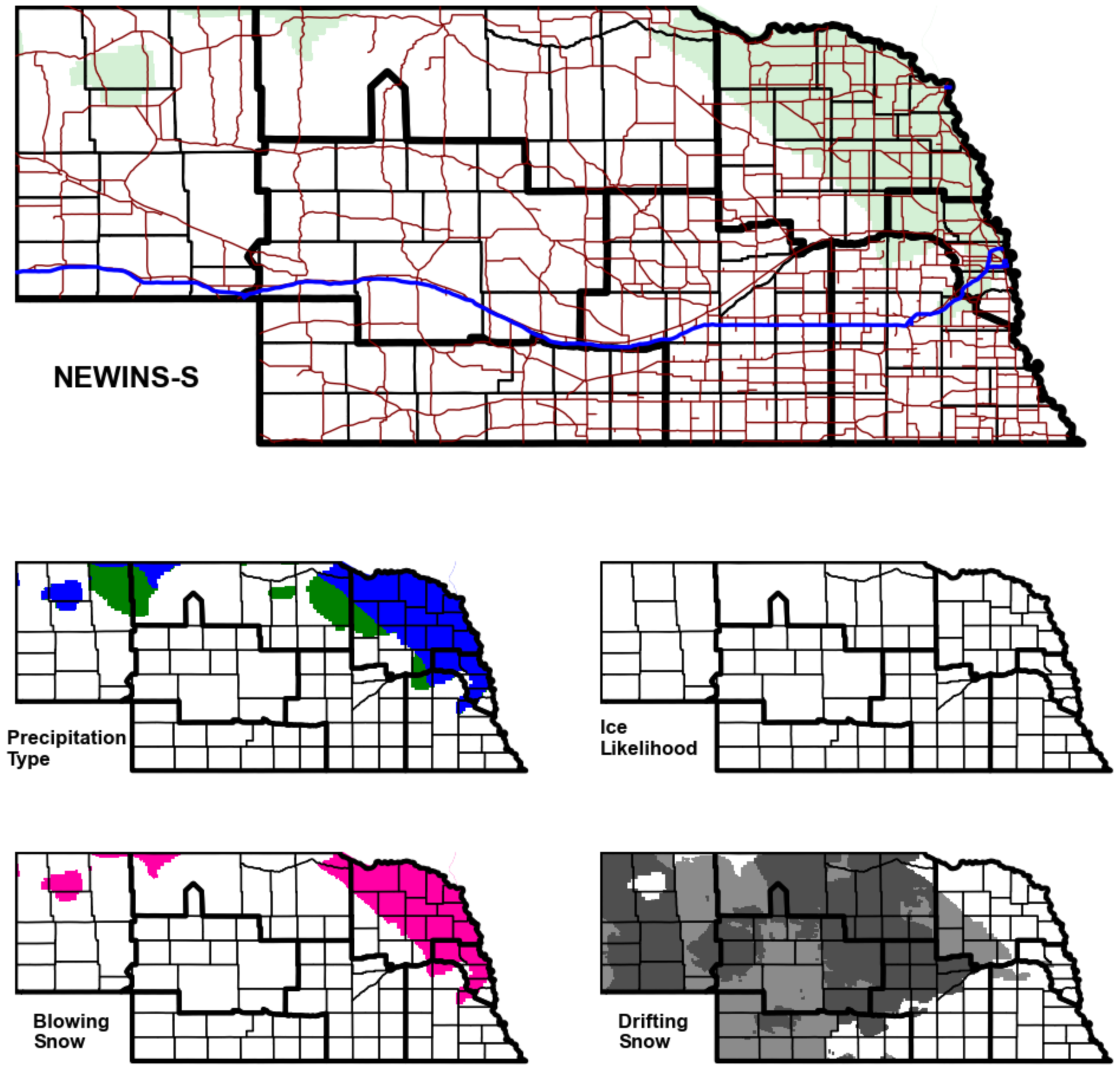

Figure 3.17 The 72-h NEWINS-P forecast from the 6:00 pm 12 December 2022 NDFD run valid for 6:00 pm 15 December comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

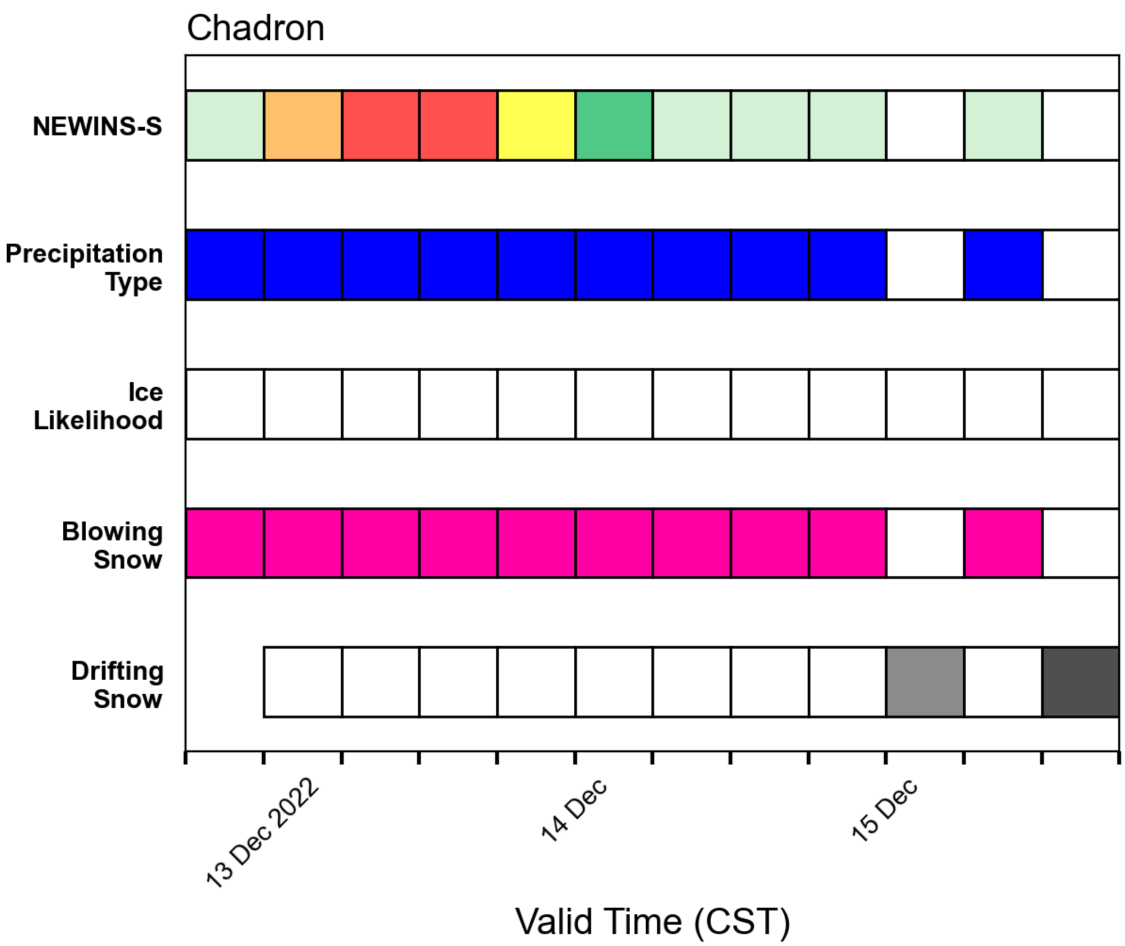

Figure 3.18 Ngram forecast from 6:00 pm 12 December 2022 NDFD run for Chadron. Valid periods when data are not calculable are left blank.

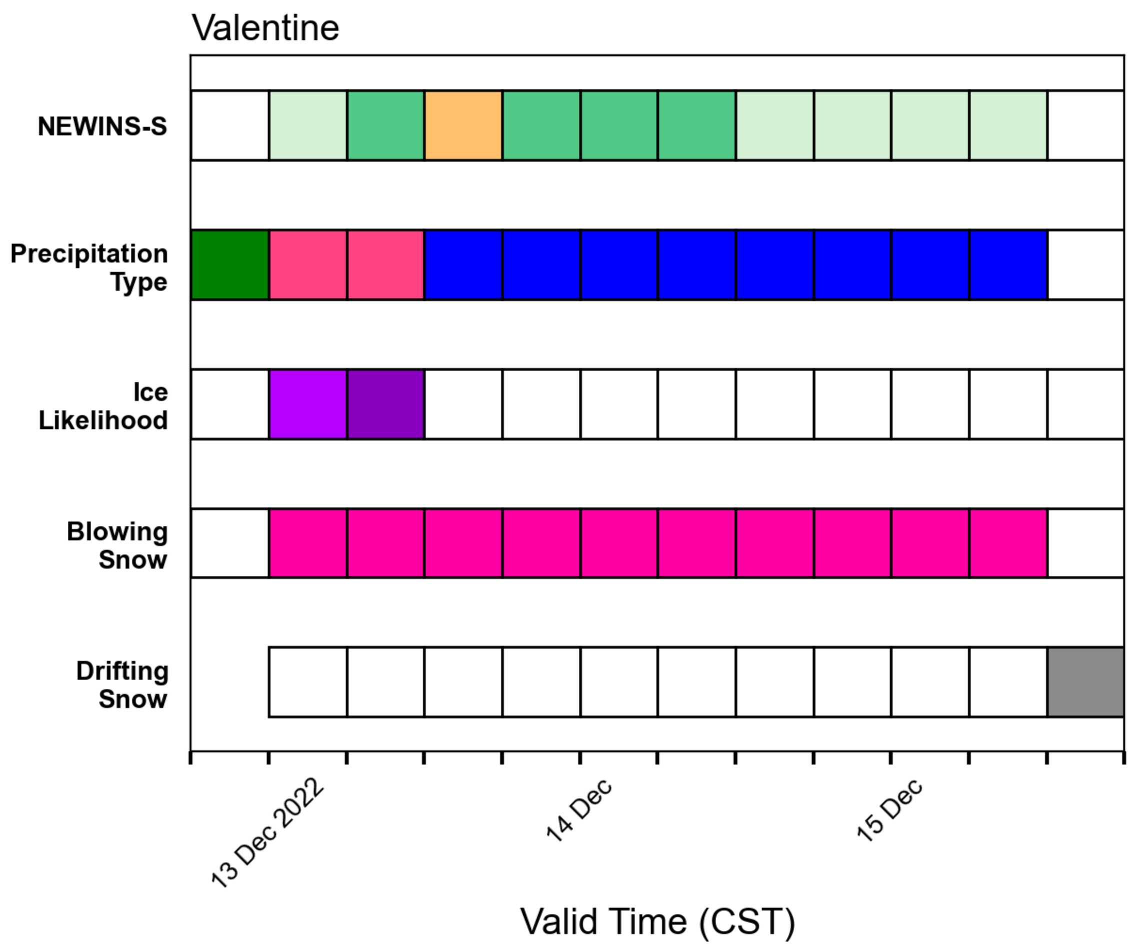

Figure 3.19 Ngram forecast from 6:00 pm 12 December 2022 NDFD run for Valentine. Valid periods when data are not calculable are left blank.

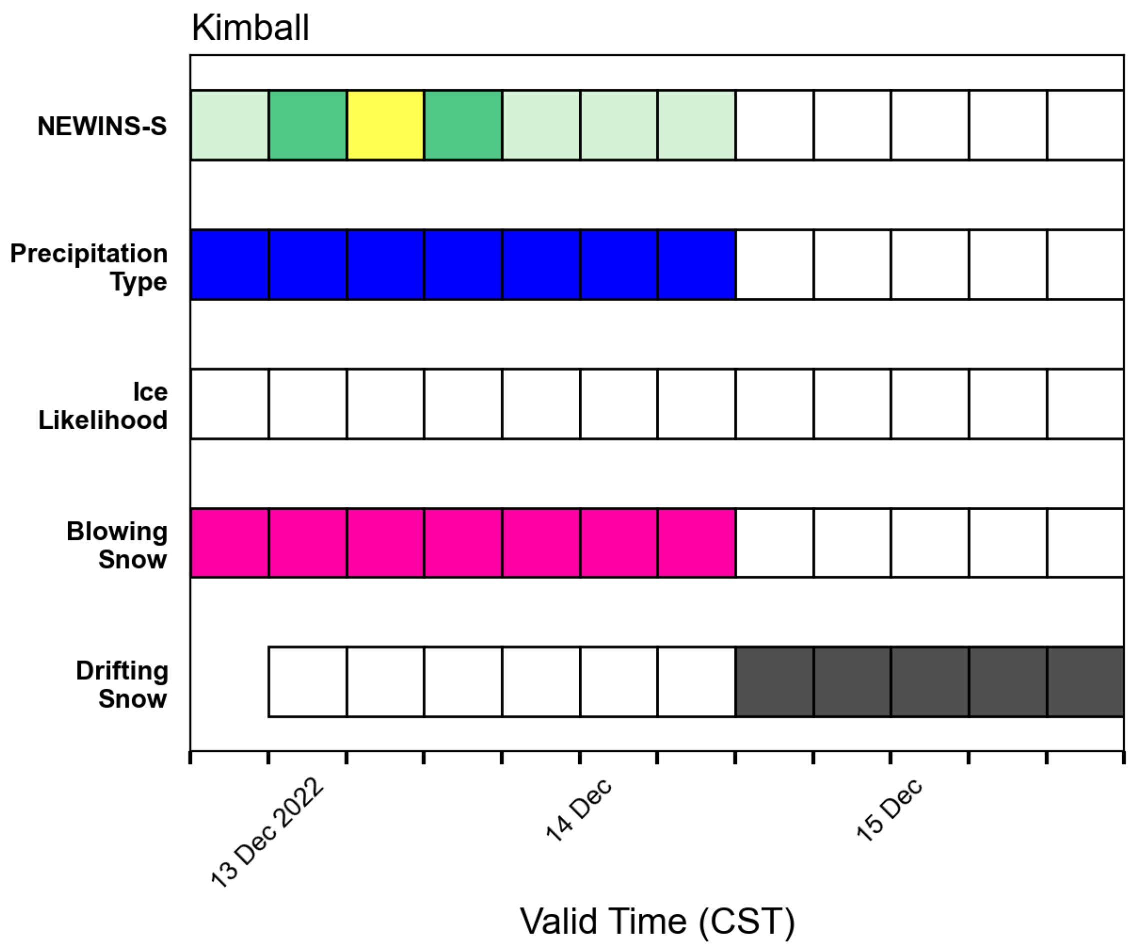

Figure 3.20 Ngram forecast from 6:00 pm 12 December 2022 NDFD run for Kimball. Valid periods when data are not calculable are left blank.

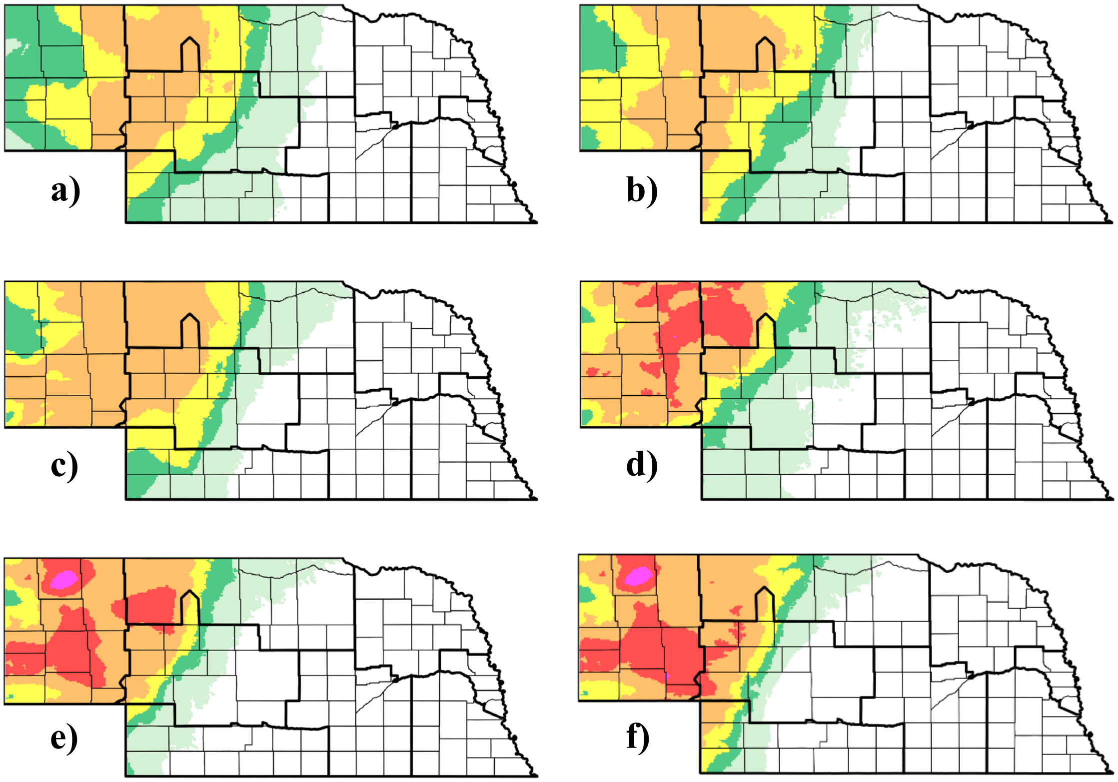

Figure 3.21 NEWINS-S valid for noon 13 December 2022 from a) NDFD Run 1 72-h forecast, b) NDFD Run 2 60-h forecast, c) NDFD Run 3 48-h forecast, d) NDFD Run 4 36-h forecast, e) NDFD Run 5 24-h forecast, and f) NDFD Run 6 12-h forecast.

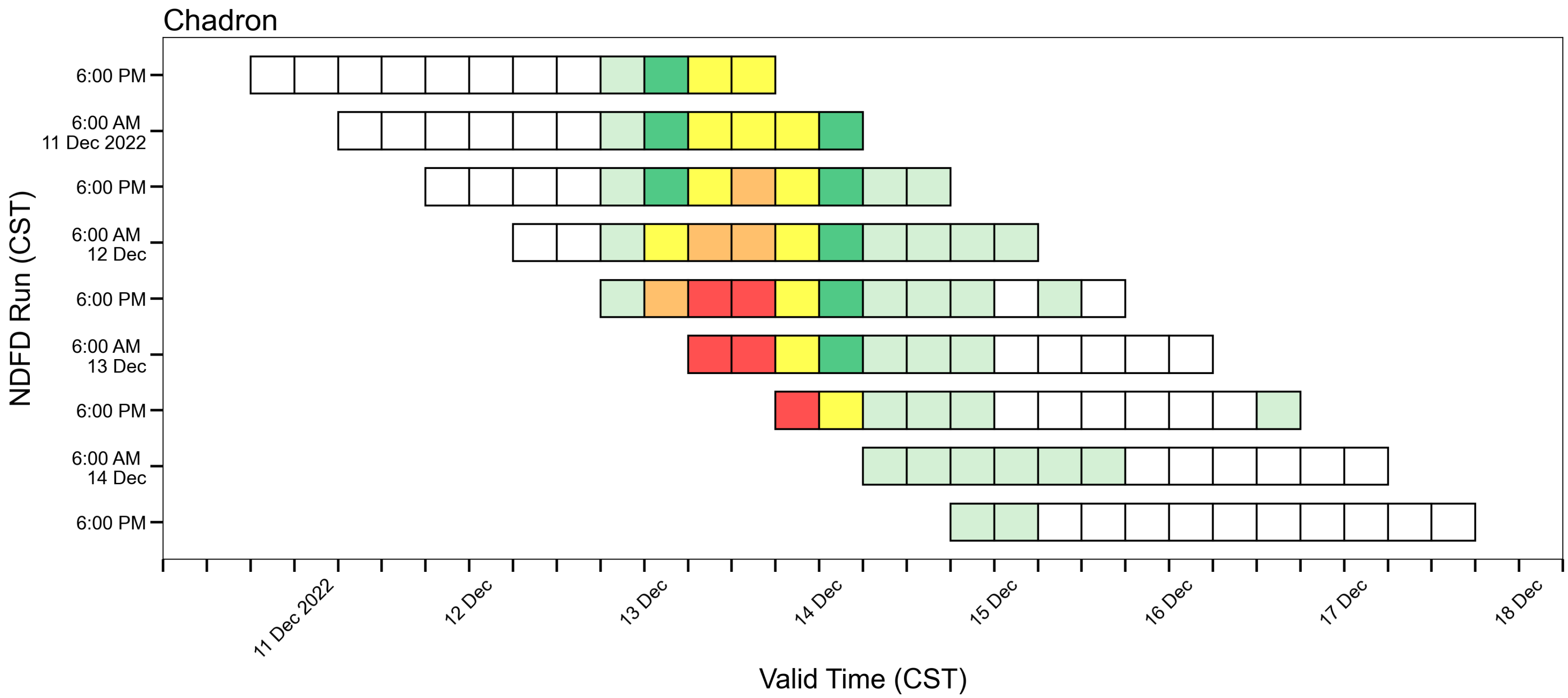

Figure 3.22 Chadron NEWINS-S time series starting at 6:00 pm 10 December 2022 and ending at 6:00 pm 17 December.

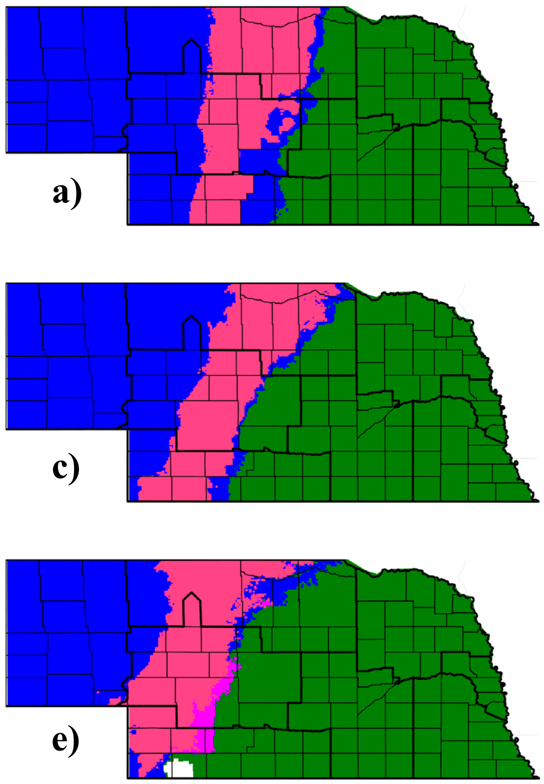

Figure 3.23 Precipitation type valid for noon 13 December 2022 from a) NDFD Run 1, b) NDFD Run 2, c) NDFD Run 3, d) NDFD Run 4, e) NDFD Run 5, and f) NDFD Run 6.

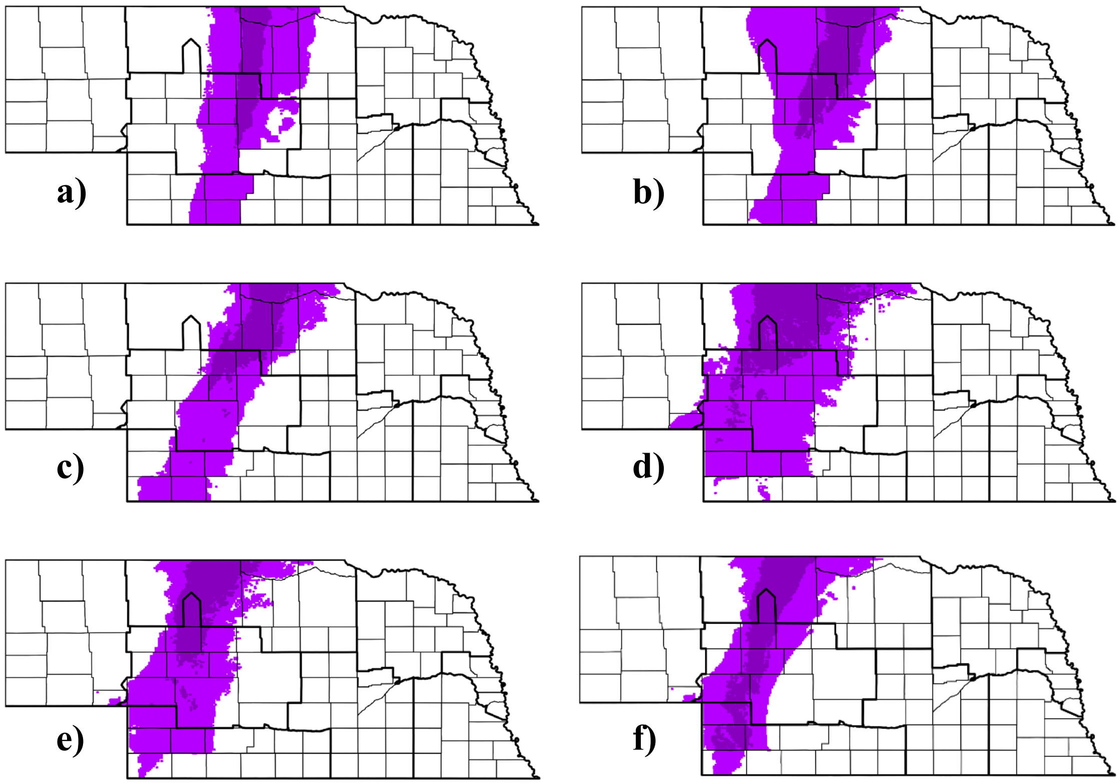

Figure 3.24 Ice likelihood valid for noon 13 December 2022 from a) NDFD Run 1, b) NDFD Run 2, c) NDFD Run 3, d) NDFD Run 4, e) NDFD Run 5, and f) NDFD Run 6.

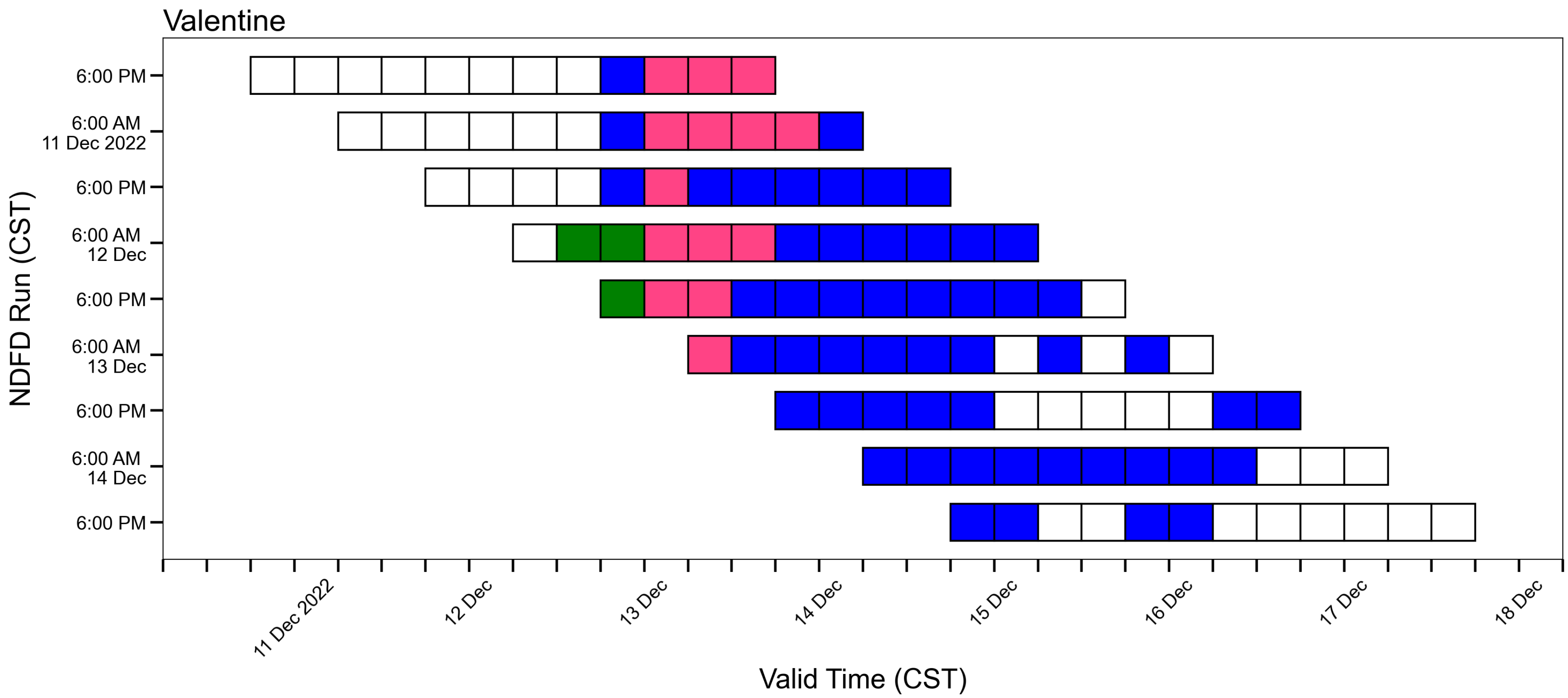

Figure 3.25 Valentine precipitation type time series starting at 6:00 pm 10 December 2022 and ending at 6:00 pm 17 December.

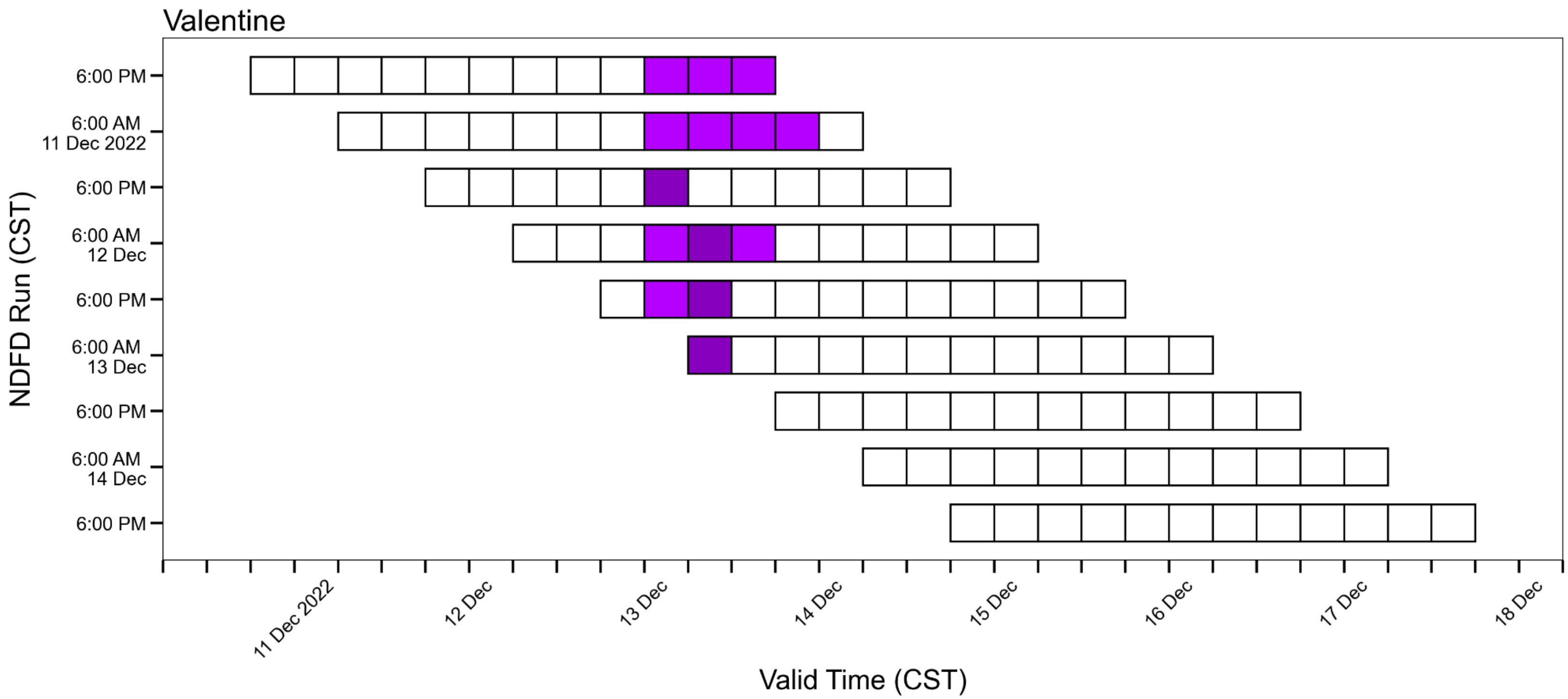

Figure 3.26 Valentine, NE, ice likelihood time series starting at 6:00 pm 10 December 2022 and ending at 6:00 pm 17 December.

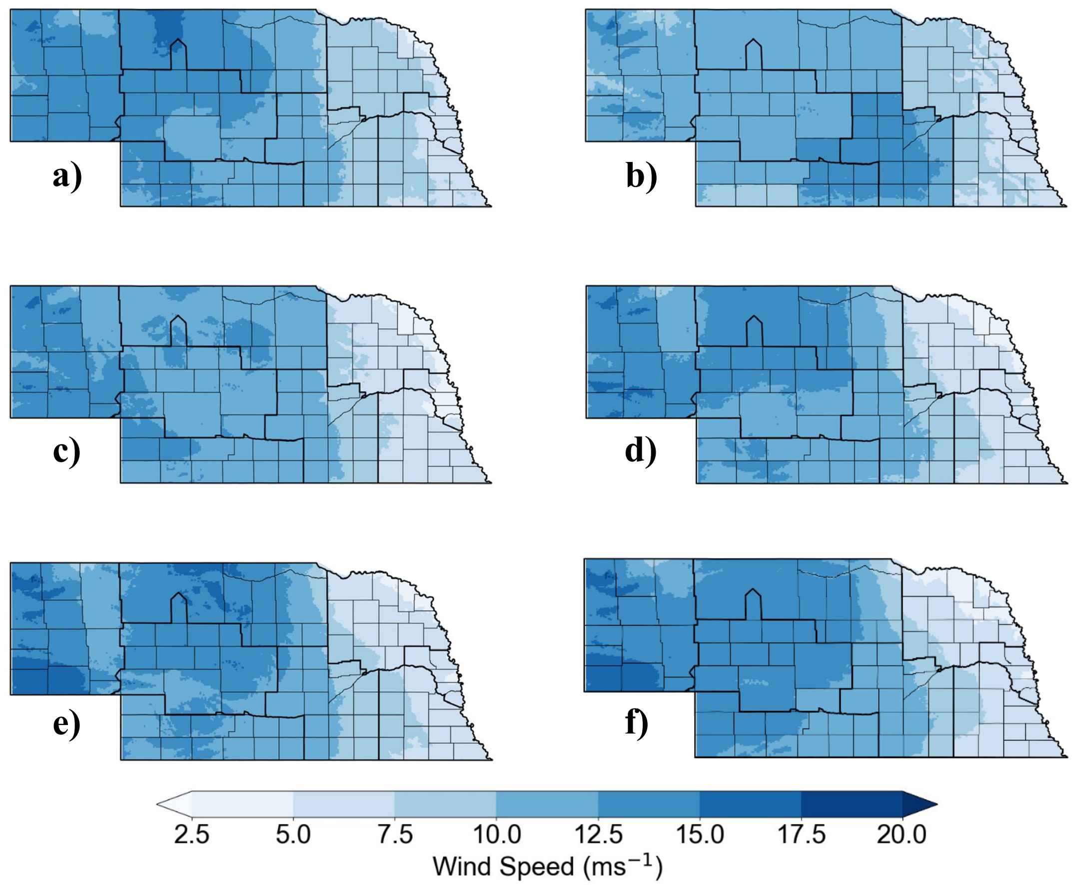

Figure 3.27 Surface wind speed valid for 6:00 pm 14 December 2022 from six NDFD runs: a) NDFD Run 3, b) NDFD Run 4, c) NDFD Run 5, d) NDFD Run 6, e) NDFD Run 7, f) NDFD Run 8.

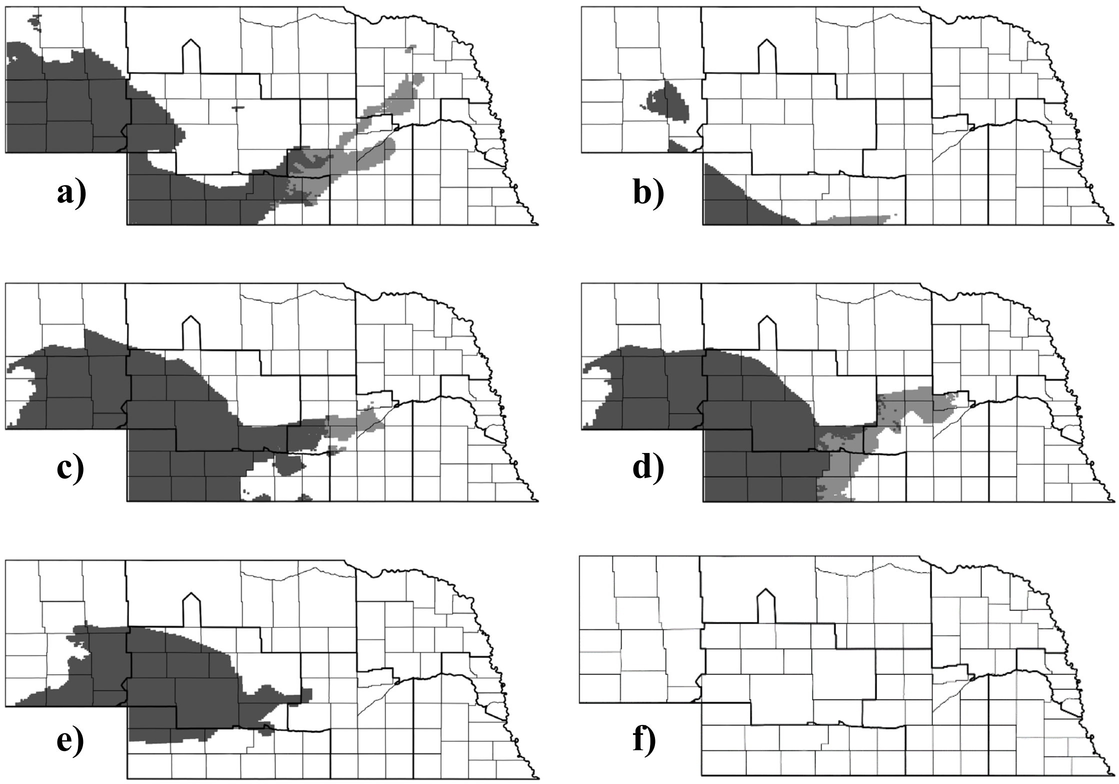

Figure 3.28 Drifting snow likelihood valid for 6:00 pm 14 December 2022 from six NDFD runs: a) NDFD Run 3, b) NDFD Run 4, c) NDFD Run 5, d) NDFD Run 6, e) NDFD Run 7, f) NDFD Run 8.

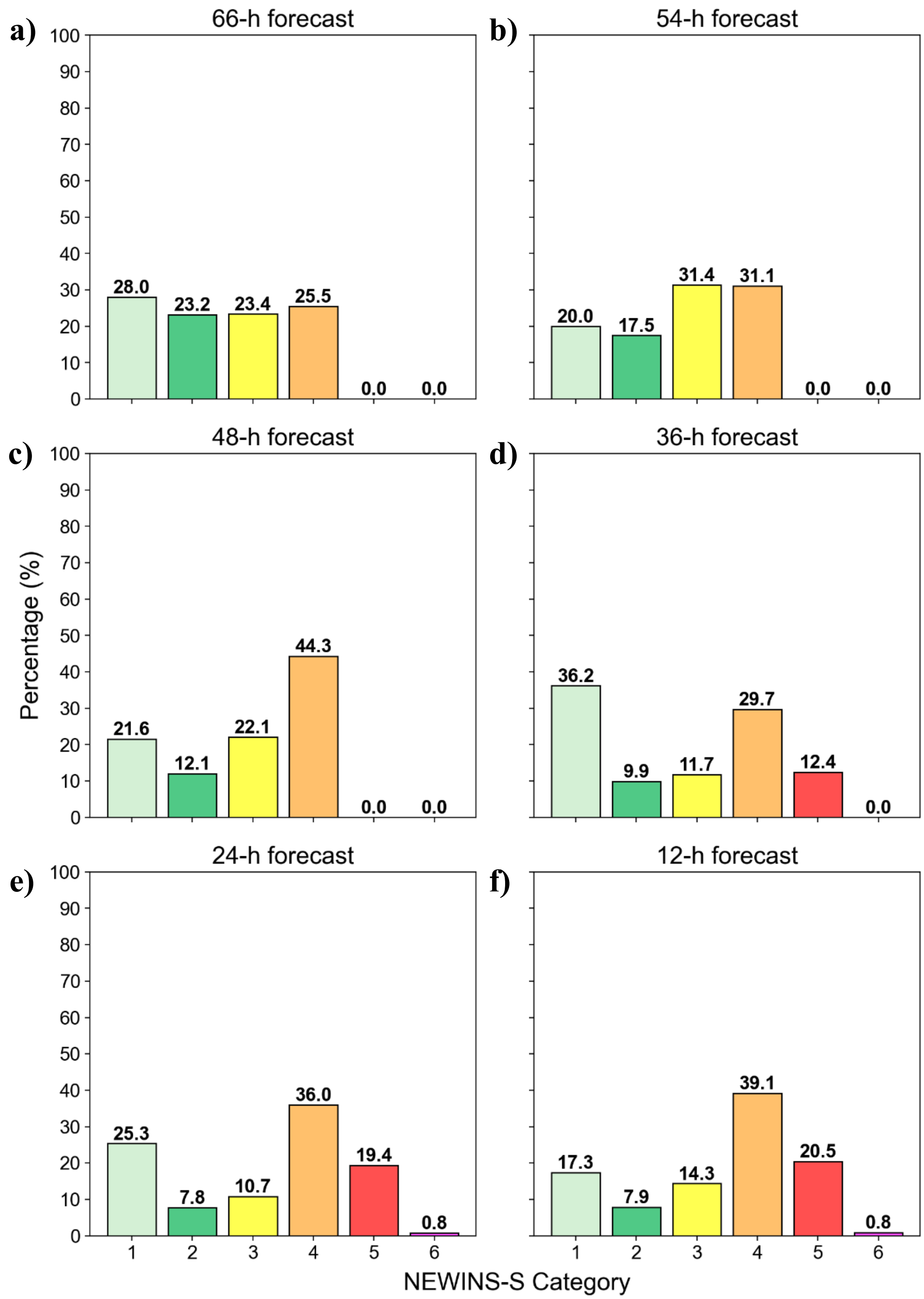

Figure 3.29 Percent statewide NEWINS-S distributions valid for noon 13 December 2022 from a) NDFD Run 1 66-h forecast, b) NDFD Run 2 54-h forecast, c) NDFD Run 3 48-h forecast, d) NDFD Run 4 36-h forecast, e) NDFD Run 5 24-h forecast, and f) NDFD Run 6 12-h forecast.

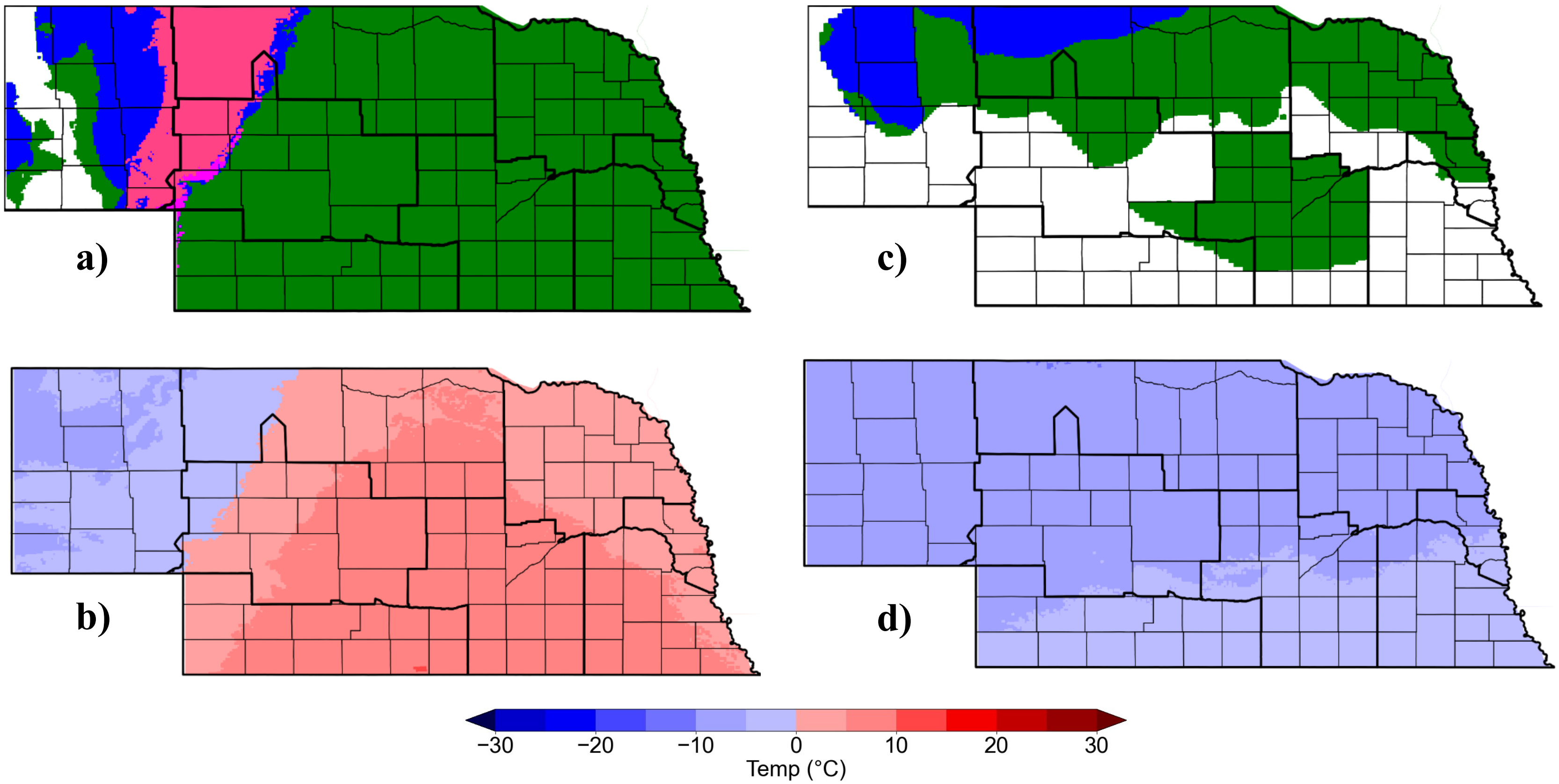

Figure 3.30 a) Precipitation type and b) surface air temperature valid for midnight 13 December 2022 from the 6:00 am 11 December NDFD run. c) Precipitation type and d) surface air temperature valid for 6:00 pm 16 December from the 6:00 pm 13 December NDFD run.

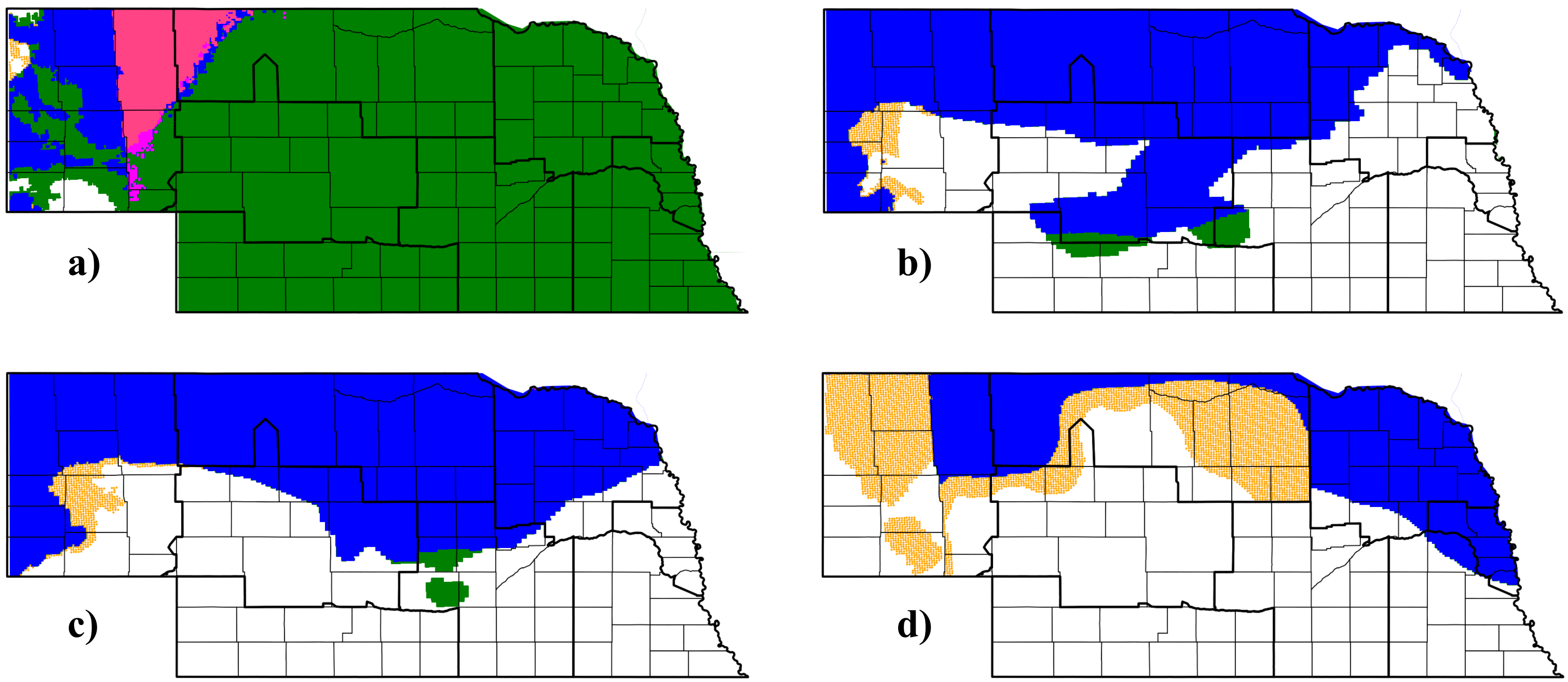

Figure 3.31 Precipitation type valid for a) midnight 13 December 2022 from NDFD Run 4, b) noon 14 December from NDFD Run 3, c) 6:00 pm 14 December from NDFD Run 7, and d) 6:00 pm 15 December from NDFD Run 8. Orange points represent snow accumulation with zero QPF.

The Chadron, Valentine, and Kimball Ngram forecasts (Figures 3.18 to 3.20) showcase the temporal changes in the components from different sectors of the system. The Chadron Ngram forecast (Figure 3.18) highlights the high NEWINS-S categories and blowing snow concerns. Between 6:00 pm 13 December and midnight 14 December, the impacts steadily increase during the onset, maximizing at NEWINS-S Category 5 between 6:00 am and 6:00 pm 13 December, and then decrease as the system moves away. Focusing on a location further east, the Valentine Ngram forecast (Figure 3.19) highlights icing concerns. Rain quickly changes to mixed precipitation with increasing ice likelihood between 6:00 pm 12 December and noon 13 December. Afterwards, mixed precipitation changes to snow and NEWINS-S categories reach as high as Category 4. The Kimball Ngram forecast (Figure 3.20) highlights the post-storm impacts with multi-day drifting snow concerns. Collectively, all Ngram forecasts emphasize the impacts during and after the storm.

The NEWINS-P forecasts showcase several instances of NWS weather forecast office forecast differences, hereafter referred to as forecast misalignment. One instance appears to occur along the transition zone. In the 6-h and 12-h forecasts (Figures 3.6 and 3.7), a sharp demarcation in precipitation type/ice likelihood can be seen in District 5. The demarcation in the precipitation type component can be seen as a sharp change in precipitation types, going from only snow to a mixture of ice and snow from west to east. In the ice likelihood component, the ice likelihood goes from none to possible from west to east. This demarcation in both the precipitation type and ice components represents the boundary between the Cheyenne and North Platte weather forecast offices (Figure 2.1), rather than a meteorological difference, and was classified as a forecast misalignment. Forecast misalignment between these two offices is also present in the 72-h forecast (Figure 3.17), this time in the drifting snow likelihood component. In

District 5, areas west of the demarcation are given a higher likelihood for drifting snow than areas east of the demarcation. In the 54-h forecast (Figure 3.14), a sharp demarcation can be seen in drifting snow likelihood along the border between Districts 4 and 6 and across eastern portions of District 6 and central portions of District 7. This demarcation represents the boundary between the North Platte and Hastings offices (Figure 2.1). Along the border between Districts 4 and 6 as well as eastern portions of District 6, areas within the Hastings office are forecast to have a higher drifting snow likelihood than areas within the North Platte office. Across central portions of District 7, drifting snow likelihood is forecasted to be higher in areas within the North Platte office than areas within the Hastings office. Through discussions between the various offices, these strong demarcations are supposed to be removed from the NDFD data, though some still exist and might affect NEWINS-P interpretations.

3.1.2 NDFD Evolution: 13-17 December 2022

To track the evolution in forecasts for NEWINS-P components at various valid times, several NDFD runs (Table 3.1) are used. The NEWINS-S categories vary extensively across western Nebraska during noon 13 December (Figure 3.21). These NDFD runs generally show the highest NEWINS-S categories expanding westward with time and an increase in severity as the event gets closer. NDFD Run 1 shows the NEWINS-S Categories 3 and 4 across eastern District 5 and western portions of Districts 6 and 8. Categories 3 and 4 expand westward in NDFD Runs 2 and 3 to include most of District 5. A severity increase occurs in NDFD Run 4 with NEWINS-S Category 4 increasing to Category 5 across eastern portions of District 5 and western portions of District 8. Category 5 is predominantly in District 5 in NDFD Run 5 with a localized area of Category 6 across northern District 5. NDFD Run 6 features no changes in the portions of District 5 covered by the Cheyenne office (Figure 2.1); however, NEWINS-S

Table 3.1 NDFD runs used for the spatial and temporal evolution of the 13-17 December 2022 Colorado Low System.

NDFD Run Number	**NDFD Run**	**NDFD Run Duration**
1	6:00 am 10 December 2022	72 hours
2	6:00 pm 10 December	72 hours
3	6:00 am 11 December	72 hours
4	6:00 pm 11 December	72 hours
5	6:00 am 12 December	72 hours
6	6:00 pm 12 December	72 hours
7	6:00 am 13 December	72 hours
8	6:00 pm 13 December	72 hours
9	6:00 am 14 December	72 hours
10	6:00 pm 14 December	72 hours
11	6:00 am 15 December	72 hours

categories increase in portions of District 5 covered by the North Platte office (Figure 2.1). The changes in NEWINS-S can be seen temporally in the 6:00 am to noon 13 December period from the Chadron NEWINS-S time series (Figure 3.22). In this time series, an increase in NEWINS-S categories can also be seen in the preceding and following valid periods. Examining NEWINS-S changes spatially and temporally show the degree of change that can occur as the event gets closer and adjustments are made within NDFD.

The precipitation type and ice likelihood components experience relatively minor changes for the noon 13 December time (Figures 3.23 and 3.24). NDFD Runs 1 and 2 show a north-to-south oriented axis of mixed precipitation with varying ice likelihood across central Nebraska. By NDFD Run 3, the axis of mixed precipitation becomes oriented northeast to southwest, causing rain to be anticipated across eastern portions of Districts 6 and 7. The shield of mixed precipitation and ice likelihood expands in NDFD Run 4 to encompass more of Districts 6 and 8 before contracting in NDFD Run 5. NDFD Run 6 sheds the eastern edge of the mixed precipitation zone, causing more areas in eastern Districts 6 and 7 to anticipate rain. Evaluating the further NDFD runs demonstrates a westward trend in mixed precipitation as the event gets closer. The changes in expected precipitation type and ice likelihood can also be shown in the Valentine time series (Figures 3.25 and 3.26). During the onset, snow is advertised in NDFD Runs 1 to 3 before changing to rain in NDFD Runs 4 and 5 for the 6:00 pm to midnight period 12 December. For the 6:00 am to noon 13 December period, there is little change in the expected precipitation type; however, there is a trend for higher ice likelihood. Overall, evaluating the changes in precipitation type and ice likelihood components spatially and temporally as well as together have shown to be helpful for diagnosing concerns during icing changes.

After the NEWINS-S categories depart, high surface wind speeds are consistently advertised for the 6:00 pm 14 December time (Figure 3.27); however, the placement of the drifting snow likelihood waivers (Figure 3.28). The fluctuation between NDFD Runs 3 and 5 is caused by changes in the coverage of NEWINS-S categories across the state. Little change occurs in NDFD Run 6 before high drifting snow likelihood is removed in portions of District 7 in NDFD Run 7 and entirely in NDFD Run 8. The removal addresses a limitation of the NEWINS-P algorithm that prevents the detection of ongoing drifting snow. In other words, since there are no NEWINS-S categories forecasted in NDFD Run 8, drifting snow cannot be forecasted.

3.1.3 Case Discussion: 13-17 December 2022

The 13-17 December 2022 Colorado Low System was a highly impactful blizzard that caused severe impacts from heavy snowfall and multi-day blowing/drifting snow impacts. The NEWINS-P forecasts for the 13-17 December 2022 Colorado Low System are shown to be valuable for diagnosing the spatial and temporal changes in both in-storm and post-storm weather hazards associated with the system. While the in-storm impacts are certainly severe for this case, the persistence of strong winds after the departure of NEWINS-S categories allows widespread drifting snow to be forecasted. Through investigating multiple NDFD runs, forecast changes in the different components can be evaluated spatially for the same time frame and temporally in a single location for multiple valid times. Among the most significant is NEWINS-S, with a change in placement of the highest categories as well as a severity increase leading up to the event. The trend towards a higher-end event can be seen when examining the statewide distribution of NEWINS-S categories (Figure 3.29). In NDFD Runs 1 and 2, there is a small increase in the coverage of Categories 3 and 4. By NDFD Run 3, there is a significant increase in Category 4 with spatial coverage increasing from 31.1% to 44.3%. NDFD Runs 4 to 6 show Category 5 making up more of the distribution. NDFD Run 1 statewide coverage of NEWINS-S Categories 1 to 3 is 74.6% and Categories 4 to 6 is 25.4%, while NDFD Run 6 statewide coverage of Categories 1 to 3 is 39.5% and Categories 4 to 6 is 61.5%. When comparing the forecast trends to the observed snowfall observations, the ramp-up in NEWINS-S categories is certainly warranted; however, the placement of the highest categories does not align with observations, with the heaviest snowfall occurring much farther east than forecasted.

Various forecast misalignments between the different NWS offices are identified in the NEWINS-P forecasts. However, investigating and comparing NDFD runs for this case leads to the discovery of other artifacts and considerations. An example of another artifact is rain occurring in meteorologically unfavorable areas. NDFD Runs 2 and 7 highlight this artifact during the onset and at the end of the storm (Figure 3.30). In both cases, rain is anticipated in areas where temperatures are well below freezing. Through the NDFD runs investigated, this artifact appears most prevalent in the form of light precipitation at the arrival and departure of storms. Another artifact discovered is snow in the precipitation type component when no QPF is present (Figure 3.31). This artifact stems from two possibilities: 1) a product of rounding or 2) failure to quality control the data (B, Barjenbruch and NDFD 2023, personal communication). The first possibility is that QPF is low enough to round down to zero; however, the internalized snow-to-liquid ratio is high enough to boost the snow above the 0.1inch threshold. For example, if the QPF at a point is 0.004 inches and the ratio is 20:1, the snow at the point is rounded to 0.1 inches. The second possibility is a result of late adjustments to QPF and failing to run a final QC check to ensure that snow amounts are in perfect agreement. Of the two possibilities, the first possibility is thought to be more likely.

3.2 Case Study: 6-8 February 2021 Alberta Clipper System

The 6 February 2021 and 7-8 February 2021 case study events are Alberta Clipper Systems that collectively brought significant snowfall across portions of Nebraska (Figure 3.32). The 6 February 2021 Alberta Clipper System produced several inches of snowfall across portions of central and eastern Nebraska (Figure 3.33). Following the passage, another Alberta Clipper System brought additional snowfall to many of the same areas with several inches occurring from 6:00 pm 6 February to 6:00 pm 8 February (Figure 3.34).

3.2.1 NEWINS-P Forecasts: 6-8 February 2021

The NEWINS-P forecasts from the representative NDFD run (Table 2.1) showcase NEWINS-S categories occurring within small periods for both Clipper Systems (Figures 3.35-3.44). The 6-h forecast (Figure 3.35) features the onset of the 6 February 2021 Clipper System with NEWINS-S Categories 1 and 2 across central and western Nebraska. NEWINS-S categories increase significantly across central Nebraska in the 12-h forecast (Figure 3.36) with a swath of Categories 3 to 5 indicated with patchy blowing snow now forecasted across western Nebraska. Categories 3 to 5 propagate eastward into eastern Nebraska in the 18-h forecast (Figure 3.37) and move out of the state by the 24-h forecast (Figure 3.38). Following the passage of the Alberta Clipper System, NEWINS-S categories increase to Categories 1 and 2 across western Nebraska in the 30-h forecast (Figure 3.39) as the 7-8 February 2021 Clipper System begins to enter the state. Categories 2 and 3 move into central and eastern Nebraska by the 36-h forecast (Figure 3.40). By the 42-h forecast (Figure 3.41), Category 3 moves out of the state with isolated Category 2 remaining over eastern Nebraska. Between the 48-h and 60-h forecasts (Figures 3.42-3.44), the second wave associated with the Alberta Clipper System moves into the state with Category 1 lingering across most of Nebraska.

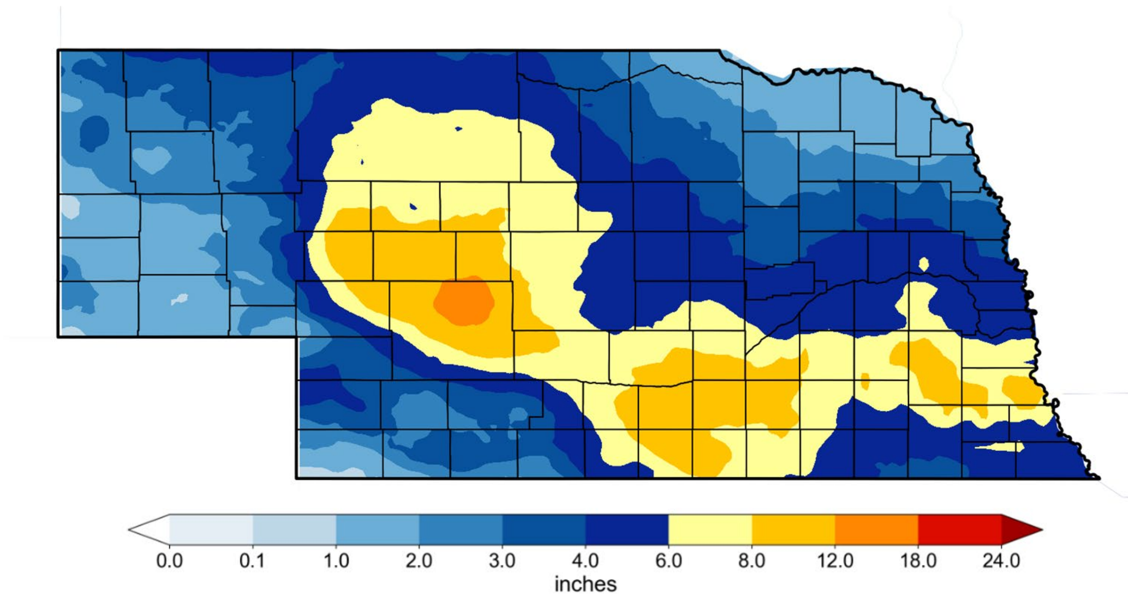

Figure 3.32 NOHRSC 72-h accumulated snowfall (inches) starting at 6:00 pm 5 February 2021 and ending at 6:00 pm 8 February (adapted from NOHRSC 2023).

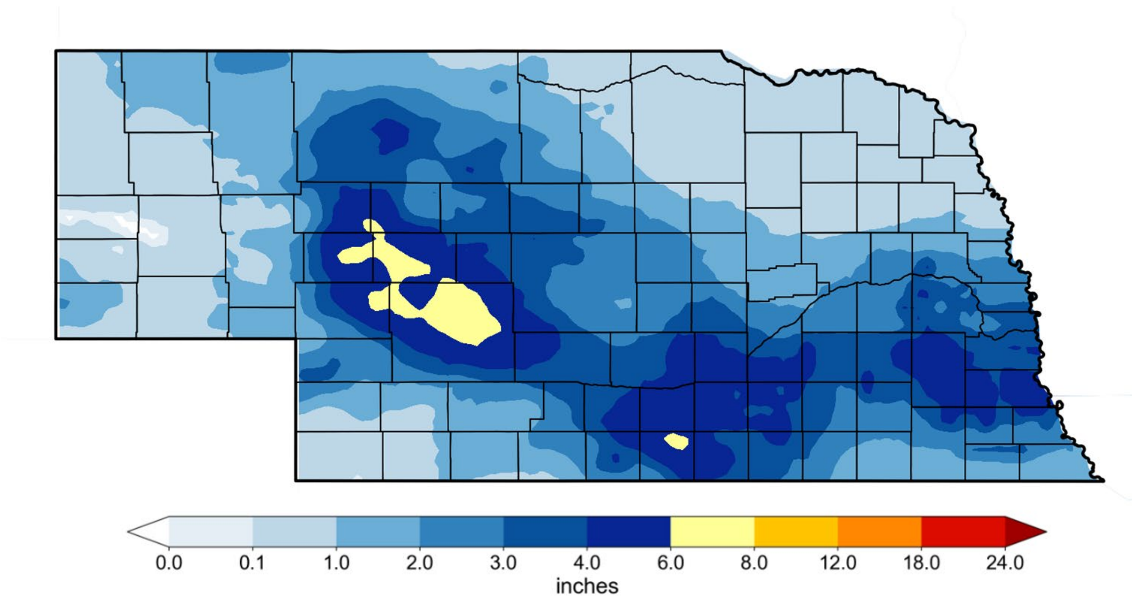

Figure 3.33 NOHRSC 24-h accumulated snowfall (inches) starting at 6:00 pm 5 February 2021 and ending at 6:00 pm 6 February (adapted from NOHRSC 2023)

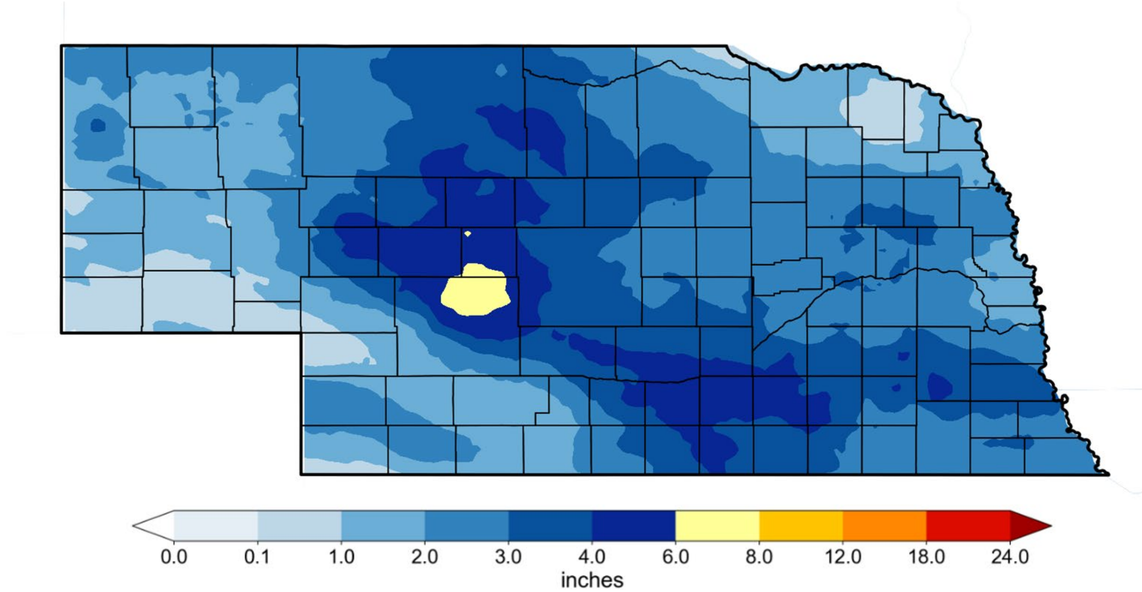

Figure 3.34 NOHRSC 48-h accumulated snowfall (inches) starting at 6:00 pm 6 February 2021 and ending at 6:00 pm 8 February (adapted from NOHRSC 2023).

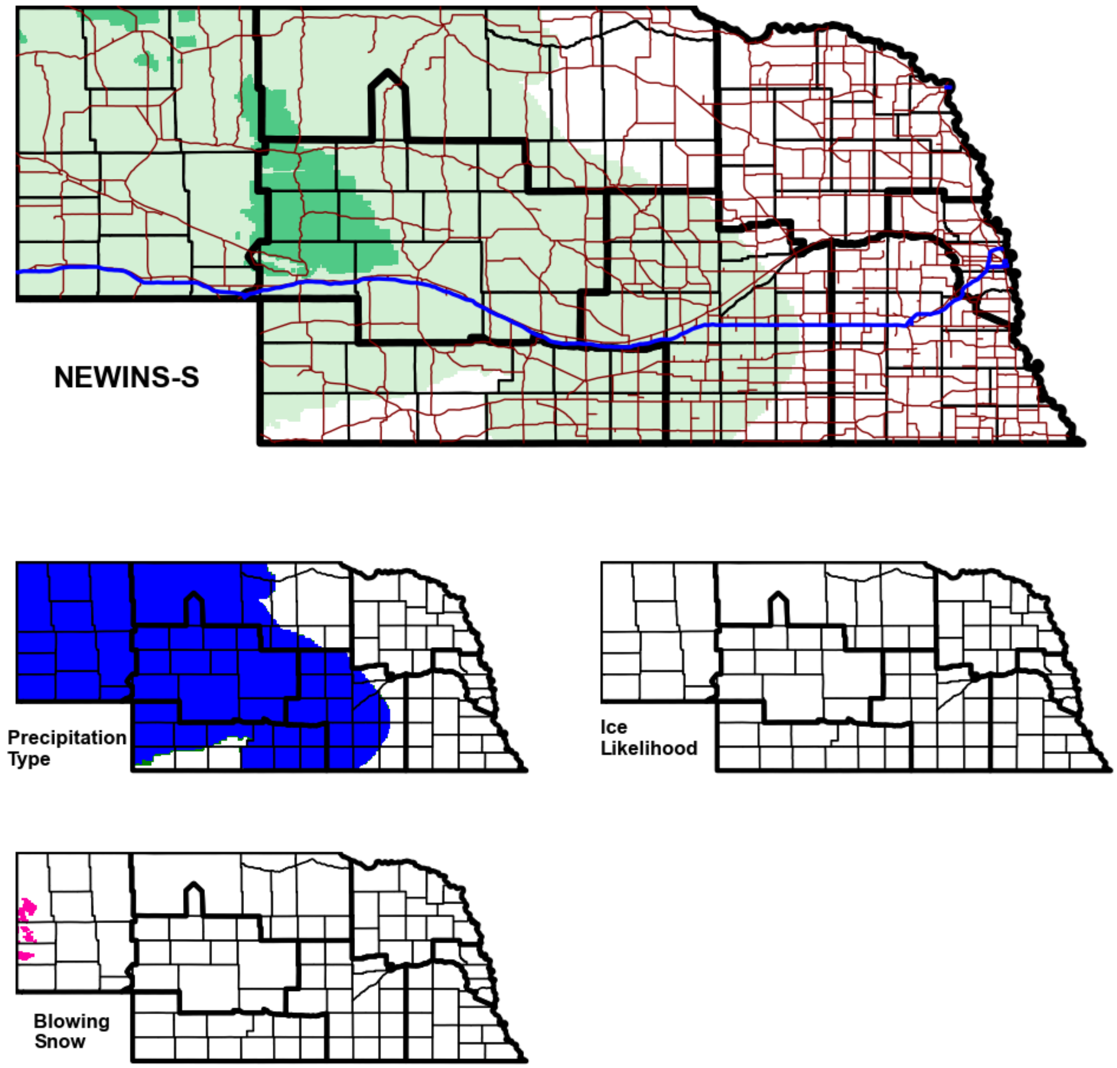

Figure 3.35 The 6-h NEWINS-P forecast from the 6:00 pm 5 February 2021 NDFD run valid for midnight 6 February comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

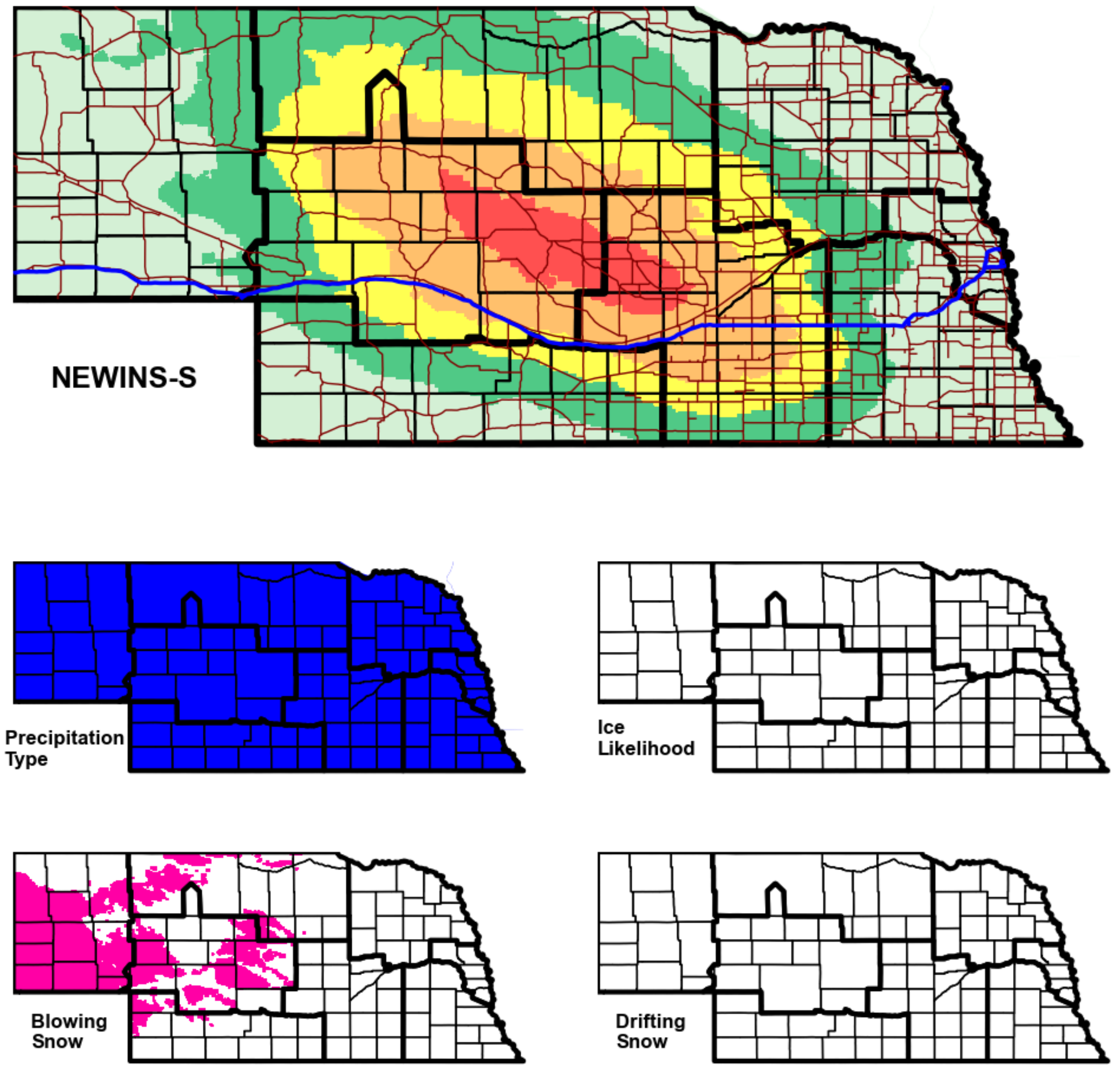

Figure 3.36 The 12-h NEWINS-P forecast from the 6:00 pm 5 February 2021 NDFD run valid for 6:00 am 6 February comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

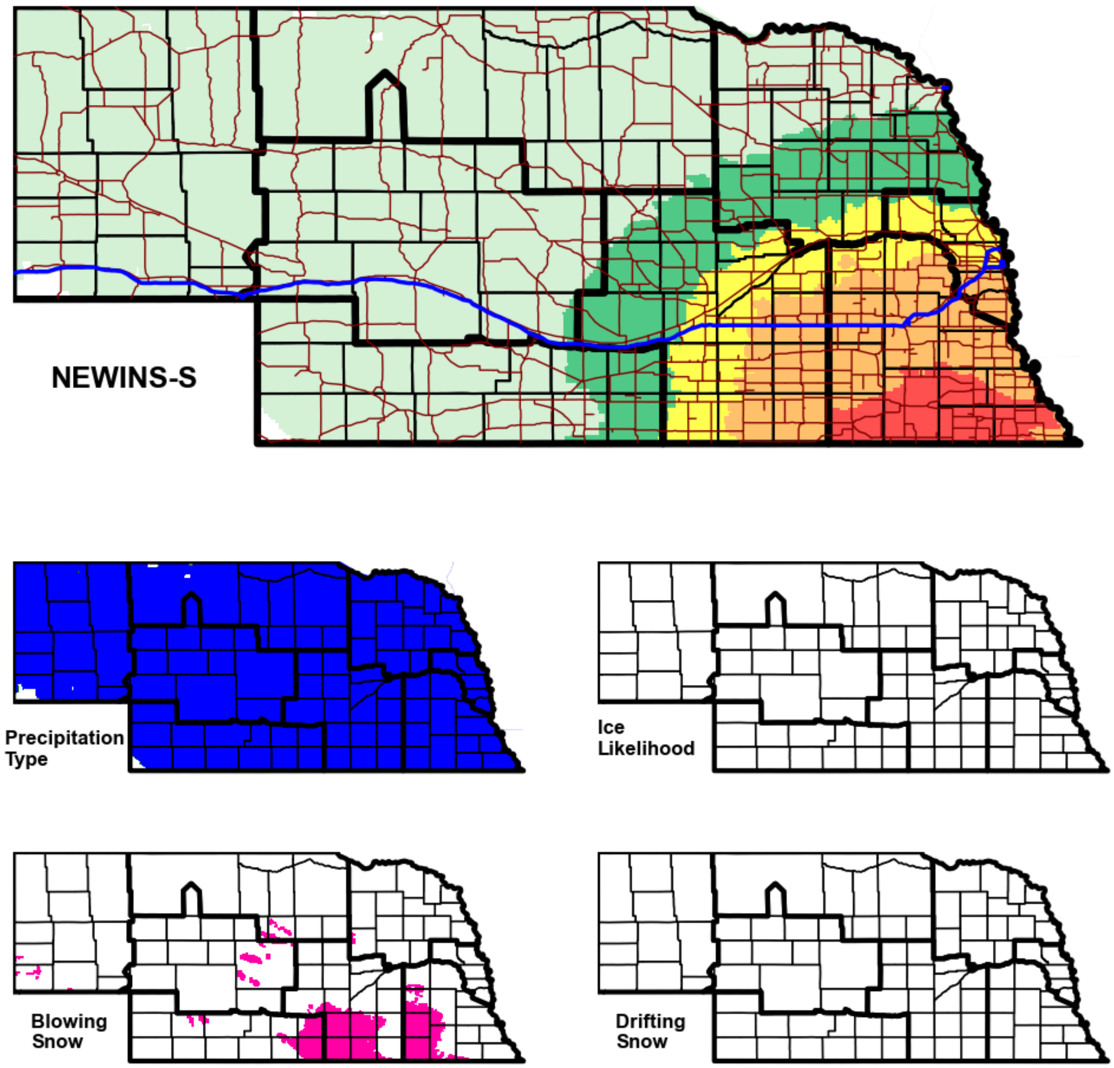

Figure 3.37 The 18-h NEWINS-P forecast from the 6:00 pm 5 February 2021 NDFD run valid for midnight 6 February comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

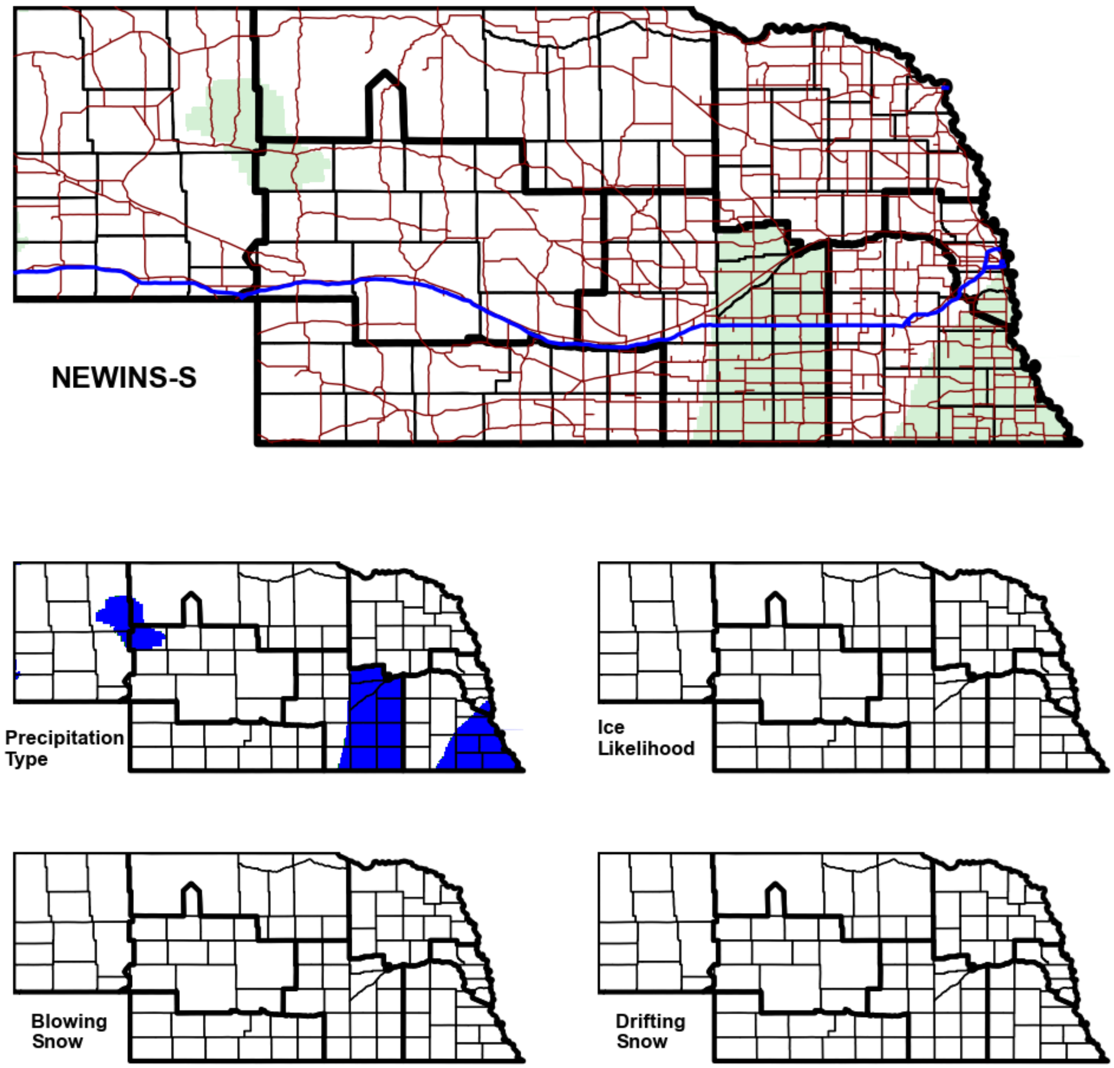

Figure 3.38 The 24-h NEWINS-P forecast from the 6:00 pm 5 February 2021 NDFD run valid for 6:00 pm 6 February comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

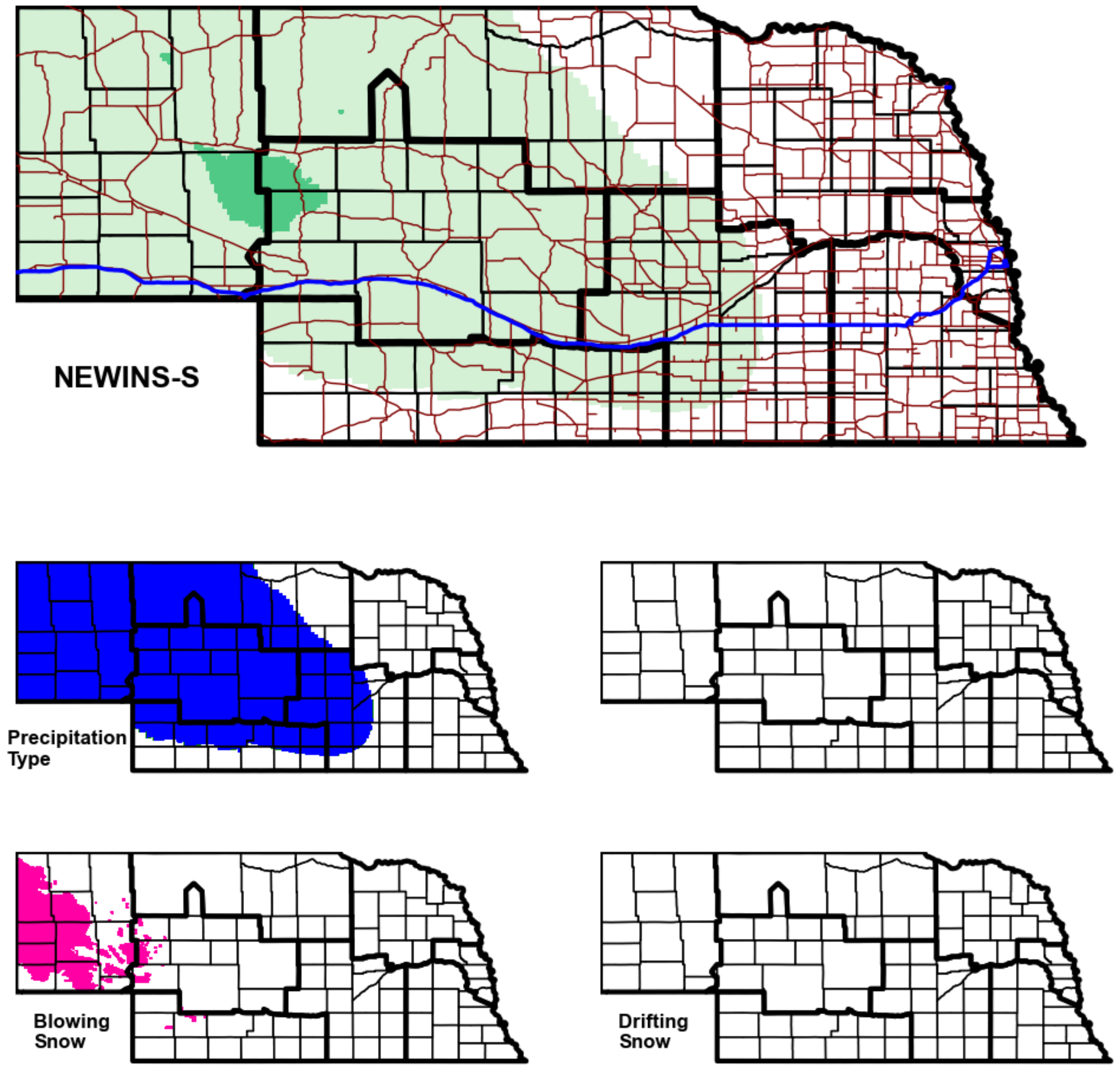

Figure 3.39 The 30-h NEWINS-P forecast from the 6:00 pm 5 February 2021 NDFD run valid for midnight 7 February comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

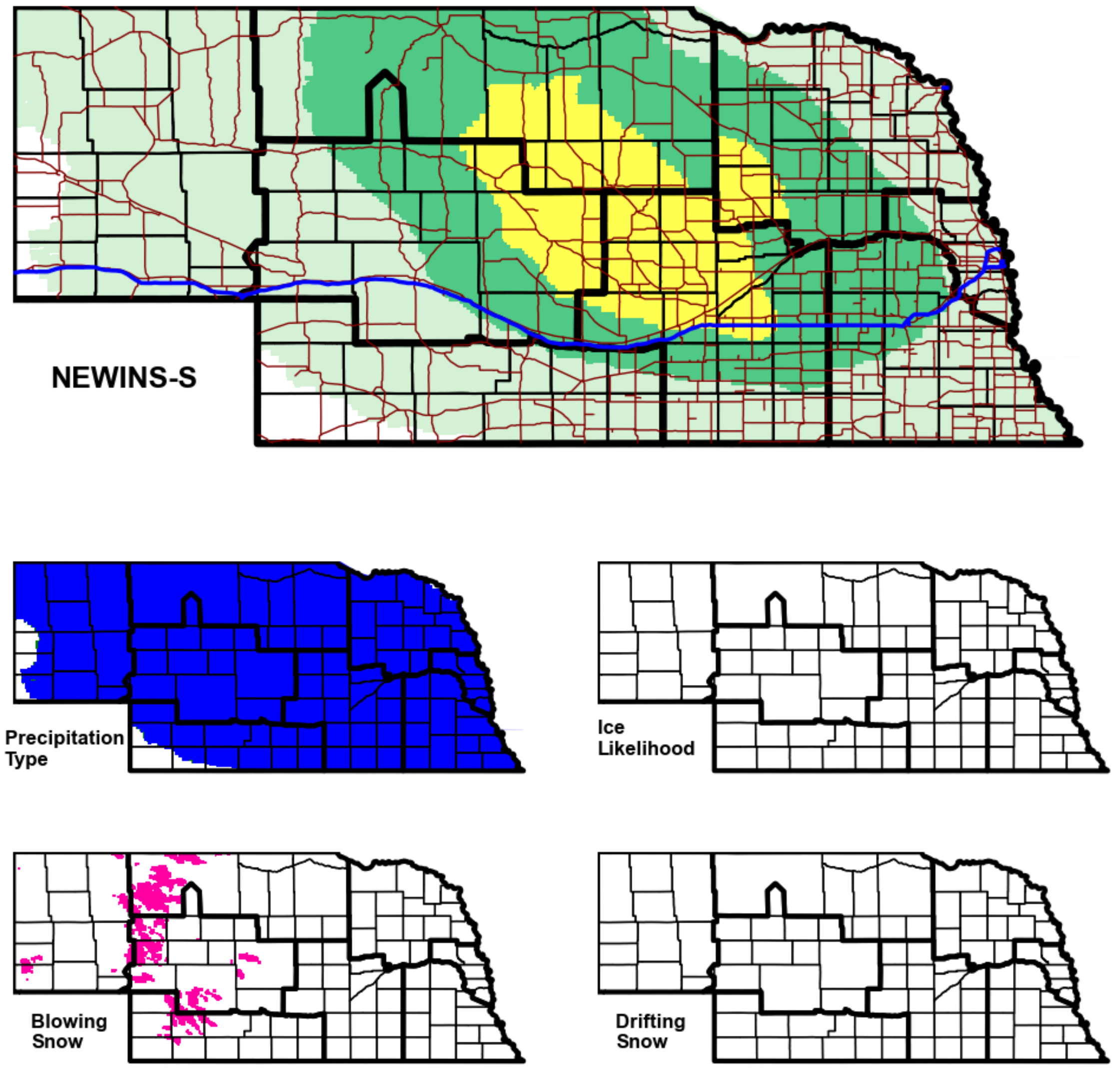

Figure 3.40 The 36-h NEWINS-P forecast from the 6:00 pm 5 February 2021 NDFD run valid for 6:00 am 7 February comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

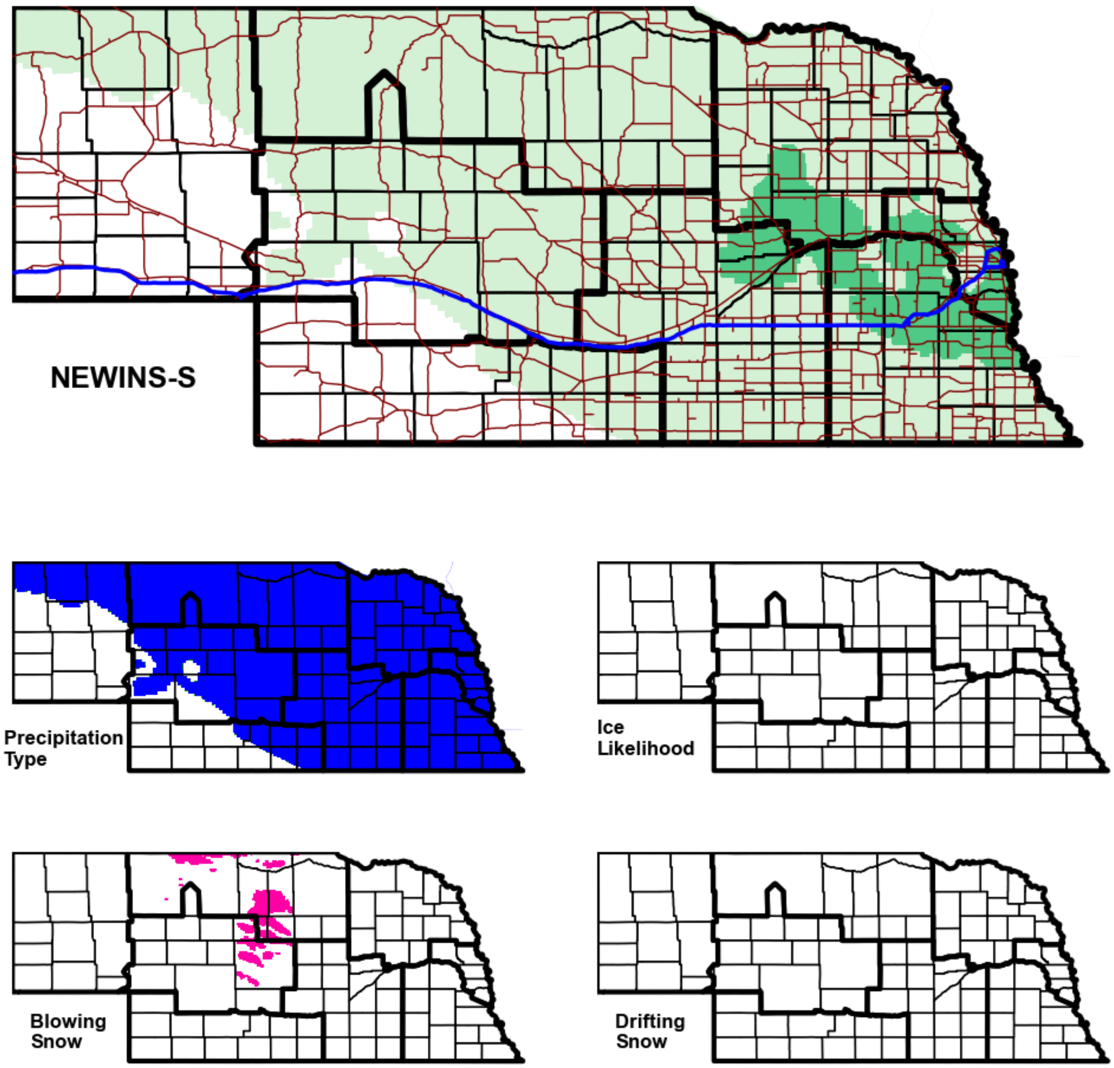

Figure 3.41 The 42-h NEWINS-P forecast from the 6:00 pm 5 February 2021 NDFD run valid for noon 7 February comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

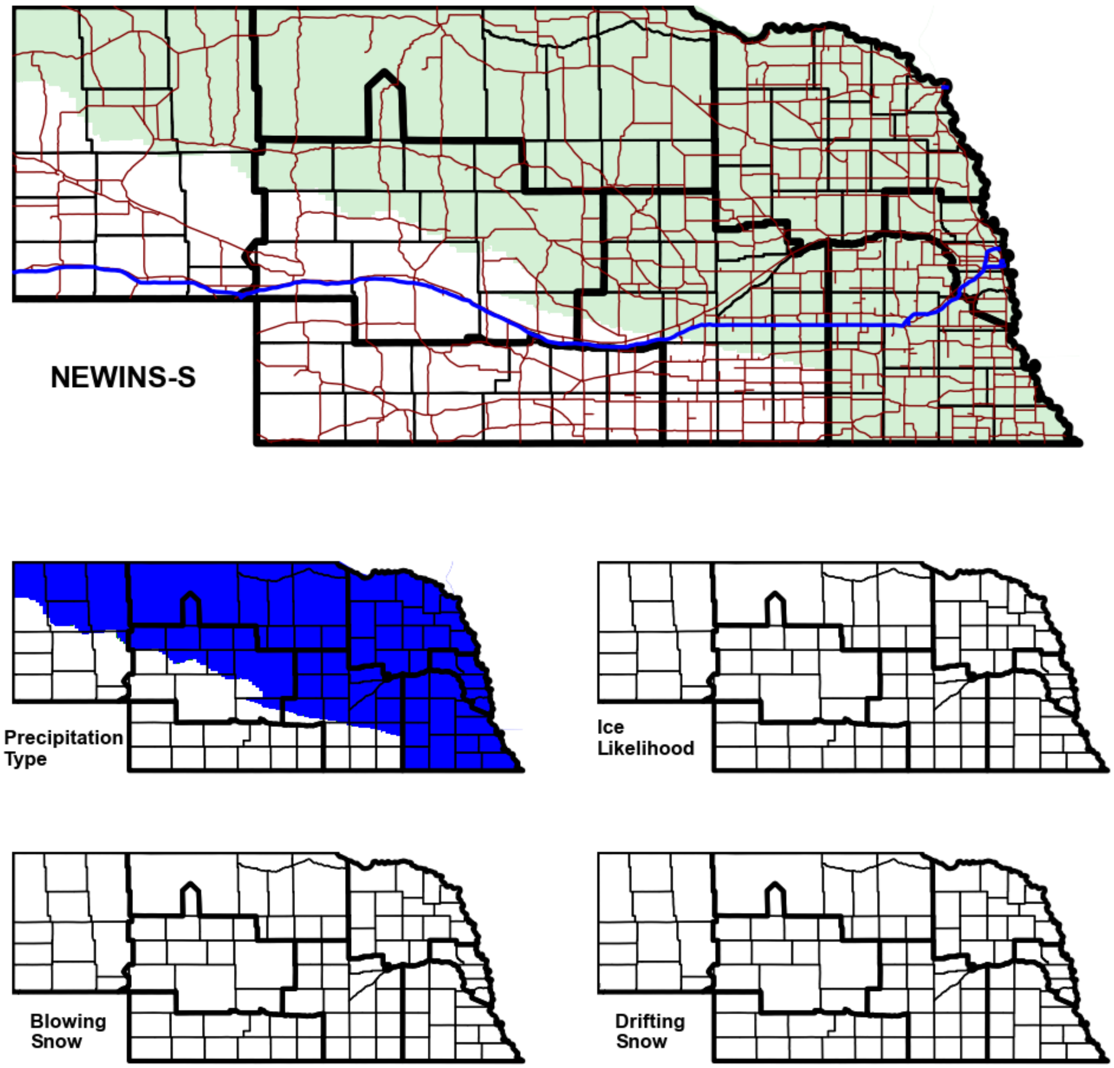

Figure 3.42 The 48-h NEWINS-P forecast from the 6:00 pm 5 February 2021 NDFD run valid for 6:00 pm 7 February comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

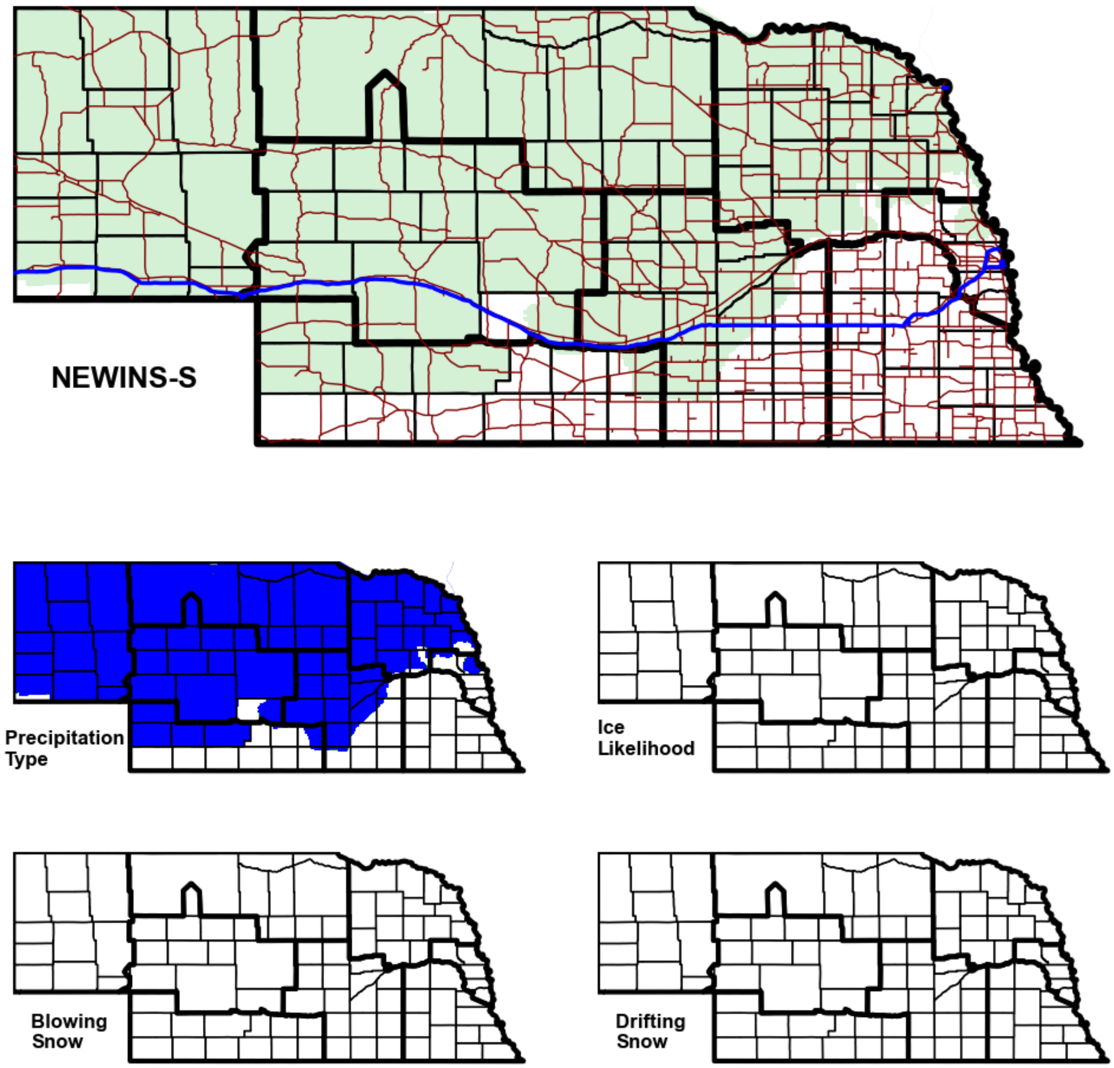

Figure 3.43 The 54-h NEWINS-P forecast from the 6:00 pm 6 February 2021 NDFD run valid for midnight 8 February comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

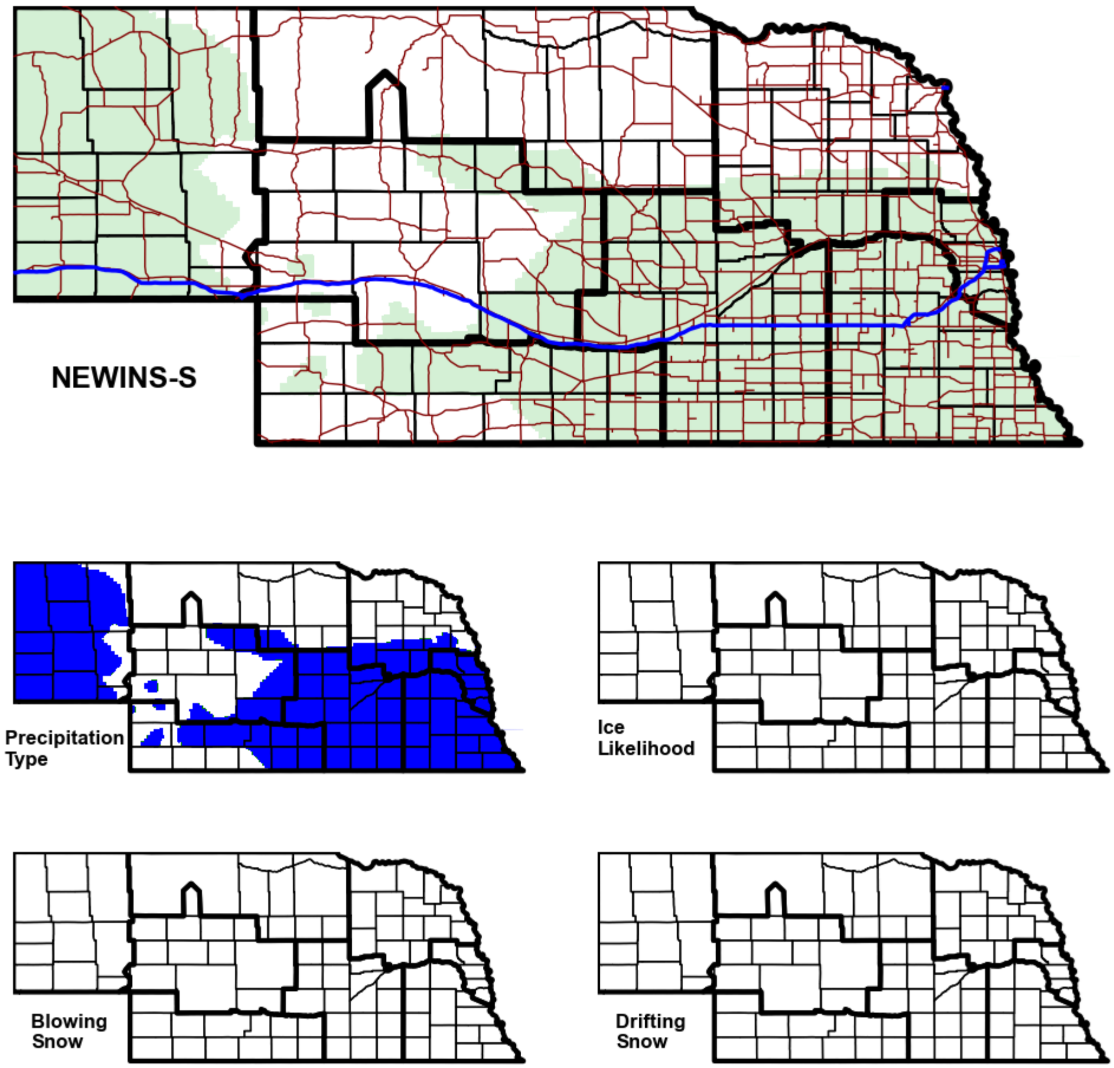

Figure 3.44 The 60-h NEWINS-P forecast from the 6:00 pm 6 February 2021 NDFD run valid for 6:00 am 8 February comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

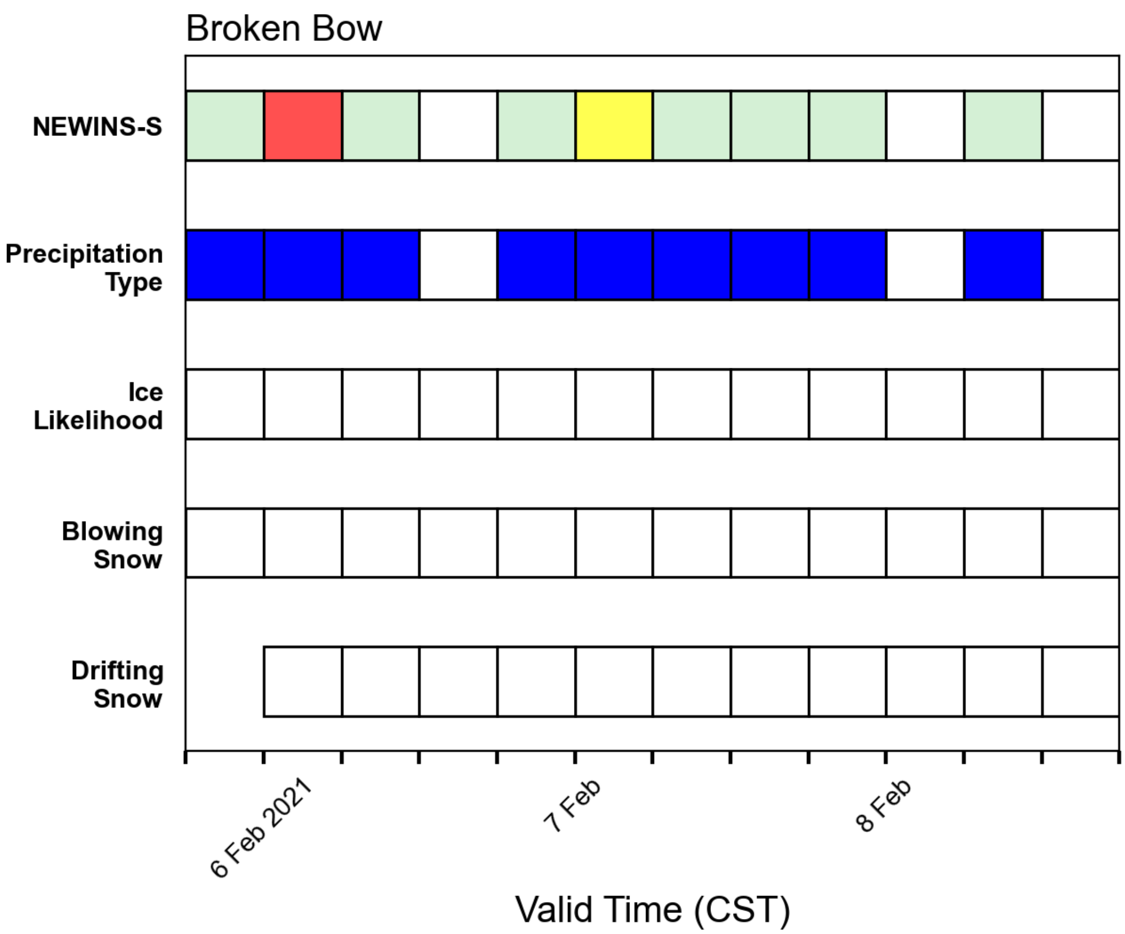

Figure 3.45 Ngram forecast from the 6:00 pm 5 February 2021 NDFD run for Broken Bow. Valid periods when data are not calculable are left blank.

The 5-6 February 2021 and 7-8 February 2021 Alberta Clipper Systems are captured temporally in Broken Bow's Ngram forecast (Figure 3.45). The onset of the 5 February 2021 Alberta Clipper System features NEWINS-S Category 1 from 6:00 pm 5 February to midnight before NEWINS-S ramps up to Category 5 between midnight and 6:00 am 6 February. As quickly as NEWINS-S increases, NEWINS-S decreases to Category 1 and then Category 0 between 6:00 am and 6:00 pm 6 February, marking the end of the 6 February system. The 6-8 February system begins to enter between 6:00 pm and midnight 6 February as NEWINS-S increases to Category 1. The peak of the event is forecasted from midnight 6 February to 6:00 am 7 February with increases to Category 3 followed by a long duration period of Category 1 representing the second wave of the system between 6:00 am to midnight 7 February.

3.2.2 NDFD Evolution: 6-8 February 2021

When inspecting the following NDFD runs (Table 3.2), the evolution in NEWINS-S for both Alberta Clipper Systems show significant spatial and temporal changes across central Nebraska (Figures 3.46-3.48). The 6 February Alberta Clipper System features a significant intensity increase in NEWINS-S categories leading up to the 6:00 am 6 February valid time (Figure 3.46). NDFD Run 1 indicates NEWINS-S Category 1 over most of central Nebraska with an increase to Category 2 occurring in NDFD Run 2 across most of District 6 and portions of Districts 4 and 7. The increase in NEWINS-S categories continues into NDFD Run 3 with Categories 3 and 4 now indicated over Districts 4, 6, and 8 and an introduction of Category 5 in NDFD Run 4 across western District 4 and eastern District 6. The 7-8 February Alberta Clipper System underwent a similar increase in NEWINS-S categories across central Nebraska for the 6:00 am 7 February (Figure 3.48). The intensity increase in NEWINS categories for both systems can be viewed from Broken Bow's time series (Figure 3.49). For the 5-6 February Alberta

Table 3.2 NDFD runs used for the spatial and temporal evolution of the 6-8 February 2021 Alberta Clipper Systems.

NDFD Run Number	**NDFD Run**	**NDFD Run Duration**
1	6:00 am 4 February 2021	72 hours
2	6:00 pm 4 February	72 hours
3	6:00 am 5 February	72 hours
4	6:00 pm 5 February	72 hours
5	6:00 pm 6 February	72 hours
6	6:00 am 7 February	72 hours
7	6:00 pm 7 February	72 hours

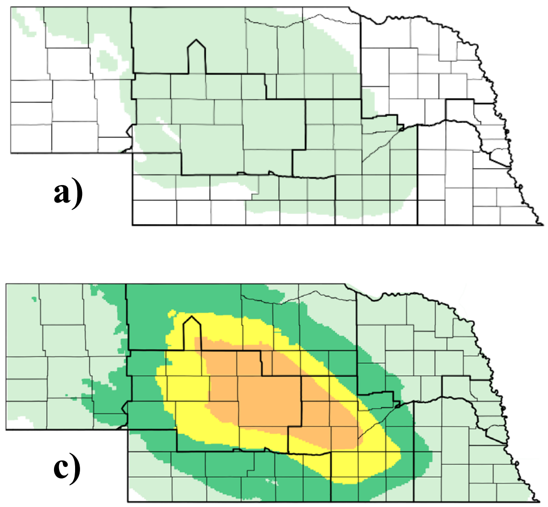

Figure 3.46 NEWINS-S valid for 6:00 am 6 February 2021 from a) NDFD Run 1 48-h forecast, b) NDFD Run 2 36-h forecast, c) NDFD Run 3 24-h forecast, and d) NDFD Run 4 12-h forecast.

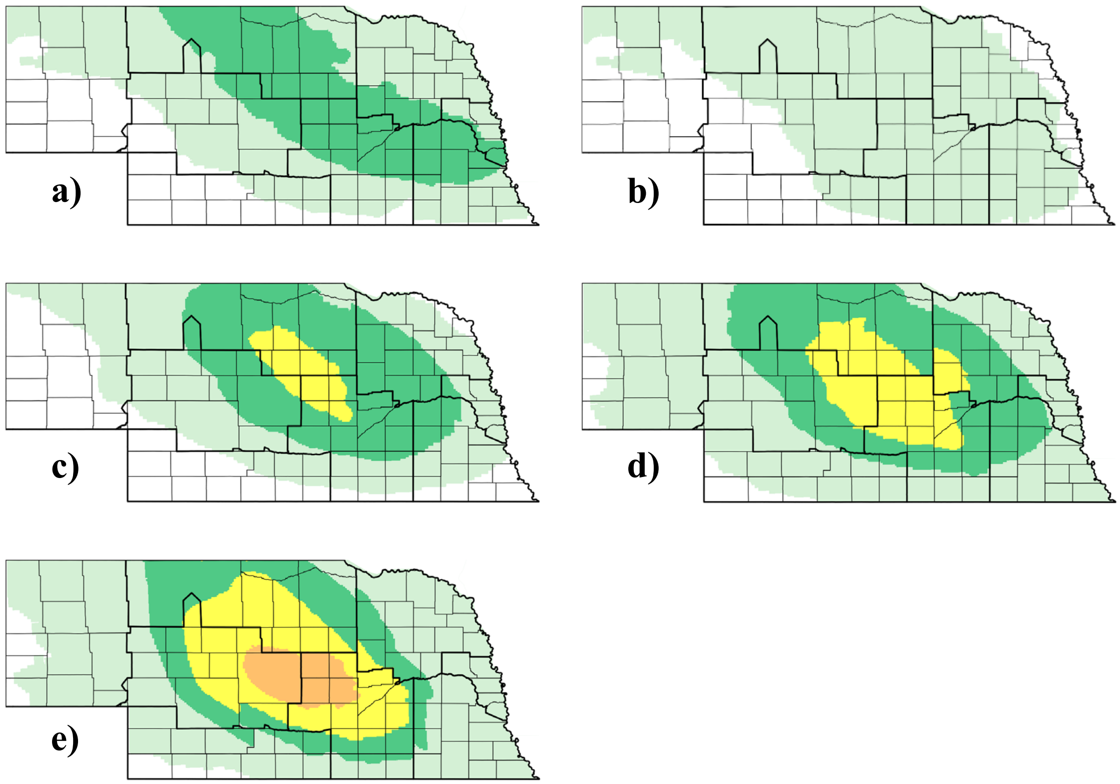

Figure 3.47 NEWINS-S valid for 6:00 am 7 February 2021 from a) NDFD Run 1 60-h forecast, b) NDFD Run 2 48-h forecast, c) NDFD Run 3 36-h forecast, d) NDFD Run 4 24-h forecast, and e) NDFD Run 5 12-h forecast

.

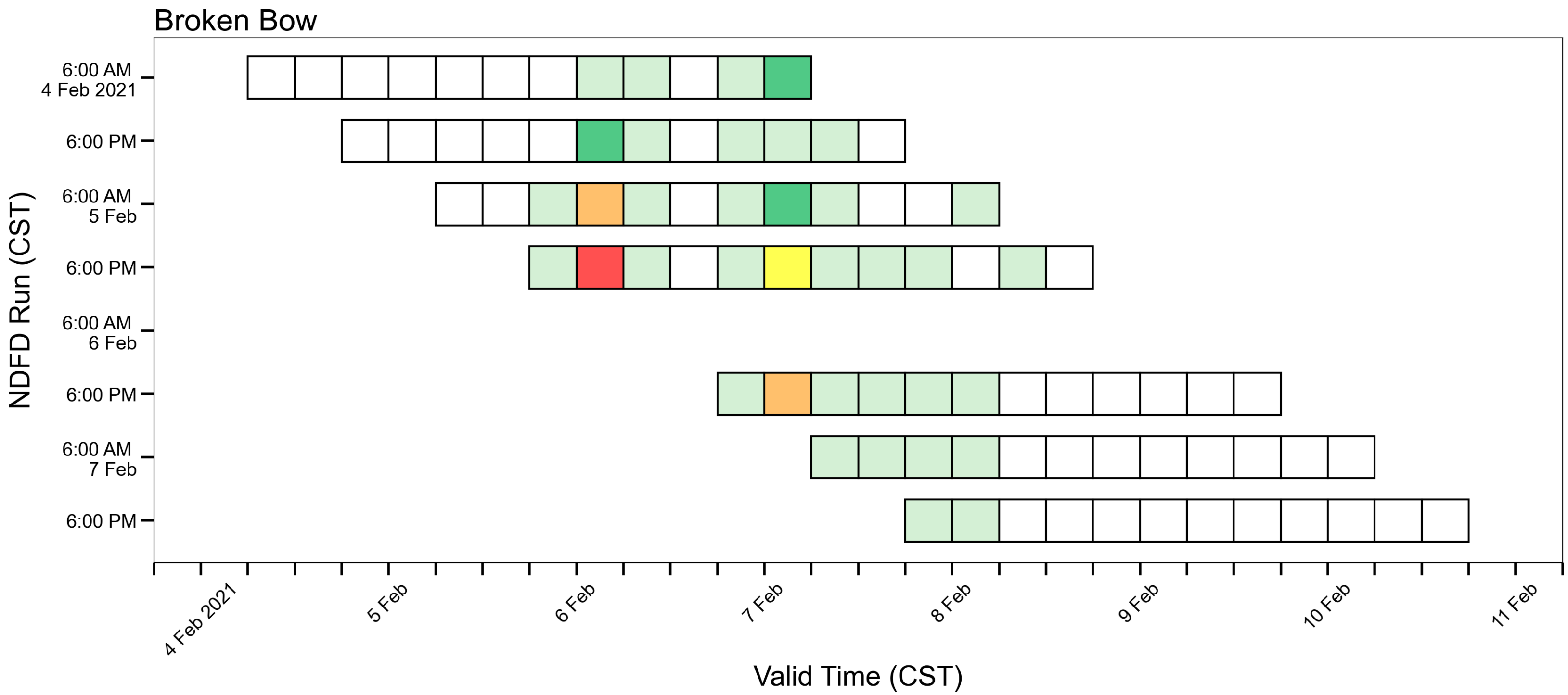

Figure 3.48 Broken Bow NEWINS-S time series starting at 6:00 am 4 February 2021 and ending at 6:00 pm 10 February.

Clipper System, there is an increase from Category 1 in NDFD Run 1 to Category 5 in NDFD Run 4 for the midnight 5 February to 6:00 am 6 February time. For the midnight to 6:00 am 7 February valid period of the 7-8 February Alberta Clipper System, NEWINS-S features a fluctuation of Categories 1 and 2 in NDFD Runs 1 to 3 before an increase to Categories 3 and 4 in NDFD Run 4 and 5.

3.2.3 Case Discussion: 6-8 February 2021

Between 6 and 8 February 2021, two Alberta Clipper Systems brought snowfall to central and eastern Nebraska within a strong arctic air mass. The NEWINS-P spatial and temporal forecasts demonstrate the quick-hitting nature of the highest NEWINS-S impacts in both Clipper Systems with the highest NEWINS-S lasting 12 to 18 h. Similar to the discussed Colorado Low System, investigating the NDFD evolution in NEWINS-S for both Alberta Clipper Systems showed an intensity increase across the state leading up to both events. Inspecting the statewide distributions for both systems is another way of showing the intensity increase in NEWINS-S categories (Figures 3.49 and 3.50). Starting with the 6 February 2021 system (Figure 3.49), NDFD Run 1 shows NEWINS-S Category 1 making up the entire distribution with a decrease in Category 1 occurring in NDFD Run 2 as Category 2 is introduced. NDFD Runs 3 and 4 feature the coverage of Category 1 continuing to decrease with Categories 3 to 5 appearing in the distribution. Overall, statewide coverage of Category 1 decreases from 100% to 38.9%, and Categories 2 to 5 increases from 0% to 61.1%. The statewide coverage of NEWINS-S categories for the 6:00 am 7 February valid time from the 7-8 February system features a general upward trend (Figure 3.50). Overall, statewide coverage of NEWINS-S Categories 1 and 2 decreases from 100% to 75.3%, and Categories 3 and 4 increase from 0% to 24.7%. When comparing the spatial trends in NEWINS-S for both Alberta Clipper Systems to snowfall observations the

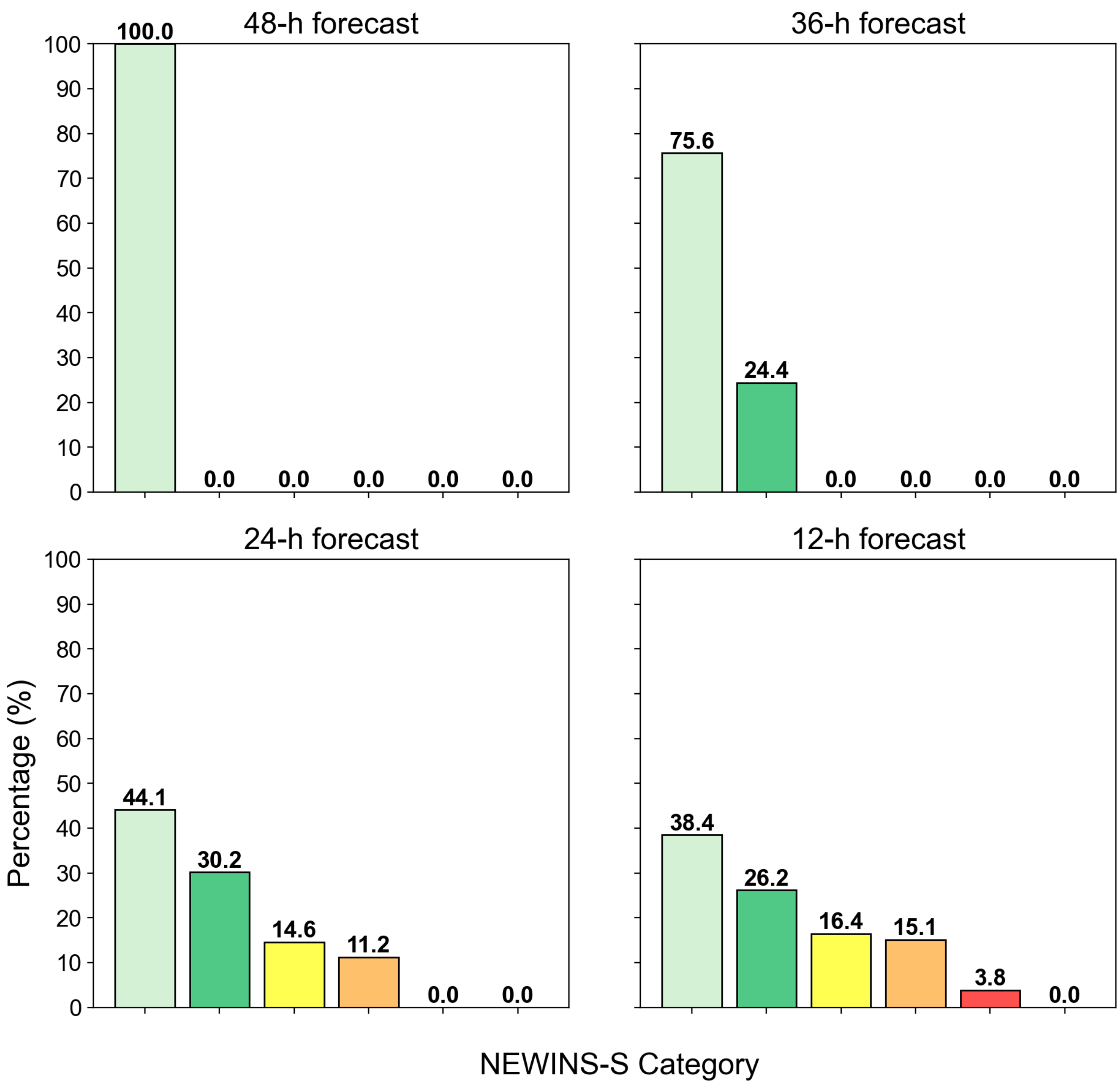

Figure 3.49 Percent statewide NEWINS-S distributions valid for 6:00 am 6 February 2021 from a) NDFD Run 1 48-h forecast, b) NDFD Run 2 36-h forecast, c) NDFD Run 3 24-h forecast, d) NDFD Run 4 12-h forecast.

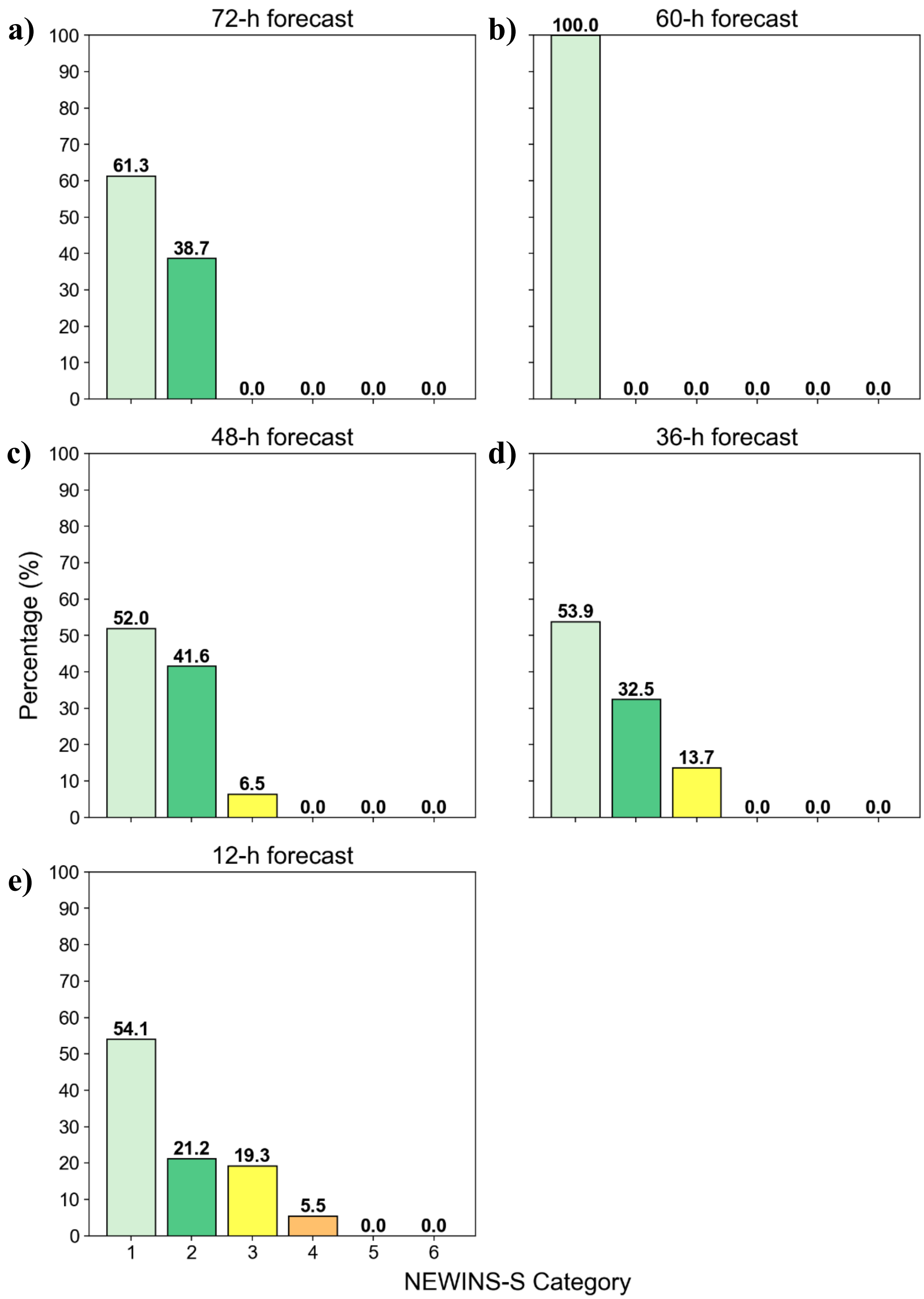

Figure 3.50 Percent statewide NEWINS-S distributions valid for 6:00 am 7 February 2021 from a) NDFD Run 1 72-h forecast, b) NDFD Run 2 60-h forecast, c) NDFD Run 3 48-h forecast, d) NDFD Run 4 36-h forecast, and e) NDFD Run 5 12-h forecast.

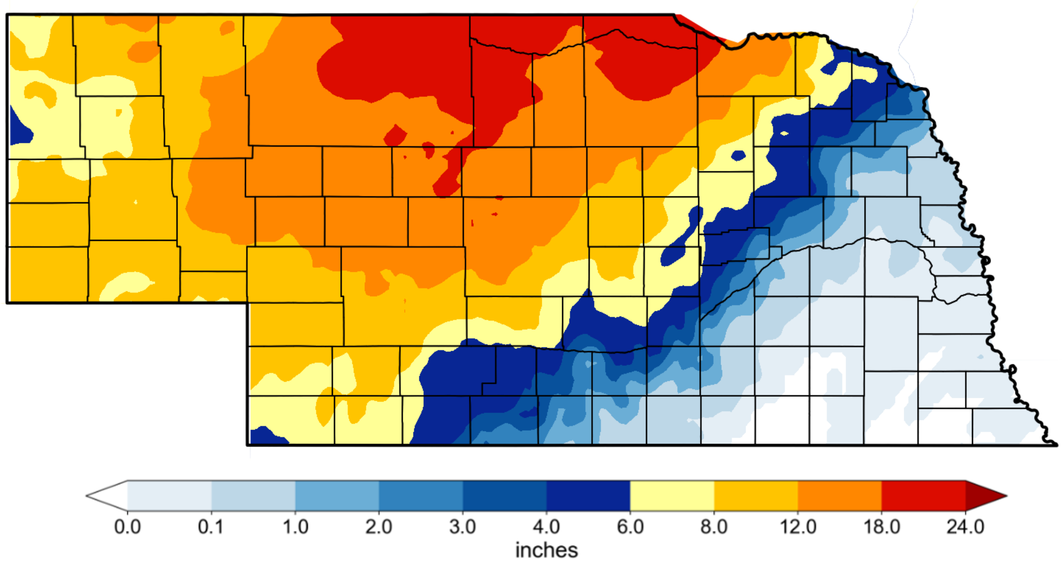

Figure 3.51 NOHRSC 48-h accumulated snowfall (inches) starting at 6:00 pm 1 January 2023 and ending at 6:00 pm 3 January (adapted from NOHRSC 2023).

intensity increase in categories for both Alberta Clipper Systems are justified. The observations would suggest the highest NEWINS-S is verified further southwest than indicated.

3.3 Case Study: 2-3 January 2023 Colorado Low System

The 2-3 January 2023 case study event is a Colorado Low System that produces significant snowfall across central and western Nebraska (Figure 3.51), causing large disruptions to travel. Across north-central Nebraska, well over 12 to 18 inches of snowfall occurred with 2 to 3 inch-per-hour snowfall rates within this system (NWS 2023). In addition to the snowfall, significant icing occurred in portions of south-central and eastern Nebraska.

3.3.1 NDFD Evolution: 2-3 January 2023

Assessing the evolution through multiple NDFD runs of NEWINS-S categories for the 6:00 am 3 January valid time shows a significant upward trend in both the intensity and coverage of NEWINS-S categories leading up to the event (Figure 3.52). NDFD Run 2 has a widespread area of NEWINS-S Category 1 with Categories 2 and 3 across portions of Districts 3 and 8. NDFD Run 3 shows an intensity increase to Category 4 across eastern portions of District 8 before being removed in NDFD Run 4. By NDFD Run 5, NEWINS-S categories begin to increase significantly across north-central Nebraska with Categories 3 to 5 indicated. The intensity increase in NEWINS-S categories continues into NDFD Run 6 with widespread Categories 4 to 6 now being indicated. NDFD Run 7 shows an increase in coverage of Categories 4 to 6 across north-central Nebraska. For the midnight to 6:00 pm 3 January period, NEWINS categories increase from Categories 2 and 3 in NDFD Runs 2 to 4 to Categories 4 to 6 in NDFD Runs 5 to 7. The increase also applies to the periods before and after midnight to 6:00 pm 3 January, indicative of a trend toward a stronger event.

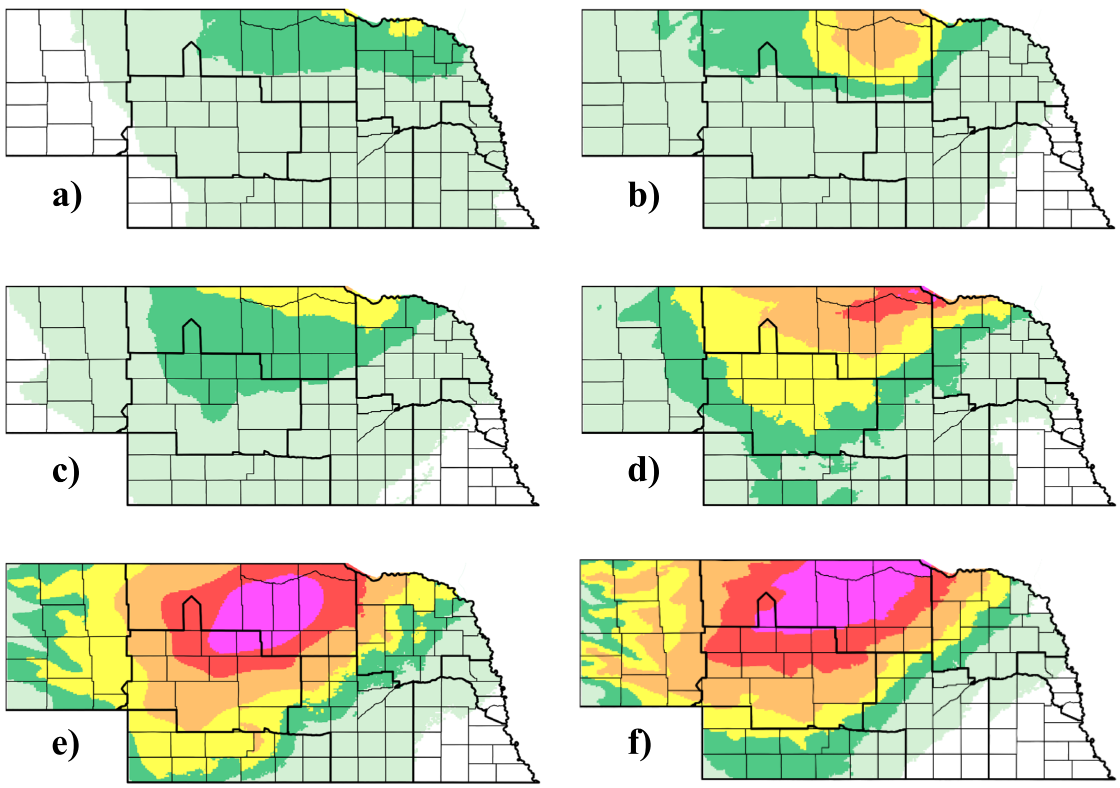

Figure 3.52 NEWINS-S valid for 6:00 am 3 January 2023 from a) NDFD Run 2 72-h forecast, b) NDFD Run 3 60-h forecast, c) NDFD Run 4 48-h forecast, d) NDFD Run 5 36-h forecast, e) NDFD Run 6 24-h forecast, and f) NDFD Run 7 12-h forecast.

3.3.2 Case Discussion 2-3 January 2023

The 2-3 January 2023 Colorado Low System brought strong in-storm impacts to Nebraska, producing heavy snowfall in north-central Nebraska and severe icing in portions of central and eastern Nebraska. Assessing the NEWINS-P spatial and temporal forecasts for the 2-3 January 2023 case showcases concerns through high NEWINS-S categories across northern Nebraska and varying ice likelihood across central and eastern Nebraska. The forecasts also show little to no post-storm impacts following the passage of the system. Through the investigation of multiple NDFD runs leading up to the peak of the event, an upward trend in NEWINS-S categories can be seen for the peak of the event spatially and temporally, similar to the 13-17 December 2022 Colorado Low System. However, the changes occur over a much larger spatial area and are more significant when inspecting the statewide NEWINS-S distributions (Figure 3.53). In NDFD Run 2, 99.2% of the distribution comprises NEWINS-S Categories 1 to 2. Categories 3 and 4 begin to take up more of the distribution by NDFD Run 5. The distribution becomes spread out in NDFD Runs 6 and 7 as the percentage of Categories 4 to 6 increases. NDFD Run 1 statewide coverage of Categories 1 to 3 is 100% and Categories 4 to 6 is 0%, while NDFD Run 6 statewide coverage of Categories 1 to 3 is 52.3% and Categories 4 to 6 is 47.7%. When comparing the spatial forecast trends to snowfall observations for the peak of the event, the intensity increase in NEWINS-S categories was justified with the heaviest snowfall occurring in generally the same locations as the trends indicated; however, the later NDFD runs are too aggressive with NEWINS-S, as no reports reach the Category 6 caliber. The precipitation type and ice likelihood experienced significant variability when comparing NDFD runs. The expansion of mixed precipitation and ice likelihood was warranted when inspecting ice

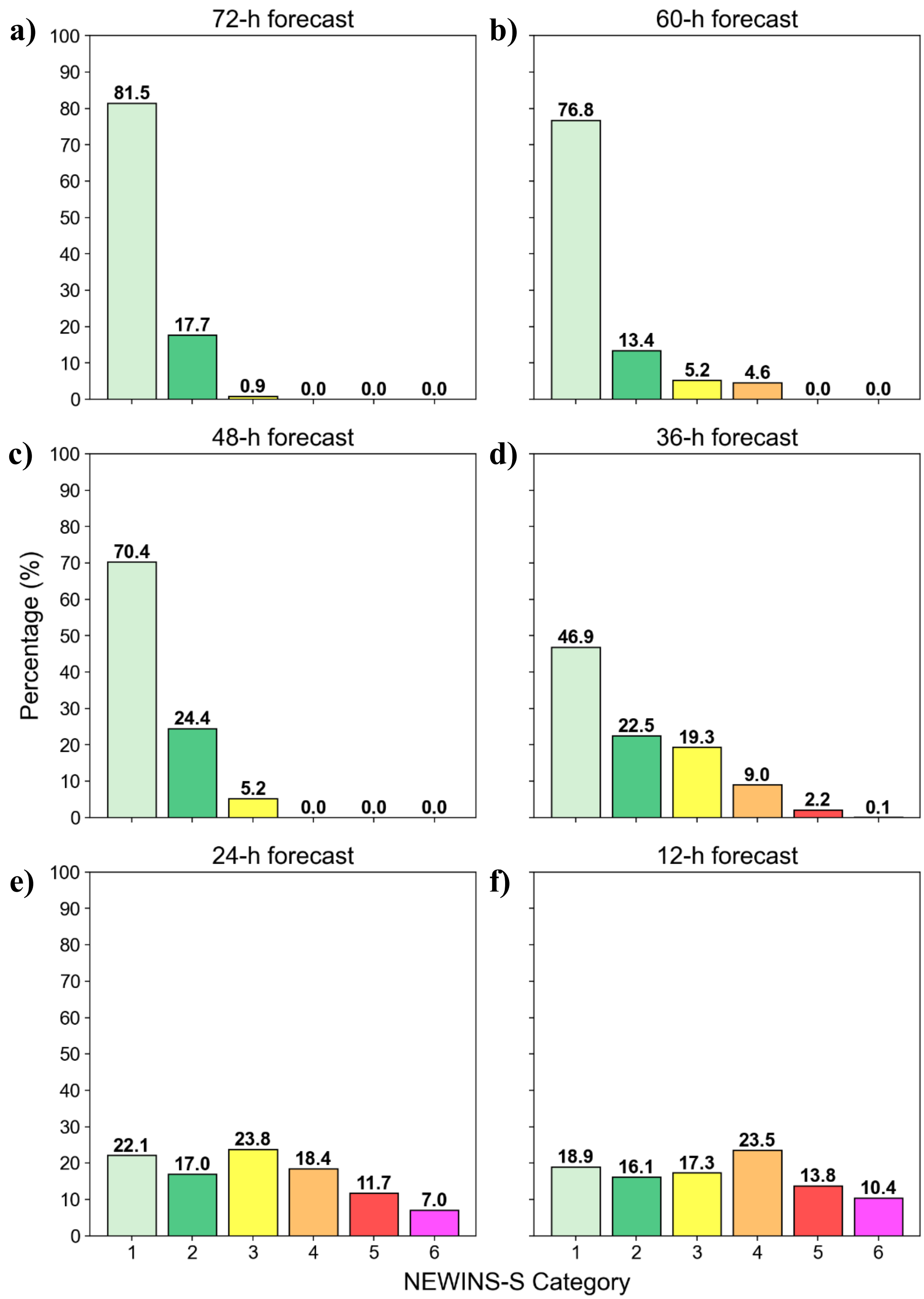

Figure 3.53 Percent statewide NEWINS-S distributions valid for 6:00 am 3 January 2023 from a) NDFD Run 2 72-h forecast, b) NDFD Run 3 60-h forecast, c) NDFD Run 4 48-h forecast, d) NDFD Run 5 36-h forecast, e) NDFD Run 6 24-h forecast, and f) NDFD Run 7 12-h forecast.

observations. This case study event also identified additional misaligned forecasts between different NWS forecast offices.

3.4 Case Study: 18-19 January 2023 Colorado Low System

The 18-19 January 2023 case study event was a Colorado Low System that produced a high-impact widespread winter storm containing a swath of significant snowfall across most of the state (Figure 3.54). Across portions of central Nebraska, snowfall totals over 12 inches were common with localized areas receiving 24 inches that resulted in many locations setting single-day snowfall records (NWS 2023a). Further south and east, the system produced significant icing in portions of southeast Nebraska.

3.4.1 NDFD Evolution: 18-19 January 2023

Evaluating spatial changes in NEWINS-S for the noon 18 January valid time from several NDFD runs reveals significant intensity and coverage adjustments (Figure 3.55). In NDFD Run 1, NEWINS-S Categories 2 to 4 are indicated across southwestern Nebraska. However, by NDFD Runs 2 and 3, the highest NEWINS-S categories trend northward and expand in coverage to include much of central Nebraska. Small locational changes occur in NDFD Run 4 with continued expansion of the highest categories. By NDFD Run 5, there is a significant intensity increase across central Nebraska with widespread Category 5 and a patch of Category 6 being indicated.

3.4.2 Case Discussion: 18-19 January 2023

The 18-19 January 2023 Colorado Low System caused significant impacts from heavy snowfall across central Nebraska and icing impacts across southeastern Nebraska. Using both the NEWINS-P spatial and temporal forecasts showed these concerns occurring within a 24-30 h period with no post-storm impacts from drifting snow. The peak of the event featured significant

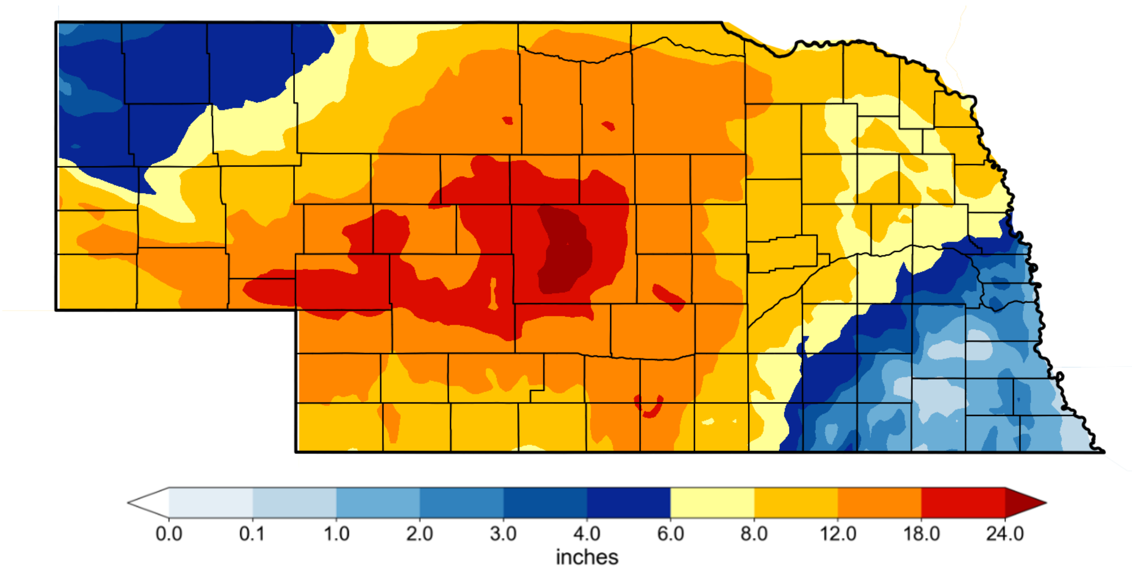

Figure 3.53 NOHRSC 48-h accumulated snowfall (inches) starting at 6:00 pm 17 January 2023 and ending at 6:00 pm 19 January (adapted from NOHRSC 2023).

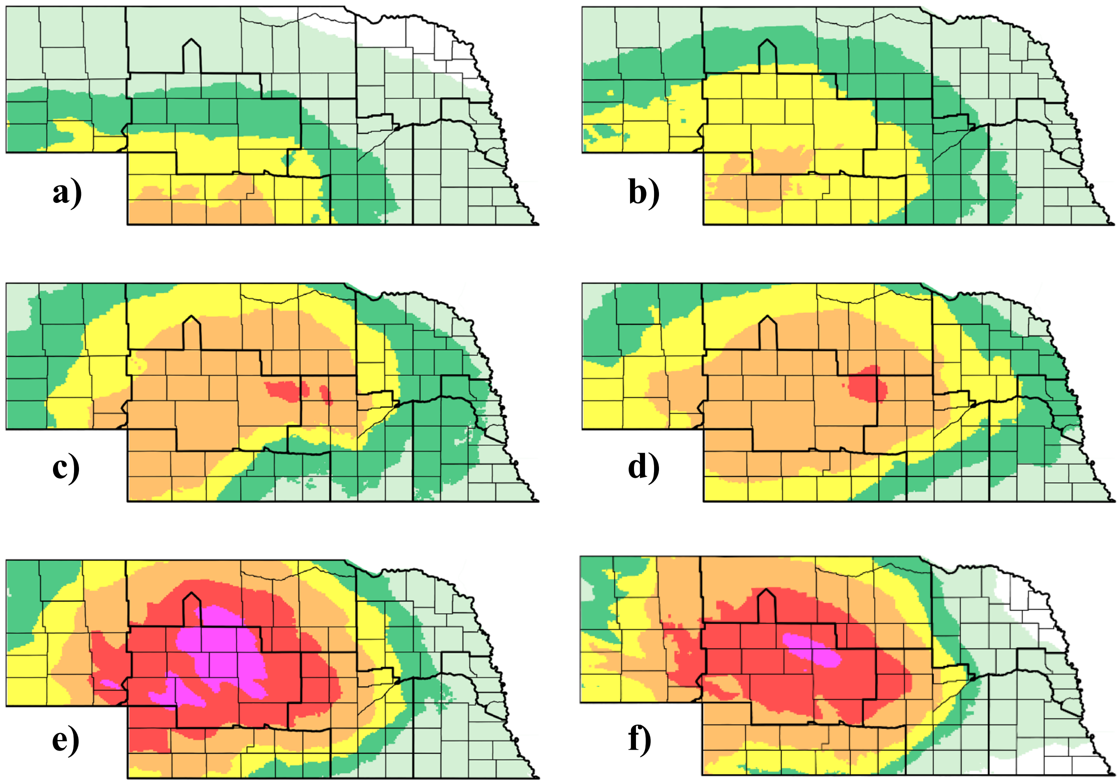

Figure 3.54 NEWINS-S valid noon 18 January 2023 from a) NDFD Run 1 72-h forecast, b) NDFD Run 2 60-h forecast, c) NDFD Run 3 48-h forecast, d) NDFD Run 4 36-h forecast, e) NDFD Run 5 24-forecast, and f) NDFD Run 6 12-h forecast.

spatial and temporal changes in NEWINS-S and precipitation type and ice likelihood components. When evaluating NEWINS-S, this system shares a familiar theme with the previously discussed Colorado Low Systems in that there are shifts in both the placement and severity of NEWINS-S as the event gets closer. Inspecting the statewide distributions in NEWINS-S categories is another way to showcase the intensity increase (Figure 3.56). NDFD Run 1 shows Category 1 making up most of the distribution with progressively less of Categories 2 to 4. By NDFD Run 2, there is more spread Categories 1 to 3 that continues to grow in NDFD Runs 4 and 5 as the percentage of Categories 5 and 6 increases. Overall, statewide coverage of NEWINS-S Categories 1 to 3 decreases from 94.8% to 47.3%, and Categories 4 to 6 increases from 5.2% to 52.7%. This intensity increase in NEWINS-S categories for the noon 13 January timeframe is justified when looking at snowfall observations with the heaviest snowfall occurring in areas indicated to receive the highest NEWINS-S categories.

3.5 Case Study: 24-25 November 2018 Colorado Low System

The 24-25 November 2018 case study event is a Colorado Low System that produces a few to several inches of snowfall across most of the state, with higher snowfall occurring across portions of northwestern and southeastern Nebraska (Figure 3.57). This area of higher snowfall in southeastern Nebraska also features strong impacts from strong winds and blizzard conditions, causing multiple winter storm and blizzard warnings to be posted.

3.5.1 NDFD Evolution: 24-25 November 2018

Figures 3.58 to 3.61 evaluates the spatial and temporal evolution in NEWINS-S from NDFD runs for northwestern and southeastern Nebraska at locations where the heaviest snowfall occurred. Starting with northwestern Nebraska, while the placement of NEWINS-S categories experiences little change, there is a trend for higher NEWINS-S categories for the midnight

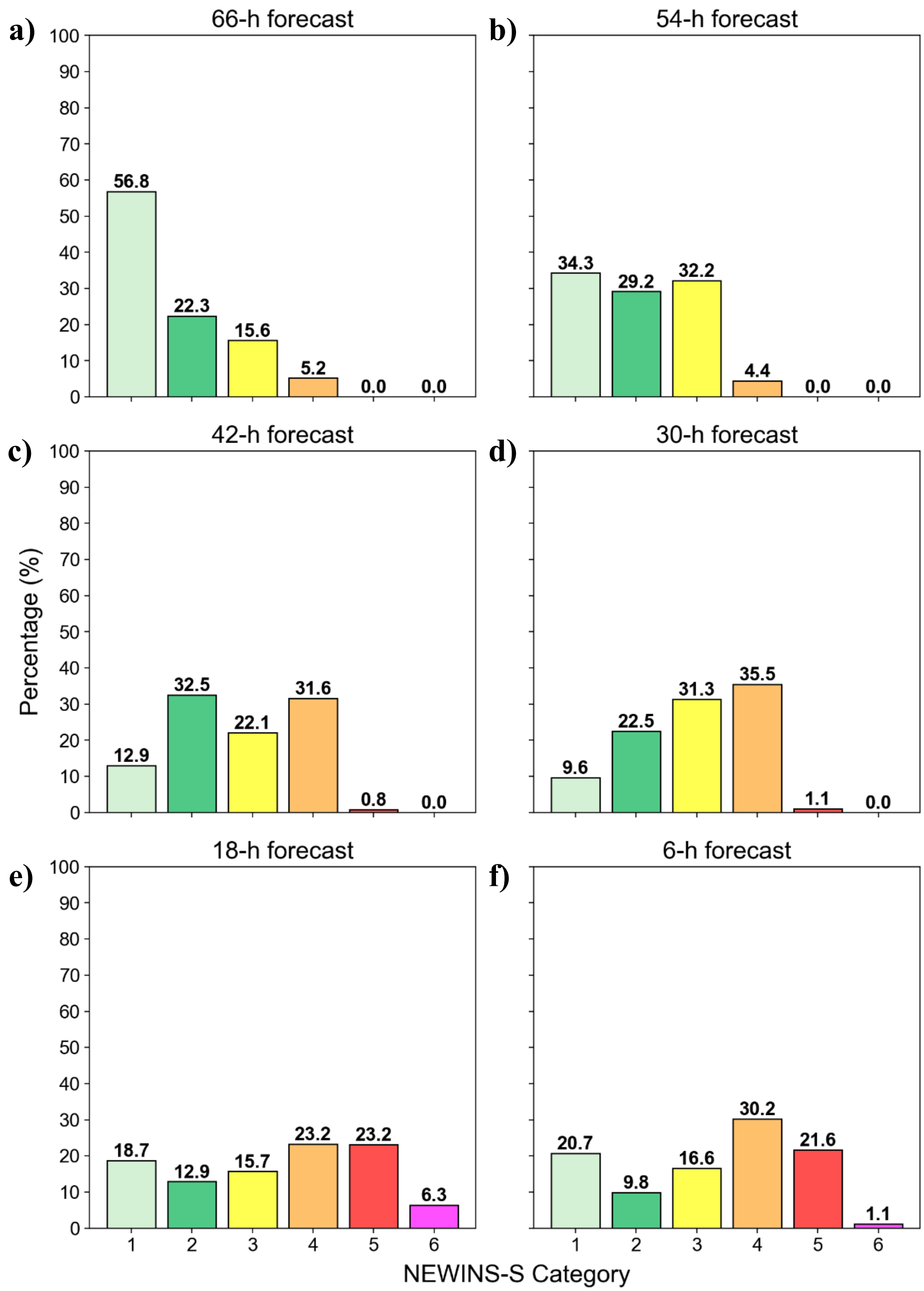

Figure 3.55 Percent statewide NEWINS-S distributions valid for noon 18 January 2023 from a) NDFD Run 1 66-h forecast, b) NDFD Run 2 54-h forecast, c) NDFD Run 3 42-h forecast, d) NDFD Run 4 30-h forecast, e) NDFD Run 5 18-h forecast, and f) NDFD Run 6 6-h forecast.

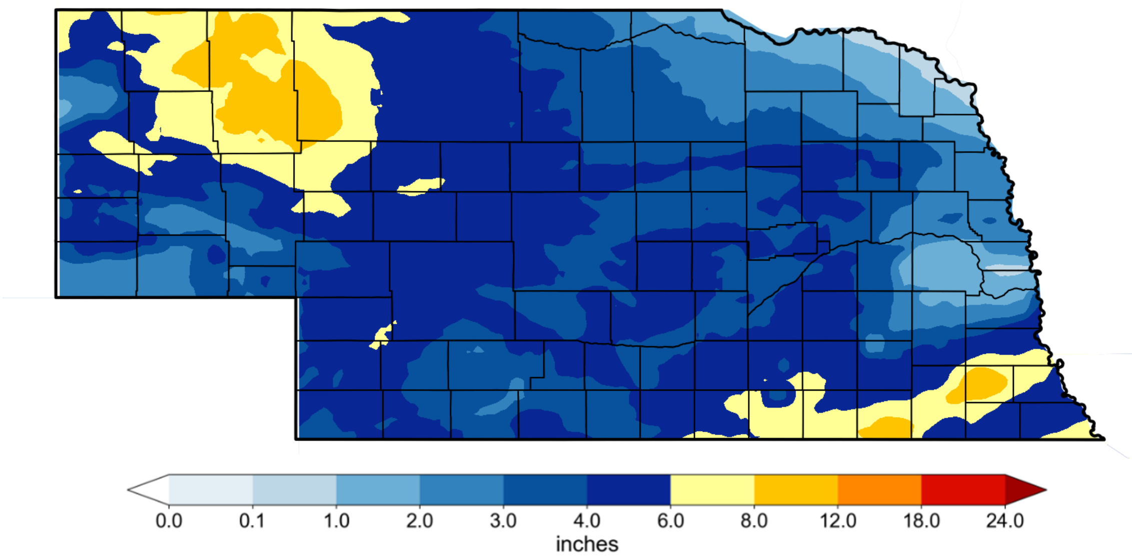

Figure 3.56 NOHRSC 48-h accumulated snowfall (inches) starting at 6:00 pm 23 November 2018 and ending at 6:00 pm 25 November (adapted from NOHRSC 2023).

25 November valid time (Figure 3.58). NDFD Run 1 shows widespread Category 2 and isolated Category 3 across north-central Nebraska. By NDFD Run 2, there is a notable increase in Category 3 areas and an introduction of Category 4 across the region. NDFD Runs 3 and 4 feature an expansion in Category 4 to include western District 8 and portions of District 5. Lastly, NDFD Run 5 expands Category 4 southward to include northern District 6. Southeastern Nebraska experiences an increase in NEWINS-S categories for the noon 25 November with larger changes in the placement of high NEWINS-S categories than the previous example (Figure 3.59). The general indication of a system is present in NDFD Runs 1 and 2 with NEWINS-S Categories 2 to 4 across southeast Nebraska. Category 5 is introduced and confined to far-southeastern District 1 in NDFD Runs 3 and 4. The coverage of Category 5 increases in NDFD Run 5 with a widespread area of Category 6 occupying southeastern District 1. Across these NDFD runs, the gradient in NEWINS-S categories sharpens as the event gets closer. In NDFD Run 6, the difference between Category 1 and Category 6 is approximately 45-50 miles. This is a good illustration of how variable NEWINS-S categories can change over a short distance.

3.5.2 Case Discussion: 24-25 November 2018

The 24-25 November 2018 Colorado Low System produces widespread snowfall across Nebraska as a deepening surface low passes to the southeast, leading to blizzard conditions across the southeastern portion of the state. Overall, the NEWINS-P forecasts showcase all in-storm impacts occurring in an 18-h period with no post-storm impacts such as drifting snow. Evaluating the NDFD evolution in NEWINS-S for northwestern and southeastern Nebraska, two areas that received the heaviest snowfall, shows an intensity increase in NEWINS-S. Northwestern Nebraska contains mostly Categories 1 to 2 in NDFD Run 1 and spreads to a

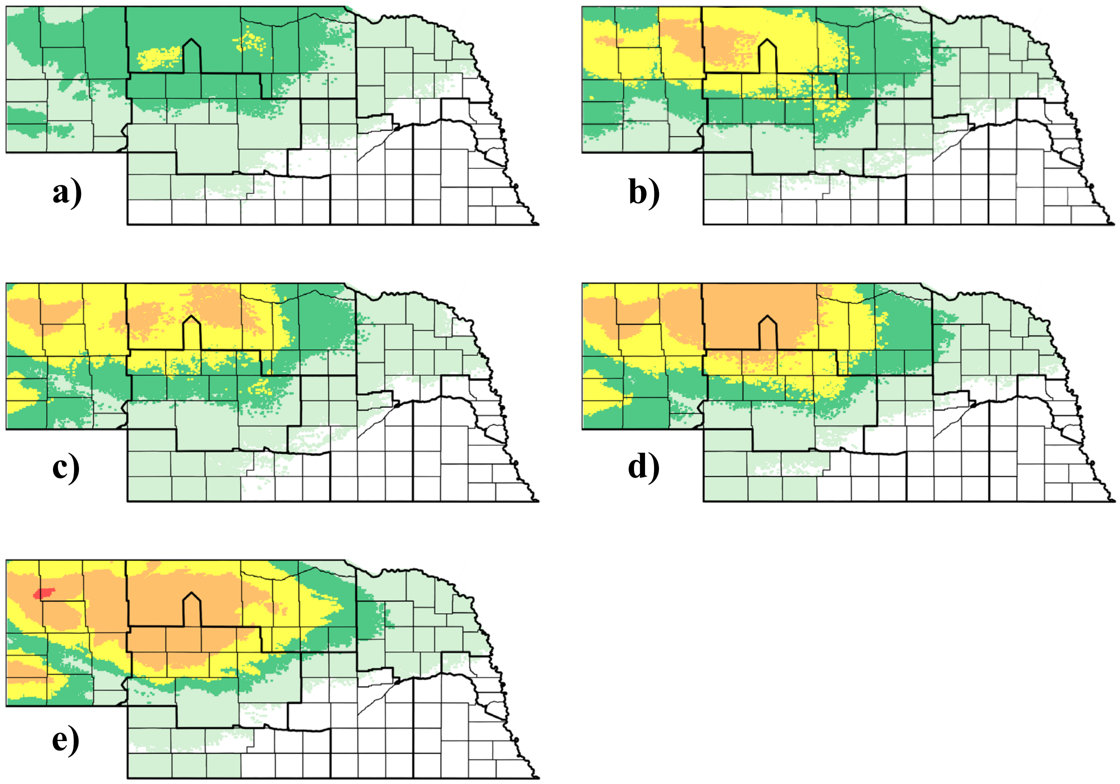

Figure 3.57 NEWINS-S valid for midnight 25 November 2018 from a) NDFD Run 1 60-h forecast, b) NDFD Run 2 48-h forecast, c) NDFD Run 3 36-h forecast, d) NDFD Run 4 24-h forecast, and e) NDFD Run 5 12-h forecast.

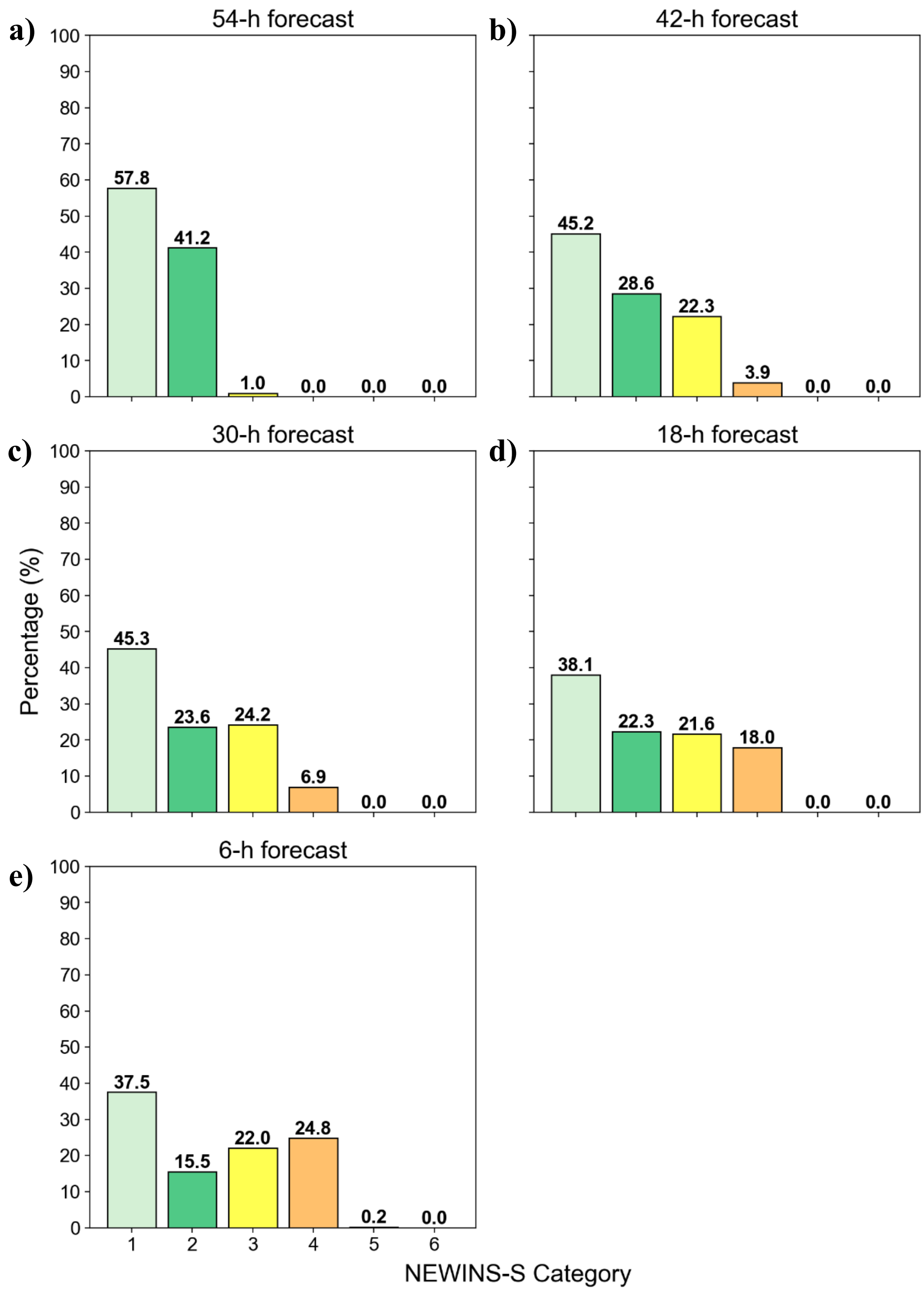

Figure 3.58 Percent statewide NEWINS-S distributions valid for midnight 25 November 2018 from a) NDFD Run 1 54-h forecast, b) NDFD Run 2 42-h forecast, c) NDFD Run 3 30-h forecast, d) NDFD Run 4 18-h forecast, and e) NDFD Run 5 6-h forecast.

distribution of Categories 1 to 4 in NDFD Run 6 (Figure 3.60). Overall, between NDFD Runs 1 and 6, statewide coverage of Categories 1 and 2 decreases from 99.0% to 53.0%, and Categories 3 to 5 increase from 0% to 47.0%. Across southeastern Nebraska, Categories 1 to 4 are indicated in NDFD Runs 1 to 4 before there is a large increase in the coverage of Categories 5 and 6 NDFD Runs 5 and 6 (Figure 3.61). When comparing NDFD Run 1 from NDFD Run 6, the coverage of Categories 1 to 4 decreases from 100% to 78.4%, while Categories 5 and 6 increase from 0% to 21.6%.

3.6 Case Study: 1-2 December 2018 Colorado Low System

The 1-2 December 2018 case study event is a Colorado Low System that produces significant snowfall across portions of central Nebraska (Figure 3.62). Across north-central Nebraska, a widespread 12 to 24 inches of snowfall occurs, while the southern maximum produces 8 to 18 inches with less snowfall between the two areas.

3.6.1 NDFD Evolution: 1-2 December 2018

Evaluating the evolution in NEWINS-S for the noon 1 December valid time through several NDFD runs showcases the spatial and temporal trends in NEWINS-S (Figures 3.63). The NDFD runs generally highlight spatial changes in both the placement and intensity of NEWINS-S (Figure 3.63). NDFD Runs 1-4 show the focus for highest NEWINS-S categories shifting from far northeastern Nebraska to north-central Nebraska as well as an increase in coverage, which could be indicative of either a slowing of the system or a shift in the track. Additionally, in NDFD Run 4, Category 4 is introduced to a large portion of north-central Nebraska. By NDFD Runs 5 and 6, the placement of the highest NEWINS-S categories experiences little change; however, there is an increase in NEWINS-S categories in NDFD Run 6 with Category 5 now indicated across portions of District 8.

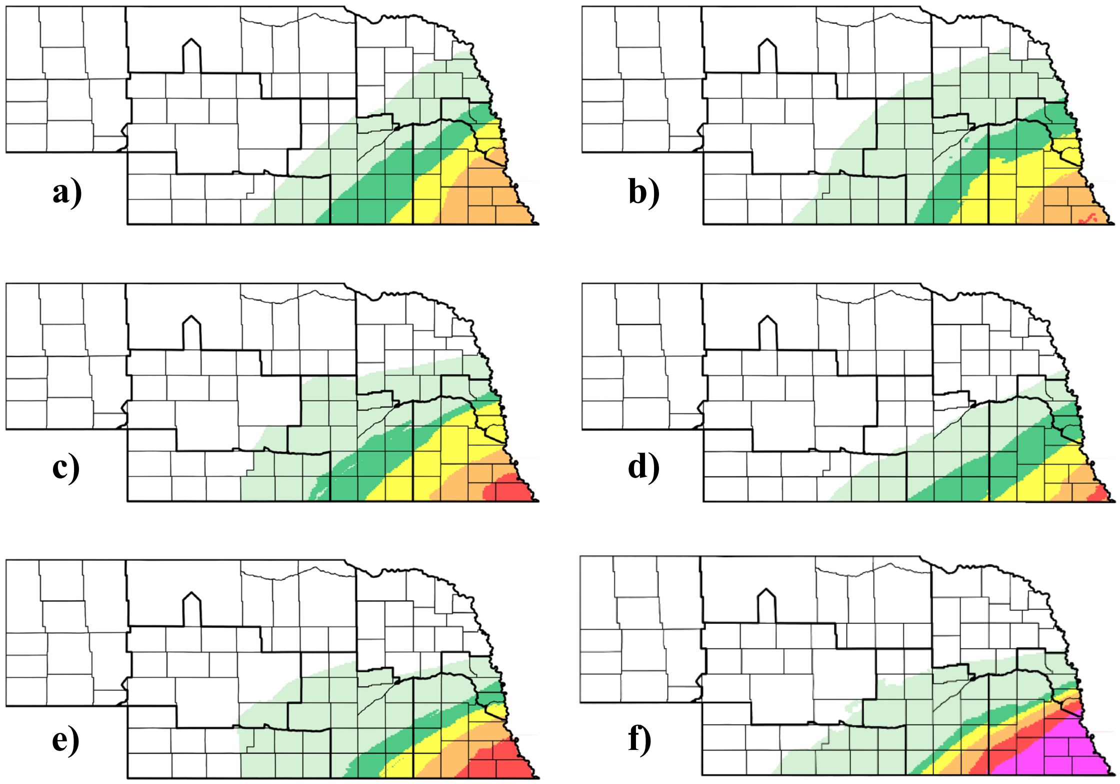

Figure 3.59 NEWINS-S valid for noon 25 November 2018 from a) NDFD Run 1 72-h forecast, b) NDFD Run 2 60-h forecast, c) NDFD Run 3 48-h forecast, d) NDFD Run 4 36-h forecast, e) NDFD Run 5 24-h forecast, and f) NDFD Run 6 12-h forecast.

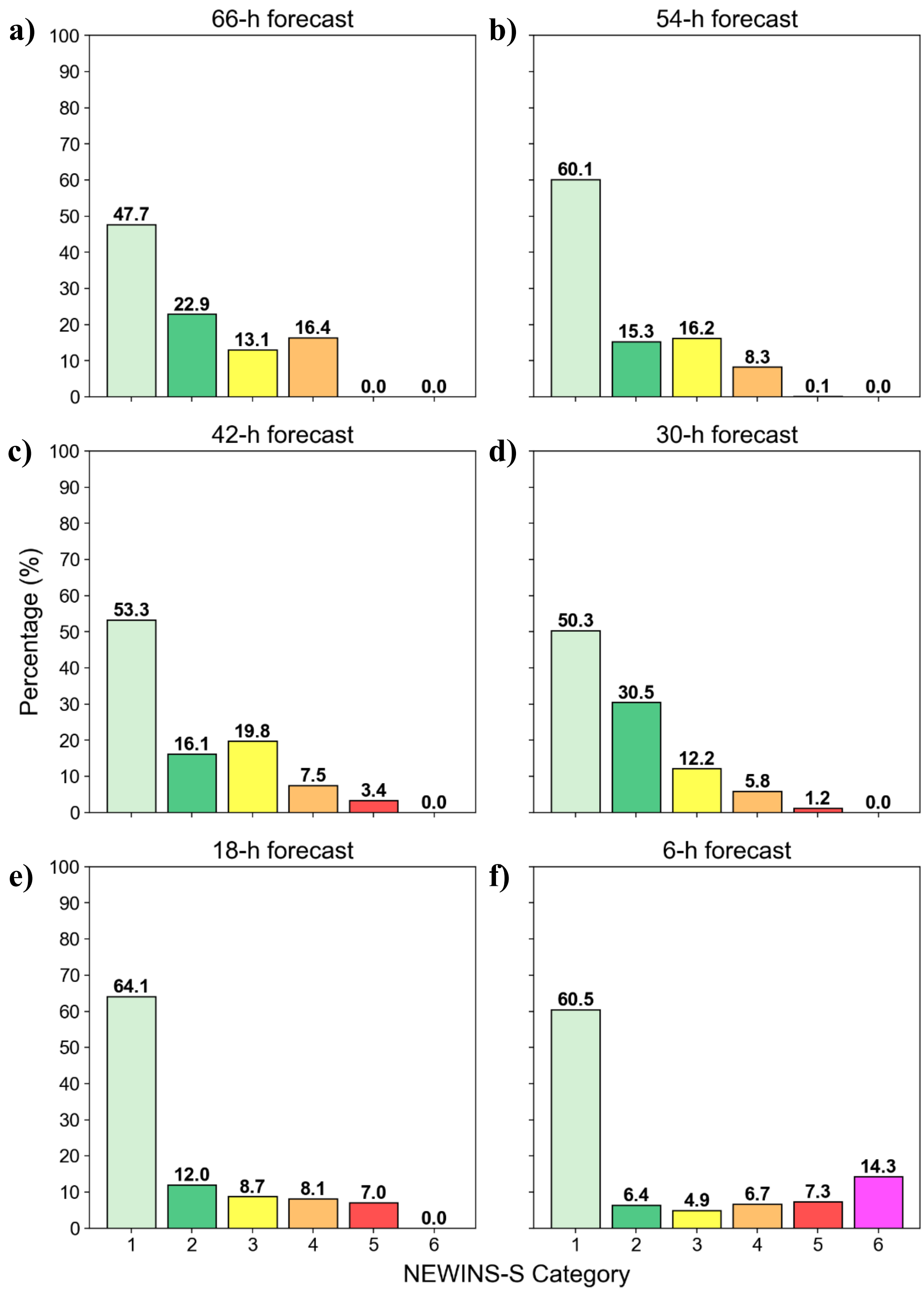

Figure 3.60 Percent statewide NEWINS-S distributions valid for noon 25 November 2018 from a) NDFD Run 1 66-h forecast, b) NDFD Run 2 54-h forecast, c) NDFD Run 3 42-h forecast, d) NDFD Run 4 30-h forecast, e) NDFD Run 5 18-h forecast, and f) NDFD Run 6 6-h forecast.

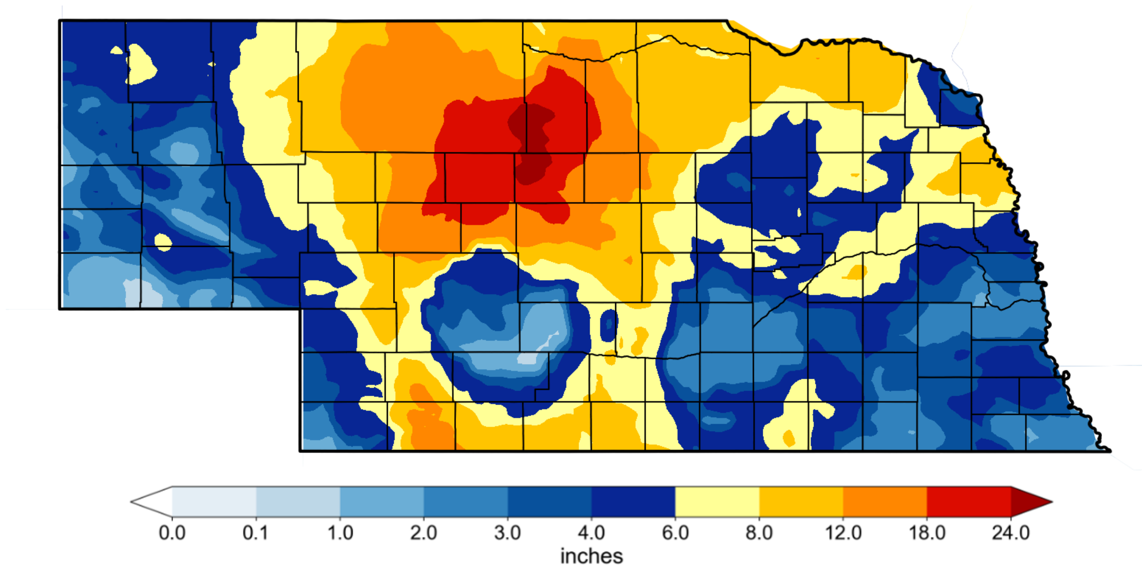

Figure 3.61 NOHRSC 48-h accumulated snowfall (inches) starting at 6:00 pm 30 November 2018 and ending at 6:00 pm 2 December (adapted from NOHRSC 2023).

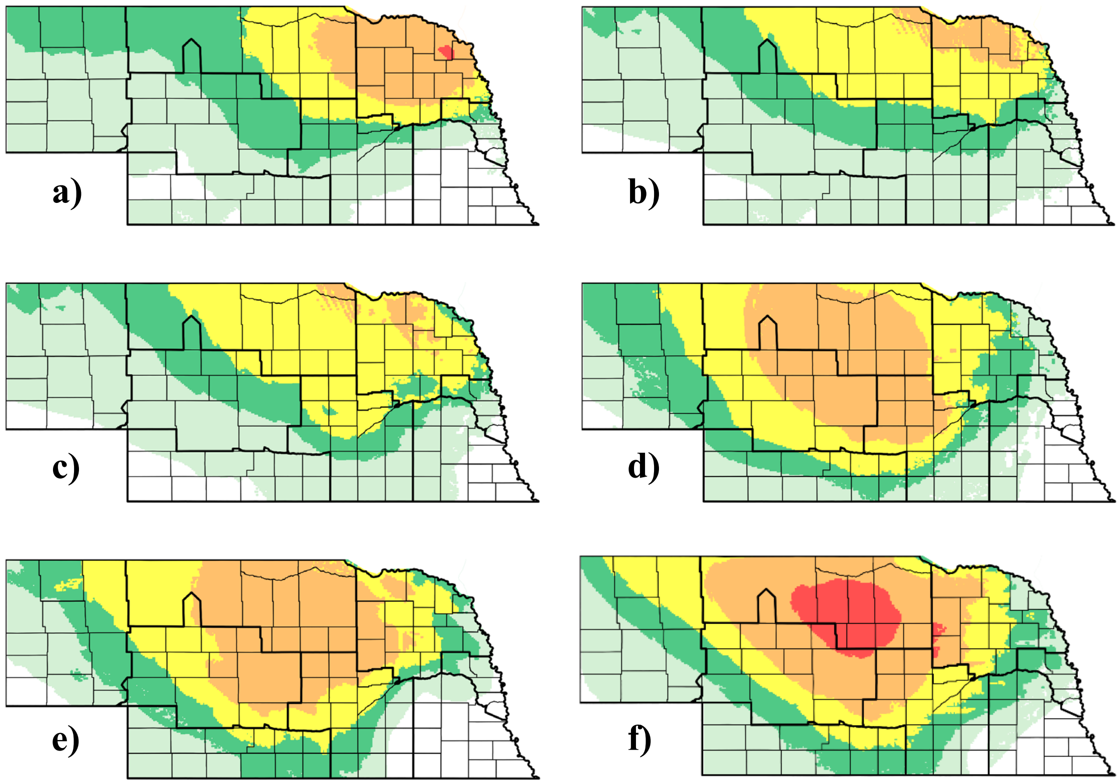

Figure 3.62 NEWINS-S valid for noon 1 December 2018 from a) NDFD Run 1 72-h forecast, b) NDFD Run 2 60-h forecast, c) NDFD Run 3 48-h forecast, d) NDFD Run 4 36-h forecast, e) NDFD Run 5 24-h forecast, and f) NDFD Run 6 12-h forecast.

3.6.2 Case Discussion: 1-2 December 2018

The 1-2 December 2018 Colorado Low System produced a long duration of impacts across a large section of the state, causing significant snowfall across central Nebraska. Assessing NEWINS-P forecasts both spatially and temporally highlights the NEWINS-S and blowing snow impacts occurring for 48 to 60 h in some locations. The forecasts also showcase significant forecast misalignments and previously discussed artifacts such as the Platte River Valley. The high number of misalignments is to be expected since the NDFD did not have effects installed at this time to reduce misalignments (NWS 2023, personal communication). Investigating the evolution in NEWINS-S for the noon 1 December valid time revealed a change in placement and an increase in NEWINS-S categories across north-central Nebraska. Evaluating the statewide trends in NEWINS-S categories shows the focus from lower NEWINS-S to higher NEWINS-S (Figure 3.64). In NDFD Runs 1 to 3, Categories 1 to 2 make up most of the distribution. However, by NDFD Run 4, there is a notable decrease in Category 1 and an increase in Category 4. Category 5 is introduced in NDFD Run 6. Comparing NDFD Run 1 to Run 6, the percentage of Categories 1 and 2 decreases from 73.8% to 45.7%, while the percentage of Categories 3 to 5 increases from 26.2% to 54.5%. When comparing these spatial trends in NEWINS-S (Figure 3.63) to snowfall observations (Figure 3.62), the general increase in NEWINS-S categories leading up to the event was justified; however, the highest snowfall occurred west of where the highest NEWINS-S was indicated. Additionally, the NEWINS-S categories ended up being too low within the heaviest axis, even though Category 6 was occurring within the region.

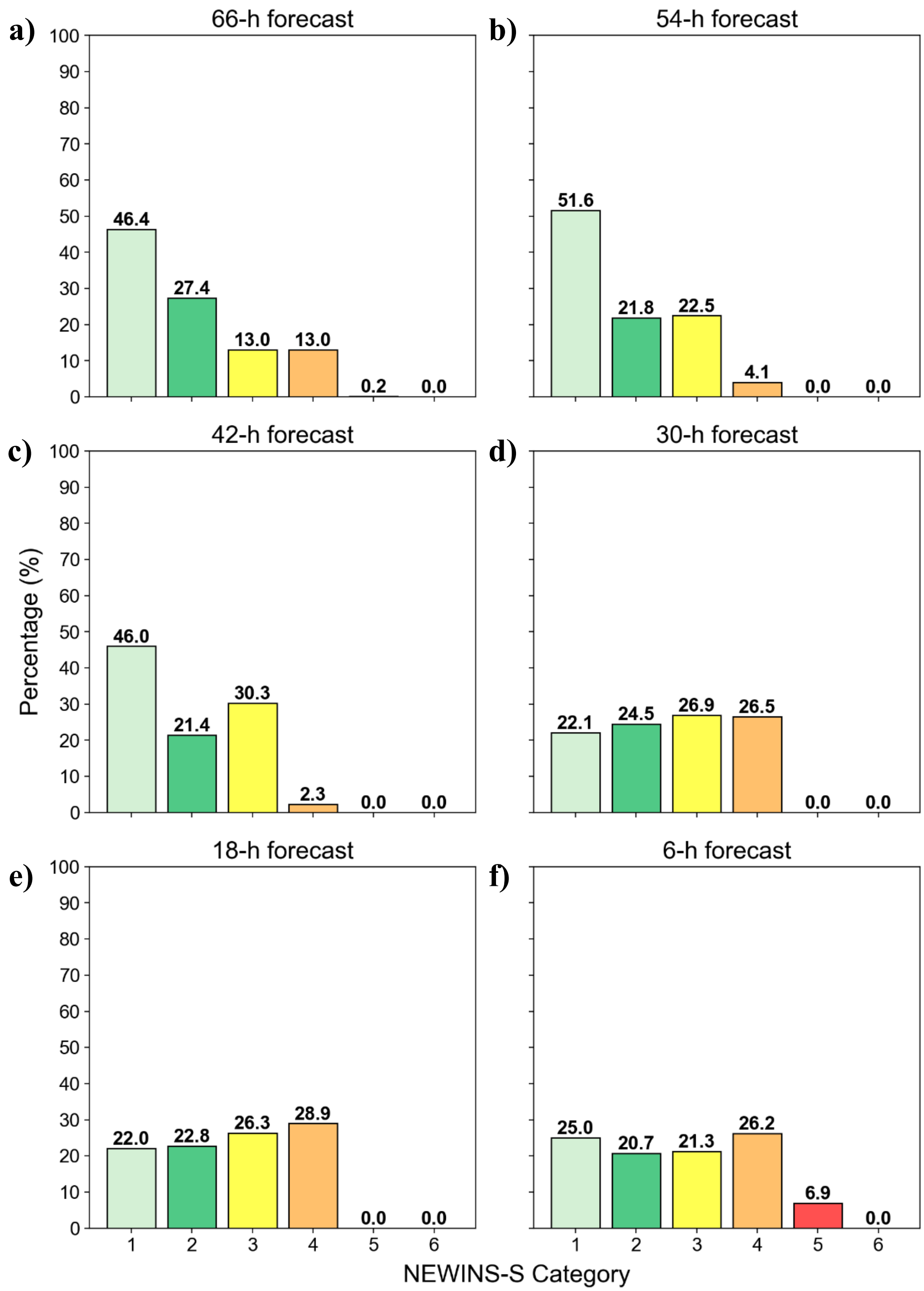

Figure 3.63 Percent statewide NEWINS-S distributions across valid for noon 1 December 2018 from a) NDFD Run 1 66-h forecast, b) NDFD Run 2 54-h forecast, c) NDFD Run 3 42-h forecast, d) NDFD Run 4 30-h forecast, e) NDFD Run 5 18-h forecast, and f) NDFD Run 6 6-h forecast.

3.7 Case Study: 15 February 2019 Alberta Clipper System

The 15 February 2019 case study event is an Alberta Clipper System that brings a widespread snowfall to Nebraska. The heaviest snowfall occurs through the central portion of the state, where a few to several inches are reported (Figure 3.65).

3.7.1 NDFD Evolution: 15 February 2019

The evolution in NEWINS-P from the following NDFD runs displays relatively minor adjustments in the NEWINS-S categories spatially (Figure 3.66) for the noon 15 February valid time. A swath of Categories 2 to 3 is indicated across Nebraska in NDFD Runs 1 and 2 with coverage in Category 3 increasing to include south-central Nebraska by NDFD Run 3. Category 4 is introduced within central and southeast Nebraska by NDFD Run 4. The coverage of Category 4 decreases in NDFD Run 5 to only include south-central Nebraska. Additionally, the northeastern edge of NEWINS-S categories shifts to the southwest, removing District 2 from Categories 2 to 3.

3.7.2 Case Discussion: 15 February 2019

The 15 February 2019 Alberta Clipper System brought snowfall across most of Nebraska with accompanying arctic air. The NEWINS-P forecasts have shown similarities with the 6-8 February 2021 Clipper Systems spatially and temporally with a relatively short period of impacts (< 24 h). Evaluating the evolution in NEWINS-S for the noon 15 February valid time showed relatively minor changes in the NEWINS-S categories compared to the discussed Colorado Low and Alberta Clipper Systems. Investigating the statewide distributions in NEWINS-S categories showed an increase in higher NEWINS-S categories from the earlier NDFD runs to the later NDFD runs (Figure 3.67). Little if any changes occur between NDFD Runs 1 and 2. However, for NDFD Run 3, there is a noticeable decrease in Categories 1 and 2 and an increase in

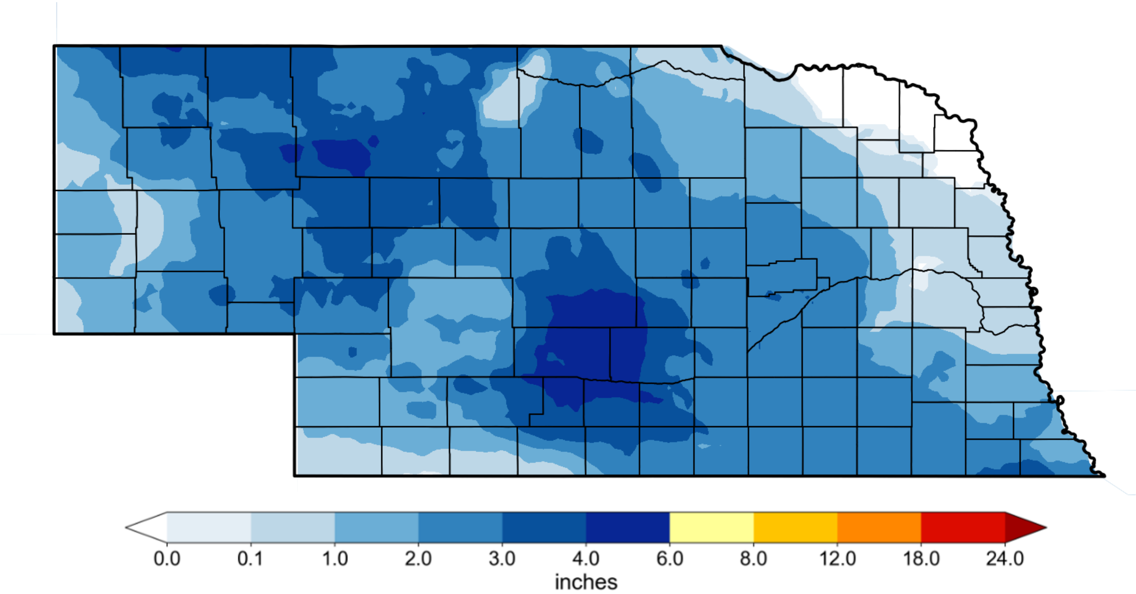

Figure 3.64 NOHRSC 24-h accumulated snowfall (inches) starting at 6:00 pm 14 February 2019 and ending at 6:00 pm 15 February (adapted from NOHRSC 2023).

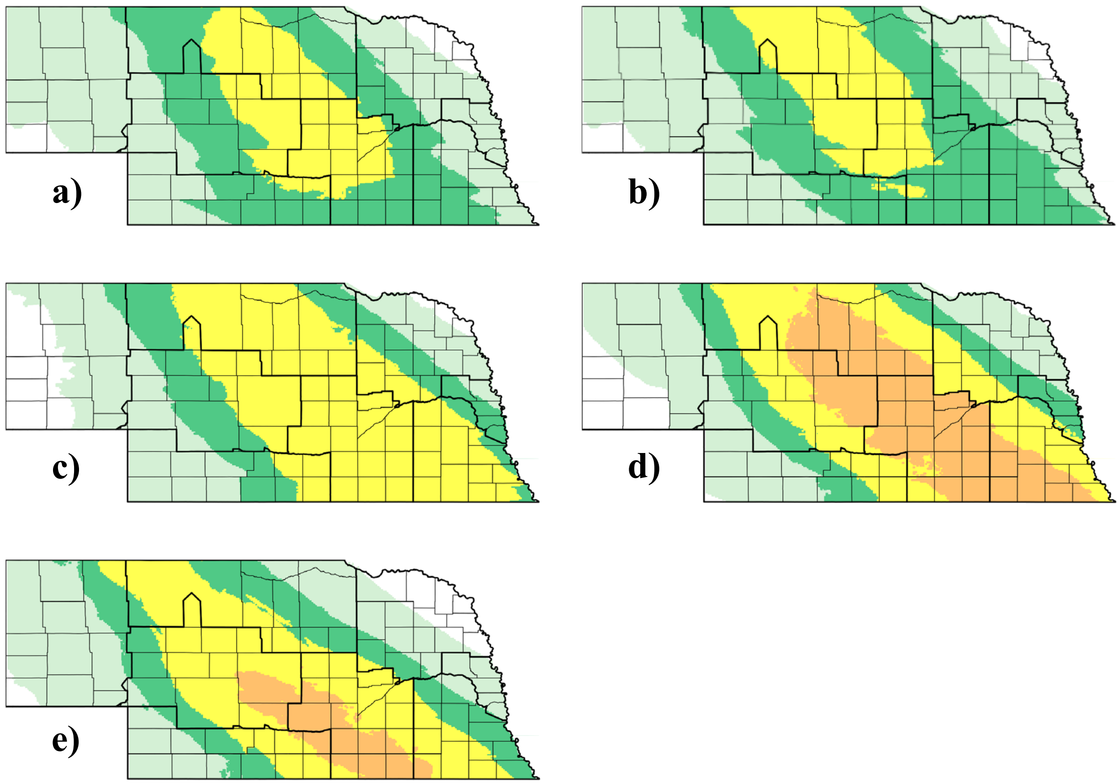

Figure 3.65 NEWINS-S valid for midnight 15 February 2019 from a) NDFD Run 1, b) NDFD Run 2, c) NDFD Run 3, d) NDFD Run 4, and e) NDFD Run 5

Category 4 occurring in NDFD Run 5. Overall, even with the last-minute decrease in higher categories, there is still an overall uptrend in intensity when comparing NDFD Run 1 with NDFD Run 6. Furthermore, the percentage of Categories 1 and 2 decreases from 78.5% to 56.3% while Categories 3 to 4 increases from 21.5% to 43.7%. Comparing the spatial trends (Figure 3.66) to snowfall observations (Figure 3.65), the last-minute decrease in NEWINS-S Category 4 was warranted with widespread 2 to 3 inches occurring across Nebraska, falling into the Category 3 caliber.

3.8 Case Study: 16-18 February 2019 Colorado Low System

The 17-18 February 2019 case study event is a Colorado Low System that follows the passage of the 15 February 2019 Alberta Clipper System. The Colorado Low System brings several inches of snowfall to most of central and eastern Nebraska with ≥ 6 inches along portions of the Missouri River Valley (Figure 3.68).

3.8.1 NDFD Evolution: 16-18 February 2019

The evolution in NEWINS-S from the NDFD runs reveal significant changes occurring within 24 hours of the midnight 17 February valid time (Figures 3.69). Overall, there is a change in the location and intensity of NEWINS-S categories. From NDFD Runs 1 to 4, the placement of the highest NEWINS-S categories remains over northeastern Nebraska. Additionally, there are little if any adjustments in intensity with widespread NEWINS-S Categories 2 to 3 across these regions. By NDFD Run 5, there is an increase in coverage of Category 3 to portions of Districts 1 and 8, all of District 2, and much of District 3. Category 3 continues to expand southward for NDFD Run 6 with the introduction of a large swath of Category 4 across eastern Nebraska.

3.8.2 Case Discussion: 16-18 February 2019

The 16-17 February 2019 Colorado Low System brings renewed snowfall to eastern

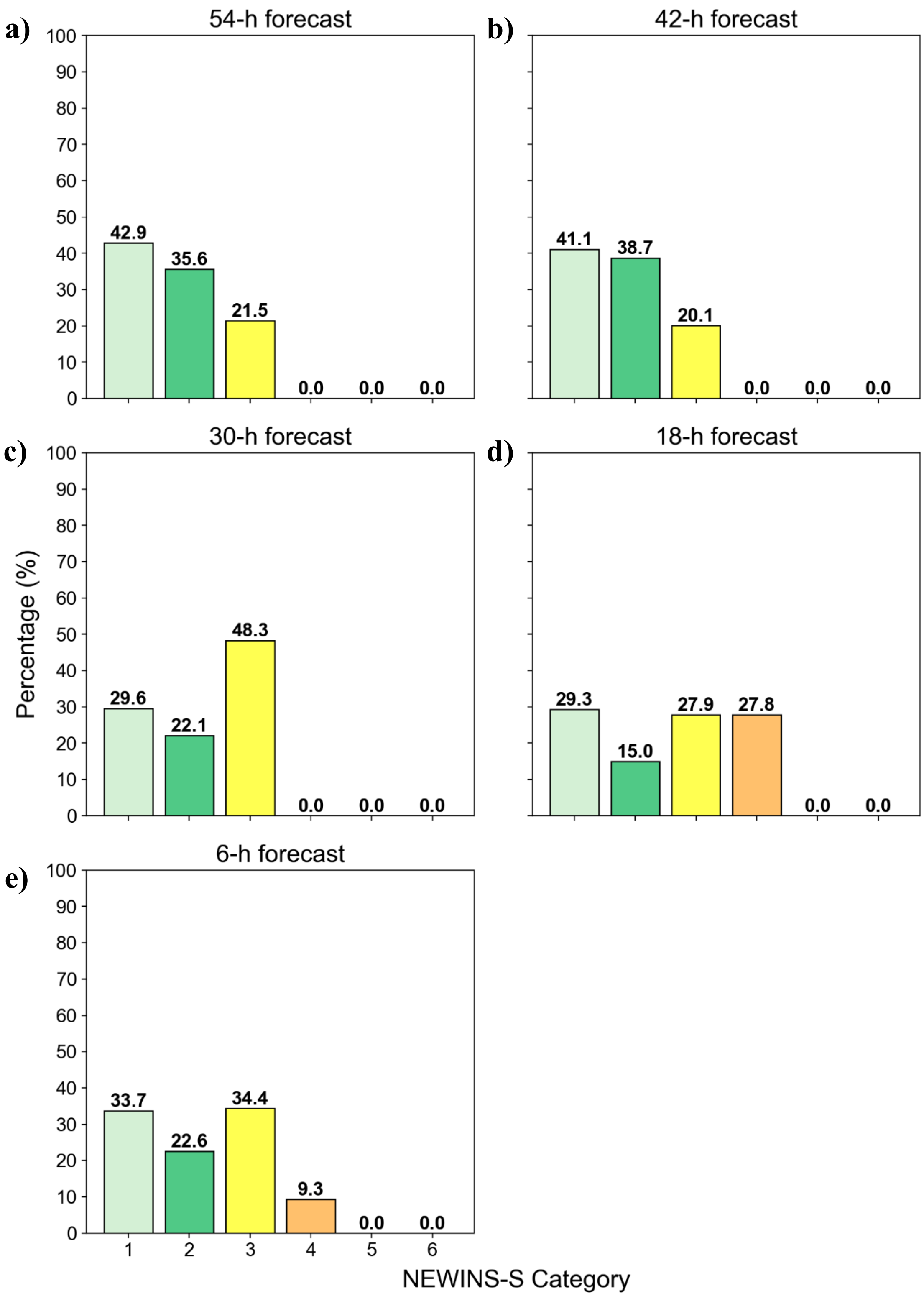

Figure 3.66 Percent statewide NEWINS-S distributions valid for midnight 15 February 2019 from a) NDFD Run 1 54-h forecast, b) NDFD Run 2 42-h forecast, c) NDFD Run 3 30-h forecast, d) NDFD Run 4 18-h forecast, e) NDFD Run 5 6-h forecast.

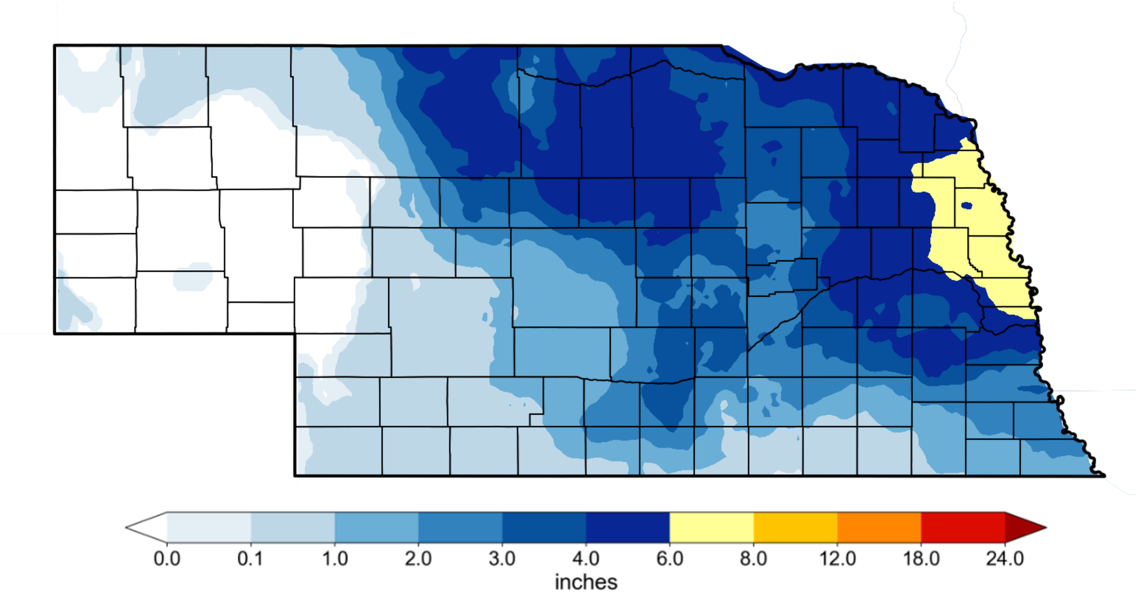

Figure 3.67 NOHRSC 24-h accumulated snowfall (inches) starting at 6:00 pm 16 February 2019 and ending at 6:00 pm 17 February (adapted from NOHRSC 2023).

Nebraska following the passage of the 15 February 2019 Alberta Clipper System. Evaluating the NEWINS-P forecasts for the event shows the impacts are mostly confined to northeastern Nebraska with the temporal forecast highlighting the short window of impacts. Inspecting the evolution in NEWINS-S for the midnight 16 February valid time shows little, if any, changes until within 24 h when the highest NEWINS-S categories significantly shift southward with a coincident intensity increase in NEWINS-S. Investigating the statewide distributions of NEWINS-S categories is another way to showcase the intensity increase (Figure 3.70). NDFD Runs 1 to 4 display little change in the distribution of categories, showing mostly Categories 1 and 2 and a small percentage of Category 3. However, there is a notable increase in Category 3 in NDFD Run 5 with Category 4 being introduced in NDFD Run 6. When comparing the spatial trends (Figure 3.70) to the snowfall observations (Figure 3.68), the shift southward in the highest categories is warranted; however, the intensity changes within 24 h are too aggressive, as many places do not verify with Category 4 caliber snowfall (Figure 2.6).

3.9 Discussion

The investigation of NEWINS-P spatially and temporally on six Colorado Low and three Alberta Clipper Systems from the 2018-19 winter season to 2022-23 has yielded a framework for a predictive winter storm severity index. Analyzing the five different components of the NEWINS-P framework (NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood) spatially and temporally at a 6-h temporal resolution manifested the many winter weather hazards happening at different times within the different system types. The NEWINS-S component was effective at representing the corridors of snow accumulation severity at different periods of the storm. The precipitation type component provided helpful information regarding the different sectors of the case study events (cold sector, transition zones,

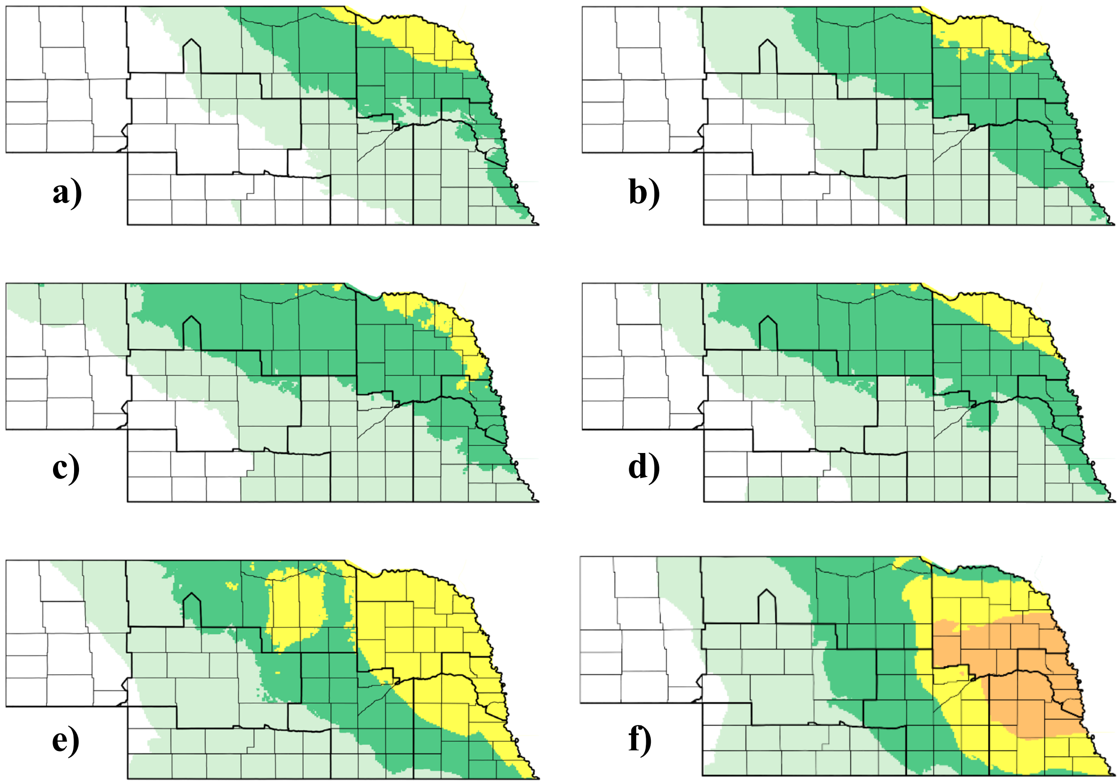

Figure 3.68 NEWINS-S valid for midnight 17 February 2019 from a) NDFD Run 1, b) NDFD Run 2, c) NDFD Run 3, d) NDFD Run 4, and e) NDFD Run 5, and NDFD Run 6.

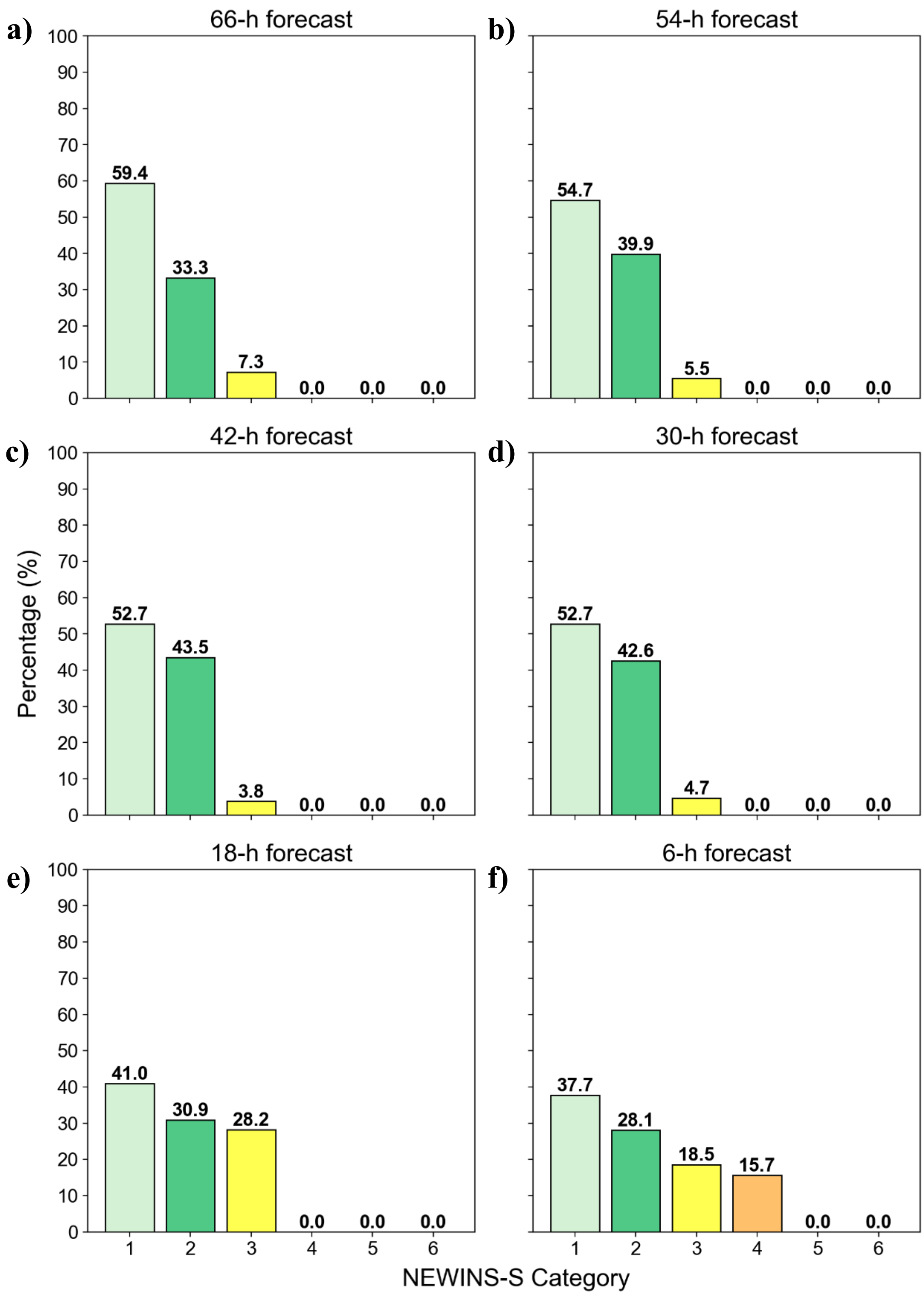

Figure 3.69 Percent statewide NEWINS-S distributions valid for midnight 17 February 2019 from a) NDFD Run 1 66-h forecast, b) NDFD Run 2 54-h forecast, c) NDFD Run 3 42-h forecast, d) NDFD Run 4 30-h forecast, e) NDFD Run 5 18-h forecast, and f) NDFD Run 6 6-h forecast.

and warm sector). The ice likelihood component was shown to be effective when used in conjunction with the precipitation type component since it can identify regions of increasing icing potential, something the precipitation type component failed to detect. The blowing snow component was shown to highlight regions that had concurrent high wind speeds with NEWINS-S categories, leading to blowing snow concerns. The drifting snow component successfully highlighted regions of elevated wind speeds in areas NEWINS-S was previously forecasted. Overall, the NEWINS-P spatial forecasts showed Colorado Low Systems carried more in-storm impacts than Alberta Clipper Systems across Nebraska. Moreover, the Colorado Low Systems had a higher intensity and coverage of NEWINS-S categories, more types of precipitation, and more blowing snow concerns than Alberta Clipper Systems. The Colorado Low Systems were also shown, for the most part, to produce these impacts over a longer duration than Alberta Clipper Systems. Post-storm impacts such as drifting snow were not shown to occur in many of the case studies, except for the 13-17 December 2022 Colorado Low System, as the highest wind speeds occurred during the system rather than afterward. The Ngram forecasts complemented the spatial forecasts by displaying all the impacts onto one graphic for each point location and showcasing the general progression of each system at a point location.

Evaluating multiple NDFD runs prior to and after the representative NDFD runs revealed the evolution the NEWINS-P components can experience through time. The largest and most significant change was found to be in the NEWINS-S component with a notable increase in the NEWINS-S categories across Nebraska relative to the preceding 72-h forecast. The increase was evident in all case-study events and implied there was a trend for the NDFD to ramp-up the impacts as the event got closer. At the time of reporting, there was no way to indicate if this was model or human driven. However, the most likely possibility was model driven and was often a case of snow accumulation or uncertainty within the track (B. Barjenbruch 2024, personal communication). Starting with the case of snow accumulation, the NWS observed that numerical weather prediction tended to become more overzealous with snow accumulation as the event drew closer. The other possibility was model uncertainty within the track. Since the NWS often used a blended model to make forecasts, the snow accumulation can be too low due to smoothing. For example, if half the models forecasted the highest snow accumulation to occur on the eastern side of the state and the other half forecasted the highest snow accumulation to occur on the western side of the state, then the forecast would have featured more widespread snow accumulation at a reduced intensity.

Through investigating the NDFD runs for all the different case studies, there was a prevalent systematic artifact within the NDFD known as forecast misalignment. This artifact affected the quality of the data and interpretations of the NEWINS-P components. While the forecast misalignments were relatively minor in the more recent cases, the 2018-19 case-study events featured significant misalignments in many of the NEWINS-P components. This provided justification for discussing the winter seasons in reverse chronological order to put more weight on the cases with better data. A change in the methodology led to NDFD misalignments being less common in more recent cases (B. Barjenbruch 2024, personal communication). Each NWS forecast office used to produce QPF for their respective county warning area, which led to more misalignments due to collaborative disagreements and time constraints. However, the current methodology consists of all offices receiving a QPF output from the Weather Prediction Center, which led to a drastic reduction in the number of misalignments.

Chapter 4 Summary and Conclusions

Winter storms produce many different weather hazards that can cause severe societal impacts both during and after the storm. Several agencies have developed WSIs to help better quantify and distribute the impacts from these storms. However, most of these WSIs are assessed from statistical relationships for atmospheric data over a winter season rather than an individual winter storm. For NDOT, the NEWINS provides a new and independent framework to evaluate a winter season based on individual winter storms. However, the main limitation is that NEWINS, along with most WSIs, are used from a historical perspective rather than being predictive.

The objective of this study was to translate the previously developed NEWINS framework to be a predictive tool. Additionally, this work sought to expand the previous NEWINS framework to consider impacts during winter storms such as freezing rain induced ice accumulation events as well as blowing snow and impacts after winter storms such as drifting snow conditions. By utilizing NWS gridded forecasts from the NDFD, a predictive winter severity index known as NEWINS-P provided a notable increase in both spatial and temporal resolution compared to NEWINS. Instead of assessing historical data for points within each maintenance district at a 24-h temporal resolution, NEWINS-P used gridded forecast data at a 6-h temporal resolution at an approximately 2.5 square mile pixel size. The NEWINS-P framework used NDFD parameters such as QPF, snow accumulation, ice accumulation, and surface wind speed to create five components to forecast impacts spatially and temporally from different weather hazards for up to 72 hours in advance. These components were anticipated snow severity (NEWINS-S), precipitation type, ice likelihood, blowing snow, and drifting snow likelihood. This study investigated multiple select case studies from the 2018-19 winter season through the 2022-23 winter season to show the validity of NEWINS-P. These case studies consisted of six Colorado Low and two Alberta Clipper Systems chosen based on their impacts within the state. These systems tended to cause the most travel disruptions across Nebraska, with Colorado Low Systems bringing widespread heavy snowfall, blizzard conditions, and mixed precipitation due to abundant moisture from the Gulf of Mexico and Alberta Clipper Systems bringing a different set of conditions and impacts such as light snowfalls before and after passage, and strong winds and freezing temperatures after passage.

The investigation of NEWINS-P on the case studies has yielded a framework for a predictive winter storm severity index. The NEWINS-P framework was shown to be a valuable forecast tool for diagnosing the many winter weather hazards spatially and temporally for the Colorado Low and Alberta Clipper Systems assessed. The NEWINS-P spatial forecasts for the case studies showed Colorado Low Systems carried more in-storm impacts than Alberta Clipper Systems. Moreover, the Colorado Low Systems had a higher intensity and coverage of NEWINS-S categories, more types of precipitation, and more blowing snow than Alberta Clipper Systems. Post-storm impacts such as drifting snow were not shown to occur in many of the case studies, except for the 13-17 December 2022 Blizzard, as the highest wind speeds generally occur during the system rather than afterward. The Ngram forecasts complemented the spatial forecasts, with the ability of displaying all NEWINS-P forecasts onto one graphic for location.

Investigating the evolution of NEWINS-P components through time showed that most of the case studies experienced an increase in intensity across Nebraska relative to the preceding 72-hour forecast. Most notably, all case studies displayed an upward trend in NEWINS-S categories leading up to the event. The discovery of this upward trend may have implications on planning and personnel scheduling activities in the lead up to a storm. Moreover, an approaching system with lower NEWINS-S categories advertised 48-72 hours out may be something to keep a watchful eye on, as the categories could ramp up.

Although the NEWINS-P framework has been shown to be a useful tool in the case study analyses, there are several limitations to address in this study. The first limitation to address is that this study only investigated the outcomes of selected case studies, so not all winter weather possibilities are considered. Additionally, there was no forecast verification related to the NEWINS-P components, so there is no way to obtain observations at locations that are not NWS observation points to assess the performance of these forecasts. Although the number and scale of misalignments have been reduced, there are still several instances within the NDFD data between NWS offices. An important limitation of the NEWINS-P framework is its inability to extend the duration of post-storm drifting snow events beyond 72 hours after the conclusion of a winter storm. Additionally, the drifting snow component does not consider other important atmospheric information such as temperature, cloud cover, the age of snow, or time of day.

There are several recommendations that can be made to NDOT on the use of the NEWINS-P components, especially NEWINS-S. Knowing the type of storm expected to affect the state is very important in understanding the winter weather impacts. The storm type seems to have an influence in the impacts across the state and in the ramping up of the NEWINS-S categories as the storm becomes closer to the actual event. Typically, the Colorado Low System is more impactful than the Alberta Clipper System. In a Colorado Low System, a storm moving up from the west/southwest and bringing in moisture from the Gulf of Mexico, strong winds and better lift could generate more snowfall and greater impacts across the whole state depending on the storm’s track. Colorado Low Systems were found in this study to have the greatest ramp up from 72-h before the event to the actual event. Generally, the NEWINS-S categories were in the

3-4 range and increased to the 4-6 range by the time the Colorado Low System affected the state. The Alberta Clipper System, on the other hand, is a storm system that moves into the region from the north, has less moisture, colder temperatures, stronger winds, and greater temperature changes after the passage of the storm system, which can still be impactful to the state. Results indicate that NEWINS-S categories were usually less than the Colorado Low System type. For Alberta Clipper Systems, NEWINS-S categories at 72 h before the event were in the 1-3 range and usually did not increase more than 1-2 categories as the event got closer. The ramping up of NEWINS-S categories was not as great for Alberta Clipper Systems as for Colorado Low Systems. Of course, storm tracks and intensification of either event may have also produced changes in NEWINS-S categories over time.

The NEWINS-P framework was derived using a 6-h window of time because snow accumulation data within NDFD was presented at 6-h time frames and not updated until the next 6-h period. Therefore, at the time of reporting and when using NDFD data as the driving input data, 1-h runs are not advised. The best time of the day to use the NDFD runs are usually at 6:00 am or pm since there should be minimum misalignments (NWS 2024, personal communication). The framework; however, can be run every 6^{th} hour throughout any 24-h period. Additionally, the computer software code to run the NEWINS-P framework has been delivered to NDOT and sample products have been produced for usage in real-time situations (Figures 4.1 and 4.2). The framework used for these figures used our programs and NDOT will have to produce their own graphical output. The exact graphical products to be distributed by NDOT are not complete, and beyond the scope of this project; however, the process was transferred.

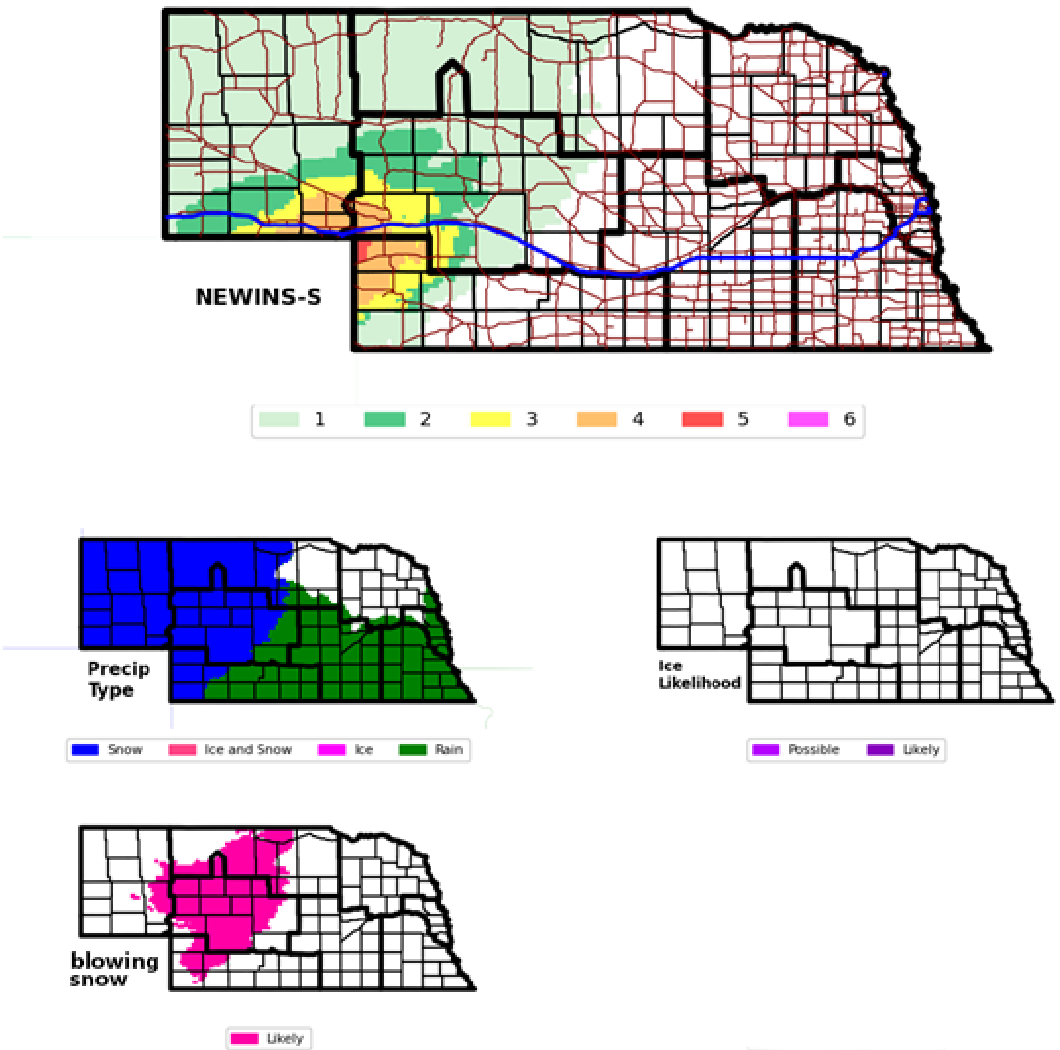

Figure 4.1 The 6-h NEWINS-P forecast from real-time NDFD data from the noon 8 March 2024 NDFD run valid for 6:00 pm 8 March comprising a) NEWINS-S, b) precipitation type, c) ice likelihood, d) blowing snow, and e) drifting snow likelihood.

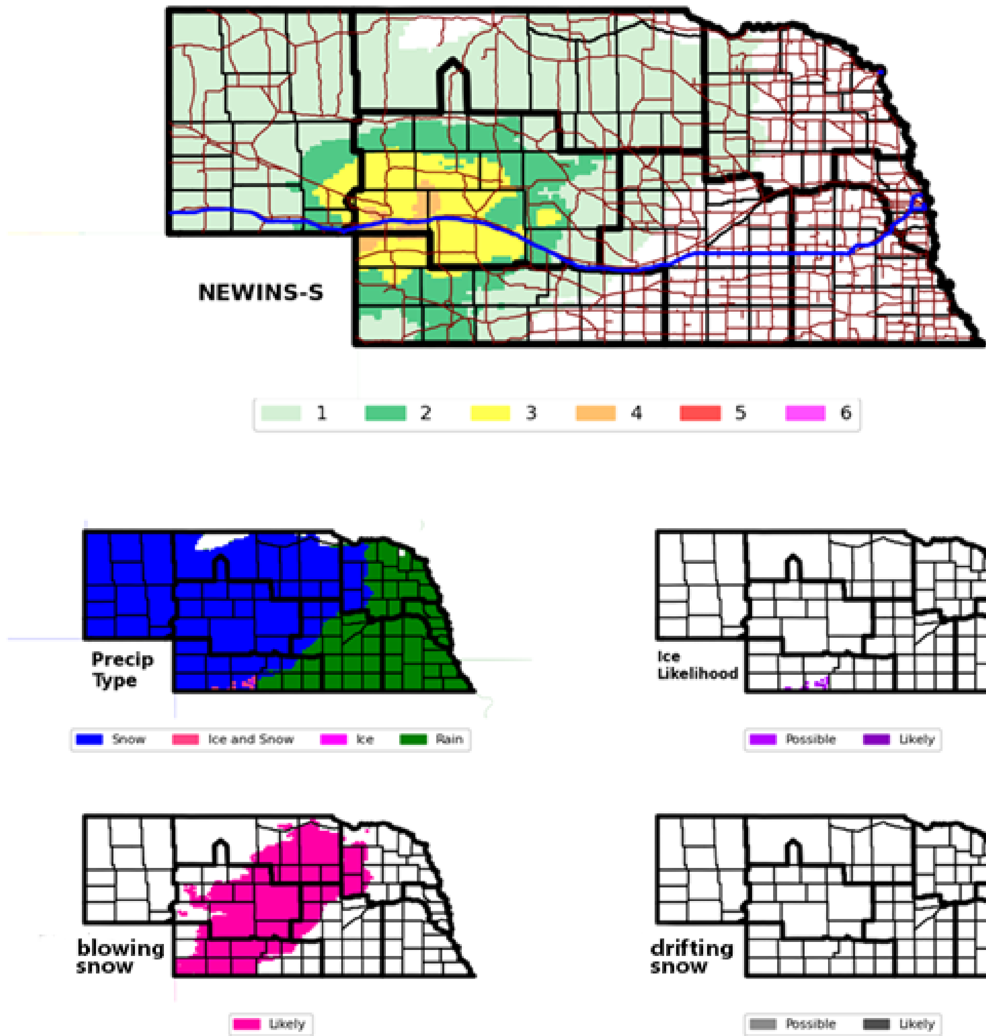

Figure 4.2 The 12-h NEWINS-P forecast from real-time NDFD data from the noon 8 March 2024 NDFD run valid for midnight 9 March comprising NEWINS-S, precipitation type, ice likelihood, blowing snow, and drifting snow likelihood.

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