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Northern Great Plains Blizzards In Past And Future Climates

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NORTHERN GREAT PLAINS BLIZZARDS IN PAST AND FUTURE CLIMATES

by

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Bachelor of Arts, University of Colorado Boulder, 2012

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A Thesis

Submitted to the Graduate Faculty

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December

2018

This thesis, submitted by Alexander Patrick Trellinger in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom this work has been done and is hereby approved.

Aaron Kennedy

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This thesis is being submitted by the appointed advisory committee as having all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Grant McGimpsey
Dean of the School of Graduate Studies

November 28, 2018
Date

PERMISSION

Title	Northern Great Plains Blizzards in Past and Future Climates
Department	Atmospheric Science
Degree	Master of Science

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Alexander Patrick Trellinger

28 November 2018

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believing in me, encouraging me, and allowing me to pursue my dreams. To my sister, thank you for always being there for me. Having a supportive family is something I am extremely grateful for and has certainly had a positive impact on my life. Thank you all so much.

ABSTRACT

Areas that reside in the high-latitudes such as the northern United States can experience hazardous conditions during the winter months due to snowstorms. When strong winds exist with falling or freshly fallen snow, blizzard conditions are able create significant personal, societal, and economic impacts for the Northern Great Plains. While the climatology for these extreme snowstorms is known, the frequency and intensity of how these events may change in a warming climate is not certain. In order to determine how extreme snowstorms may change in the future climate, climate models can be used but the horizontal and vertical grid spacing makes identifying blizzard events difficult. Moreover, climate models do not include blowing snow, which means that blizzards that don't have any falling snow are not considered. Therefore, another method must be used in order to identify these extreme snowstorm events.

The presented work will use a competitive neural network known as the Self-Organizing Map (SOM) to identify meteorological patterns associated with blizzard events over the Northern Great Plains from 1979-2015. Once these large-scale patterns are identified from observations, they will be identified in the Community Earth System Model (CESM) 4.0 20th Century forcing climate simulations run in support for the Coupled Model Intercomparison Project Phase 5 (CMIP-5). In specific, the methodology will rely on the 'Mother of All Runs' (MOAR) ensemble member, which allows for specific meteorological patterns to be identified. Blizzard events will be identified during historical time periods to determine biases, and then under future emissions scenarios.

CHAPTER I

INTRODUCTION

Background

Characteristics of Blizzards

The American Meteorological Society currently defines a blizzard as an event with "sustained wind or frequent gusts of 16 meters per second (30 knots or 35 mph) or greater, accompanied by falling and/or blowing snow, frequently reducing visibility to less than 400 meters (0.25 miles) for 3 hours or longer". Blizzard conditions can cause significant personal, societal, and economic impacts. When winds create a reduction in visibility with blowing or falling snow, hazardous roadway conditions result that cause a higher rate of traffic incidents (Tabler, 1979; Pomeroy, 1988). Nationally, approximately 800 fatalities per year are caused by winter-related motor vehicle accidents, more than doubling the deaths caused by all the convective weather events combined (Black and Mote, 2015). From 1950-1997, $8.5 billion in insured losses were associated with winter storms (Changnon, 2003), with the number of federal disaster declarations for blizzards increasing over the past half century (Coleman and Schwartz, 2017). Public safety during these events is a major concern. Travelling in a blizzard can lead to death due to exposure to low temperatures and strong winds resulting in hypothermia (Thacker et al. 2008) or possibly asphyxiation for those trapped in cars due to carbon monoxide poisoning (Hampson and Stock, 2006).

One of the most notable blizzards to impact North Dakota occurred on 4-5 April 1997 (North Dakota Department of Emergency Services, 1997). Known as Blizzard Hannah to the local media, which started naming blizzards due to the high number of occurrences in their region, this event started with a round of freezing rain and ice pellets before switching to snow. With the winds increasing after the switch to snow, blizzard criteria were met (North Dakota Department of Emergency Services, 1997; National Centers for Environmental Information Storm Data 2018). The strong winds along with the ice accumulations caused thousands of power poles to snap, cutting power to over 100,000 people in eastern North Dakota and northwestern Minnesota, and resulted in $30 million in damages to the power infrastructure. During this blizzard, the Red River was already above flood stage in Grand Forks and Fargo, ND, a result from the high number of blizzards and other large snowfall events that affected the area that winter. The additional 10-24 inches of snow across the area from Blizzard Hannah only added to the flooding that was already occurring, while making it more difficult for emergency services to reach those in need of help due to the whiteout conditions. One man died from exposure after walking away from his stalled vehicle, while thousands of livestock were reported dead as a result of the storm. The governor of North Dakota declared the state a disaster area on April 6th, and a Presidential disaster declaration came on April 7th.

Traditionally, blizzards occur as part of a larger-scale weather event associated with the juxtaposition of measurable falling snow and strong winds. However, low visibility conditions can also be created when strong winds loft previously-fallen snow (i.e. blowing snow). If winds are strong enough and visibility is reduced sufficiently, this phenomenon is termed a ground blizzard (Stewart et al. 1995). Li and Pomeroy (1997) found that the threshold wind speed, which is the wind speed required to create blowing snow conditions, is dependent on meteorological factors (temperature and wind speed), and the land-surface conditions which describe the condition of the snowpack. In general, warm and/or aged snow require higher threshold wind speeds than cold and/or fresh snow, indicating that land-surface conditions limit the number of blowing snow occurrences. Given a conducive snowpack, this type of event is controlled by physical processes including the saltation, suspension, and turbulent diffusion of snow grains. These processes are now briefly described.

Saltation is the initial motion of particles lofted upward from the ground, accelerated horizontally by the wind, and then repeatedly bounced along the surface (Mann et al. 2000). This process creates a positive feedback loop, as it causes more particles to be transported in the same manner due to their collisions at the surface. For saltation to occur, a threshold known as the friction velocity must be exceeded; this ensures that the shear stress – responsible for holding particles to the ground – is surpassed (Li and Pomeroy, 1997). The shear stress is greater when snow warms, thus requiring stronger winds to cause blowing snow in warmer conditions (Li and Pomeroy, 1997). While saltation is only able to loft snow into the first couple centimeters above the surface (Mann et al. 2000), suspension can then lift snow grains over 100 meters high (Mellor, 1965). Suspension occurs when the upward turbulent flux of snow particles is either greater or equal to the flux of particles falling due to gravity (Mellor, 1965). Turbulent diffusion becomes the dominant mechanism for snow transport when snow particle concentrations reach and exceed eye level (1-meter above ground level) (Mellor, 1965).

Low visibility conditions during blizzard events are created via falling and/or blowing snow. As defined by the American Meteorological Society, visibility is “the greatest distance in a given direction at which is it just possible to see and identify with the unaided eye 1) in the daytime, a prominent dark object against the sky at the horizon, and 2) at night, a known, preferably unfocused, moderately intense light source.” In order to facilitate measurements of visibility, instruments determine visibility using a variable known as the meteorological optical range (MOR). MOR is defined as the path length in the atmosphere required to reduce the light intensity in a beam of light that is travelling in the same direction to 0.05 of its original value (Brock et al. 2001). During a blowing snow event, visibility can be greater than 5 kilometers but the events that occur with wind speeds higher than 10 meters per second commonly have visibility of less than 1 kilometer (Baggaley and Hanesiak, 2005). From an operational standpoint, visibility criteria only exist for blizzards warnings, where visibilities need to be less than 400 meters for three hours, while winter weather advisories and warnings can be issued by the local National Weather Service Forecasting Office (NWSFO) at their discretion for other winter related conditions.

Blizzard Warnings and Declarations

As the official authority for weather in the United States, the local NWSFO is responsible for issuing blizzard warnings and declaring when a blizzard is occurring or has occurred. The NWS uses the American Meteorological Society’s definition of a blizzard (discussed previously) to determine if an event has met blizzard criteria. As automated surface observations do not exist everywhere, the visibility component of the blizzard definition is not as strictly used. Forecasters at the Grand Forks NWSFO generally look for visibilities to be less than 0.5 miles during the day and 0.75 miles at night before declaring whether or not a blizzard is occurring (personal communication, Grand Forks NWS). This variability in visibility criteria is based on day- and nighttime performance of the visibility sensor. Information from trained weather spotters are also used by the NWS in helping to determine if a blizzard is currently occurring. Due to the degree of leniency using the blizzard definition as well as using information from trained weather spotters, declaring whether or not a blizzard has occurred does remain a subjective decision. Lastly, it is the responsibility of the Warning Coordination Meteorologist (WCM) at the local NWSFO to submit each reported blizzard to the Storm Events Database at the National Center for Environmental Information.

Climatology of Blizzards in the Northern Great Plains

Whether a blizzard occurs is largely dependent on the synoptic-mesoscale forcing, as well as the land-surface conditions. In the Northern Great Plains (NGP; defined as eastern Montana, north-eastern Wyoming, North and South Dakota, and western Minnesota), several types of synoptic patterns are commonly associated with these events (Kapela et al. 1995; Rauber et al. 2002; Thomas and Martin, 2007; personal communication, Grand Forks NWS). These patterns include Alberta Clippers, Arctic Fronts, and Colorado Lows. Alberta Clippers and Colorado Lows are associated with falling snow and strong winds that lead to low visibility conditions for hours. Unlike those systems, Arctic Fronts generally create ground blizzard conditions via high winds after a frontal passage. Whether an Arctic Front is able to create a ground blizzard via blowing snow depends on the properties of the snowpack, as that will determine if the winds are strong enough to cause saltation and suspension of snow grains.

Within the Contiguous United States (CONUS), the NGP experiences the highest total number and frequency of blizzards, with Cass and Traill counties in North Dakota having experienced 111 blizzards, resulting in an average of 42.4 blizzards per 1000 km^2, from 1959-2013 (Fig. 1, Schwartz and Schmidlin, 2002; Coleman and Schwartz, 2017). Further results from Coleman and Schwartz (2017) indicate that blizzards in the NGP start as early as October, reach peak frequency during the month of January, and then decrease through the remaining winter with no reported events after April. From unpublished research at the local Grand Forks NWSFO, an average of 2.5 blizzards occur per year in their County Warning Area (CWA) within Eastern North Dakota and Northwest Minnesota. This is in part due to the favorable synoptic/mesoscale conditions that are experienced in the NGP, as the area has one of the highest frequencies of extratropical cyclone tracks in the CONUS per month in the winter (Hodges et al. 2011).

Besides meteorological factors, the characteristics of the land surface also play an important role for blizzard occurrence. Geographically, the CWA largely encompasses the Red River Valley (RRV), one of the flattest regions in the CONUS (Fig. 2, Dobson and Campbell, 2014). This area also features one of the lowest concentrations of forests per county in the CONUS (Fig. 3, Wear, 2011). As a result, there is limited frictional slowing of the winds due to terrain and forests in this region, allowing the Grand Forks NWSFO CWA to be an ideal place for blizzards to occur. The transition to more forested regions, experiencing more frictional slowing of the winds, is seen within previous blizzard climatologies as a rapid eastward decrease in the frequency of occurrence (Fig. 1).

A number of gaps still exist for the climatology of blizzards over the NGP. Within the formal literature, blizzards have largely been treated independently from the forcing mechanisms responsible for these events. Although there is a gross understanding of the patterns responsible for these events (e.g. Rauber et al. 2002; Thomas and Martin, 2007), the blizzard climatology has not been broken down by synoptic pattern. Further, it is unclear how often these patterns produce documented blizzards. Finally, interannual variability of these events has not been explored.

Blizzards in a Changing Climate

How blizzards may change in a warming climate is not certain. Multiple factors such as changing temperatures, cyclone frequency and intensity, and resultant snowfall suggest offsetting impacts will determine how the frequency and intensity of future blizzards is modified. Northern Hemisphere (NH) snow area coverage has shown a decreasing trend for the past five decades (Brown, 2000; Rupp et al. 2013). This decrease in snow cover extent has largely been tied to snow melting earlier in the NH spring months, the rate of which has been intensifying over the last four decades (Brown and Robinson, 2011; Allchin and Déry, 2017). Given higher temperatures, it should be expected that there will be less snow cover extent since the formation and melting of snow is highly dependent upon freezing temperatures. However, Brown and Mote (2009) have shown that areas in high latitudes have had this response offset due to regional increases in winter precipitation. For example, Kluver and Leather (2015) found statistically significant increasing trends in regional snowfall over the NGP from 1930-2007.

Increases in snowfall could be due to either the Clausius-Clapeyron relationship (e.g. more precipitable water at higher temperatures) or due to changes in the frequency and intensity of midlatitude cyclone activity. McCabe et al. (2001) found a statistically significant decrease (increase) in NH midlatitude (30°-60°N) cyclone frequency (intensity) within the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset from 1959-1997. In contrast, Tilinina et al. (2013) have shown an increasing trend in *both* the number and intensity of NGP extratropical cyclones on the order of 0.25-0.5 cyclones per decade from 1979-2010 within the National Aeronautics and Space Administration's Modern-Era Retrospective Analysis for Research and Applications (NASA-MERRA) reanalysis, with half of the four other reanalyses displaying the same trend. These greater intensity cyclones (as determined by the lower central pressure experienced) may have impacted blizzard conditions. However, no one to date has specifically investigated how blizzard frequency and intensity were altered by these more intense cyclones over the last several decades.

Multi-model climate model ensemble trends suggest there will be a decrease in annual snowfall in the NGP, with the transition seasons being responsible for the largest decreases (3-6 cm per year, per decade) from 2006-2100 within the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations (Krasting et al. 2013). Relative to the average temperatures experienced from 1986-2005 over the winter months, multi-model projections show an increasing trend in surface temperature over the NGP of roughly 3-4 °C for the time period of 2081-2100 within the CMIP5 simulations (Knutti and Sedláček, 2013). These two results suggest that the season length for snow cover may decrease in the future over the NGP.

Cyclone frequency and intensity in climate projections has also been investigated. Matching historical observations of cyclone frequency and intensity, climate simulations run in support of coupled intercomparison projects (e.g. CMIP5) show a decrease in wintertime NH cyclone frequency but at the same time have an increasing trend in intensity

(Lambert and Fyfe, 2006; Zappa et al. 2013). Results from Eichler et al. (2013) suggest that the NGP will experience a decrease (increase) in Alberta Clippers (Colorado Lows), which may have implications for future blizzard frequency and intensity.

Identifying blizzards within a GCM is not a straightforward process. While the governing equations of the atmosphere are solved in GCMs, this only provides information about state variables such as temperature, pressure, humidity, and winds. The coarse horizontal and vertical grid spacing require parameterizations to simulate processes such as precipitation. Provided that blizzards are defined in part by a reduction of visibility caused by blowing snow, this requires additional properties to be identified within these models. Unfortunately, the blowing snow is not currently parameterized in GCMs, and no estimate of visibility is given. Thus, these events cannot be identified directly. Therefore, another method must be used to identify these extreme events.

Objective Classification of Synoptic Patterns

Synoptic climatology has been established as a distinctive sub-field of climatology, where the goal is to relate local phenomena to synoptic patterns that the area experiences (Barry and Perry, 1973). This necessitates being able to classify atmospheric circulations and choosing weather-phenomenon-related variables to report back to these patterns. Early methods accomplished this using manual subjective classification of the synoptic pattern (Lamb, 1950). Since this time, the introduction of the computer has allowed for objective classification using automated algorithms that are based on a number of different spatial statistical methods, each of which involve some form of correlation, cluster, and/or eigenfunction analysis (Hewiton and Crane, 2002).

Self-Organizing Maps (SOMs, Kohonen et al. 1996) have become a popular method to classify synoptic patterns to investigate various weather occurrences (Sheridan and Lee, 2011). SOMs are a type of competitive neural network similar to k-means clustering, that are able to sort and classify meteorological patterns (Kohonen et al. 1996). A feature that is unique, SOMs employ a neighborhood function during the training process while patterns are sorted. Unlike other clustering methods, this procedure results in a two-dimensional space of classified nodes that span the continuum of data (Sheridan and Lee, 2011). SOMs consequently do not simply group data to separate between patterns but attempt to find nodes that are representative of nearby patterns as well (Huth et al. 2008).

SOMs have been used in a variety of research--Liu and Weisberg (2011) provide an overview of numerous earlier studies that have used SOMs in the meteorology and oceanography fields. For meteorological applications, Hewitson and Crane (2002) provide valuable information regarding SOMs and synoptic climatology, while also presenting the results of a SOM created using mean-sea level pressure (MSLP) patterns surrounding Pennsylvania. These patterns were then compared to independent precipitation data. In another study where only one variable was utilized, SOMs were used to determine physical mechanisms related to low-cloud fields near the Azores by using normalized anomalies of the 500 hPa height field (Mechem et al. 2018). This determined the prevalent synoptic patterns in the region, and subsequently established what forces were responsible for the creation of specific clouds in each pattern. Other and more numerous variables can also be used to create SOMs. Kennedy et al. (2016) used MSLP, relative humidity, geopotential heights, and zonal and meridional winds at multiple heights in the atmosphere to identify synoptic patterns. The resulting SOMs were used to improve the climatology of clouds at the Southern Great Plains (SGP) Atmospheric Radiation Measurement (ARM) site by associating cloud occurrence with synoptic patterns from SOMs.

SOMs have also been used to investigate how synoptic scale circulations are related to surface meteorological properties in the mid-high latitudes. Cassano et al. (2006) used SOMs to demonstrate the relationship between large-scale MSLP patterns and extreme temperature/wind events in Barrow, AK. SOMs were also used to create a synoptic MSLP climatology for Greenland to establish the patterns associated with precipitation events in a reanalysis (Schuenemann et al. 2008). SOMs have also been utilized to evaluate the performance of a convection-allowing model for warm-season precipitation events in the NGP (Hagenhoff, 2017). Due to the nature of SOMs and their ability to categorize various patterns based on the input cases, they are a practical tool to determine how the synoptic weather patterns relate to weather phenomena of interest.

Purpose of this Study

The purpose of this work is two-fold. The first objective is the investigation and classification of the types of synoptic-scale atmospheric patterns associated blizzards in the NGP, fulfilling the future work suggestions of Schwartz and Schmidlin (2002) and Coleman and Schwartz (2017). The second objective is the identification of blizzard-associated atmospheric patterns, which is accomplished by using SOMs to identify those patterns over the NGP within the North American Regional Reanalysis (NARR, Mesinger et al. 2006) from 1979-2015. This classification is then used to identify those patterns in the Community Earth System Model simulations (CESM, Hurrel et al. 2013). This exercise will be used to determine whether the model can reproduce the historical climatology of blizzard patterns. Further, these patterns will be classified in future greenhouse gas emission scenarios to investigate how blizzards may change in the future.

Impacts of this Study

Results from this work will assist the weather and climate communities along with regional stakeholders. Automated typing of synoptic patterns will allow forecasters to understand the typical patterns associated with blizzard events and how often they are associated with documented blizzards. It is well known that weather forecasting requires a great deal of pattern recognition using model data, and the results from the SOMs can assist forecasters in identifying possible blizzard patterns. This can potentially help increase forecasting lead time for forthcoming hazards. Since the impacts that are associated with blizzards directly influence the human population due to associated dangerous roadway conditions, various economic impacts, and diminished public safety, it is important to investigate how the frequency of blizzard patterns may change in future climates. Information from future projections can be utilized by regional stakeholders to understand future risks. Finally, this study will shed light on how capable the CESM is in reproducing the climatology of blizzard patterns. Considering 'extreme' weather events such as blizzards lie within the frontier of climate research, this information is needed to understand the status of current climate models and guide future development activities.

Limitations of this Study

This study will not attempt to identify specific blizzard events. Issues such as modeled wind biases, lack of visibility information, precipitation type, and land-surface conditions all factor in to determine whether an atmospheric pattern may result in a blizzard. Models that are currently available to study blizzards do not contain all of the necessary atmospheric variables or land-surface conditions to properly identify blizzard conditions. Instead, this study can be considered a first attempt at identifying whether patterns historically associated with blizzards may change in the future.

Organization of this Thesis

As the purpose of the study can be thought of as two separate sections; the layout of the thesis is also split. Chapter 2 will provide a description of the datasets and domain that are used. Chapter 3 will review the methodology used to determine the forcing mechanisms for blizzards in the NGP, and then present the blizzard climatology. Chapter 4 then provides the methodology used to objectively classify blizzards patterns and how that is applied to the NARR/CESM, with Chapter 5 presenting those results in NARR and Chapter 6 in the CESM. Chapter 7 will provide a discussion of both results and relate the results of the study to those discussed in the background section. Chapter 8 will offer some final thoughts and future work.

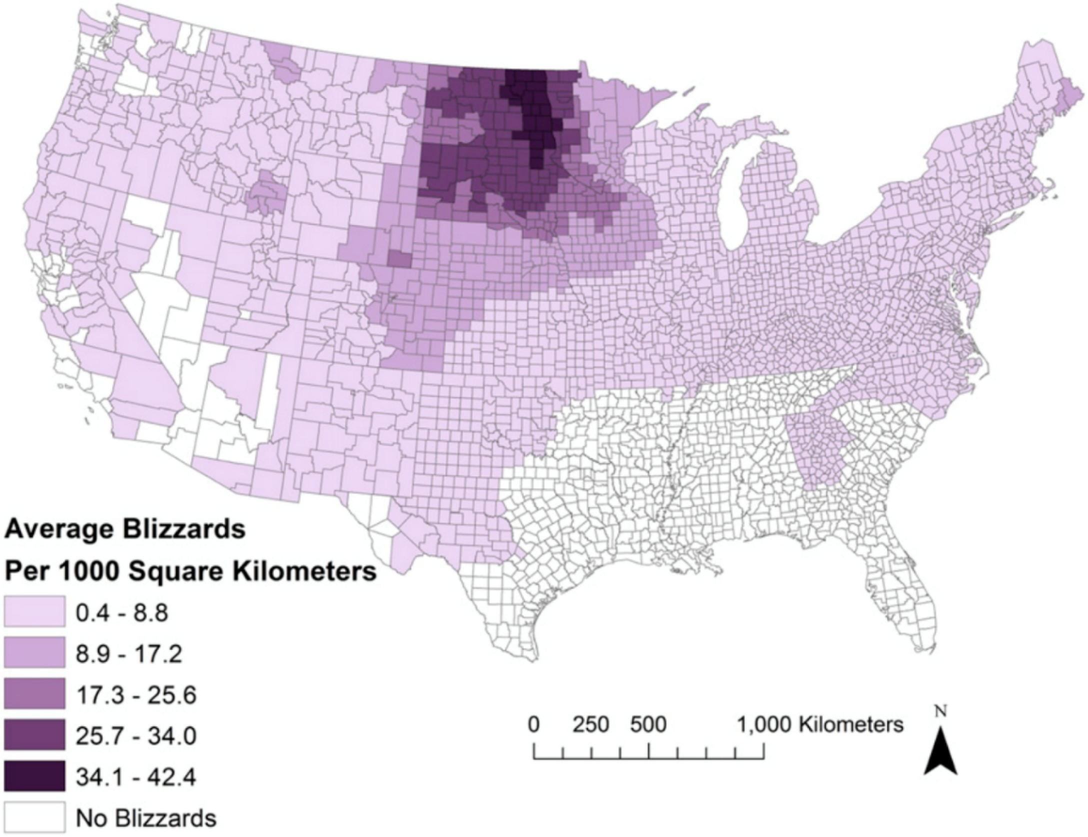


Figure 1. Average number of blizzards per 1000 km^2 for the 1959/60-2013/14 seasons. Figure and caption from Coleman and Schwartz (2017).

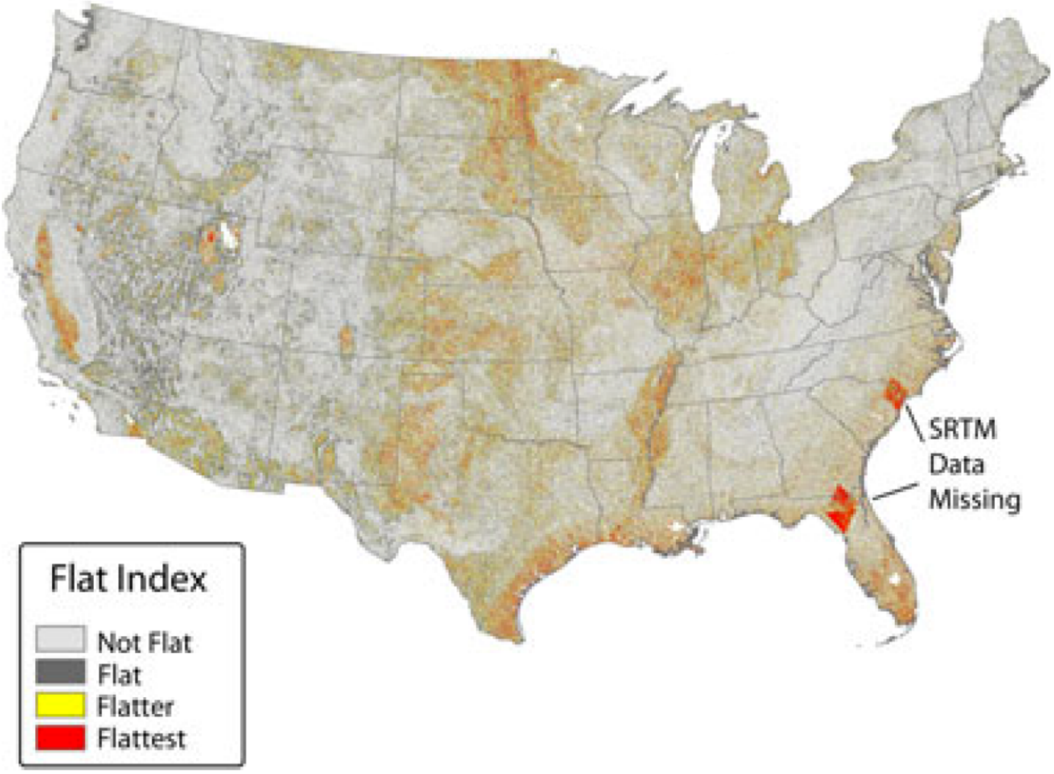


Figure 2. Flat map of the contiguous United States. Figure and caption from Dobson and Campbell (2014).

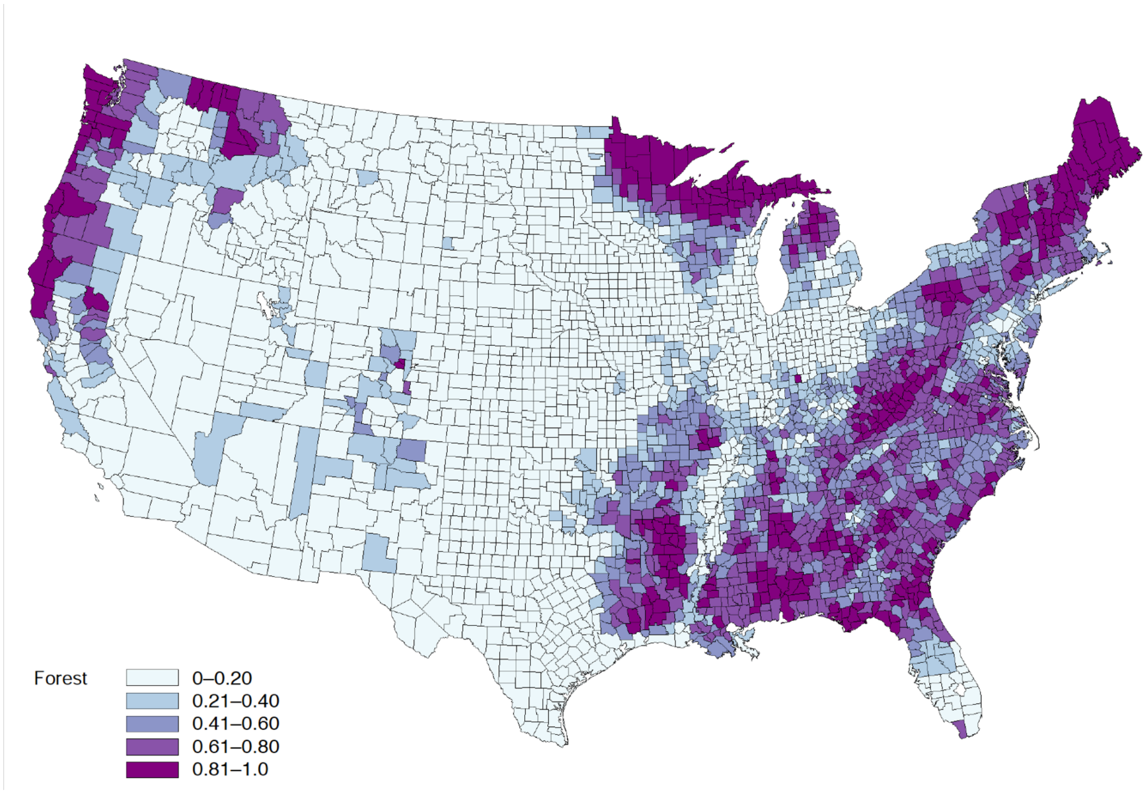


Figure 3. Concentration of forest uses (proportion of each county) on nonfederal land, 1997. Figure and caption from Wear (2011).

CHAPTER II

DATASETS AND DOMAIN

The datasets used to complete this study are reviewed in this section. A list of blizzard events was provided by the Grand Forks, ND NWSFO and this information was compared to the NCEI Storm Events Database. Atmospheric patterns associated with these events were investigated in NARR to establish the historical climatology. This information was then used to develop an objective classification method to identify atmospheric patterns associated with blizzards in the NGP. Atmospheric patterns were then classified in historical and future simulations from the CESM.

Blizzard Events Database

Blizzard events were investigated in multiple datasets for the winters of 1979-1980 to 2014-2015. A winter season was defined from October to April in the following year based on the occurrence of historical blizzards. The data set provided by the Grand Forks NWSFO included only events that occurred within the County Warning Area (CWA) of this office (Fig. 4). Originally maintained by the late Dave Kellenbenz (former forecaster for the Grand Forks NWSFO), the dataset included dates of events, some details about the weather conditions experienced during each blizzard event (e.g. visibility and wind information), and a subjective classification of the synoptic patterns associated with the events.

The blizzard event database was compared to the National Center for Environmental Information (NCEI) Storm Events Database available at https://www.ncdc.noaa.gov/stormevents/. This task was performed to ensure accuracy of the original dataset. As expected, the two databases were largely similar since the NCEI Storm Events Dataset is based on submissions by the Warning Coordination Meteorologist (WCM) at each NWSFO. Despite the overall agreement, a few of the events in the blizzard climatology data base were determined to have incorrect dates that were corrected with the assistance of reanalysis and surface data. The final list of blizzard events is provided in the Appendix.

NCEP NARR

The NCEP NARR was used to classify synoptic patterns surrounding the Grand Forks, ND NWSFO CWA (Figure 2). NARR provides a dynamically consistent atmospheric and land surface hydrology dataset for the North American domain by utilizing the NCEP Eta model combined with a fixed data assimilation system (Mesinger et al. 2006). Observations ingested into NARR include data from satellites, surface observations, aircraft, and radiosondes. NARR features a 32 km horizontal grid, with 45 vertical layers, and 3 hourly output from 1979 to the present.

Numerous investigators have evaluated the utility of the NARR to investigate properties of the atmosphere and land-surface. By comparing observed surface station temperatures to interpolated reanalysis data, Pielke et al. (2007) determined that NARR suitably captures the observed intra-seasonal and inter-annual oscillations in temperature over North America. Other studies have used NARR for hydrological modeling applications, and results show that the reanalysis adequately represents the temperature and precipitation in Manitoba Canada (Choi et al., 2009; Sung, 2012), just north of the domain of interest used in this study. Essou et al. (2016) determined that NARR had favorable characteristics for seasonal precipitation trends over the Continental United States (CONUS) when compared to an observed gridded precipitation dataset. Essou et al. (2016) also found that NARR reproduces seasonal temperature trends in the NGP, albeit with a negative temperature bias of ~1-2 °C and a slight underestimation of precipitation during the winter months. Overall, NARR has been shown to perform well over the NGP (Pielke et al. 2007; Choi et al. 2009; Sung, 2012). Results from previous studies indicate that the resolution and wide variety of variables provided by NARR make it a useful data set to investigate blizzard events.

Several variables were used from NARR in this study. These included Mean Sea Level Pressure (MSLP), surface temperatures, 900 hPa winds, and 500 hPa geopotential heights. The lower level variables were chosen because they are often used in an operational setting in order to determine if blizzard conditions are possible, while 900 hPa wind speeds were used rather than surface wind speeds since there is less confidence in the accuracy of surface variables in NARR (Messenger et al. 2006). The 500 hPa geopotential heights were used in order to compute height anomalies to mitigate seasonal variations that can bias SOMs (Kennedy et al. 2016).

NCAR CESM

The NCAR CESM is a coupled GCM that encompasses four component models in order to simulate the atmosphere, ocean, land surface, and sea-ice. The simulations used for this project were run in support of CMIP-5, and output from the Community Atmospheric Model version 4 (CAM4, Neale et al. 2013) of the Community Climate

System Model version 4 (CCSM4, Gent et al. 2011) was used as the atmospheric model. Specifically, the ‘Mother of All Runs’ (MOAR) ensemble member #6 was investigated because it was the only member with output saved with 6-hour frequency, allowing for the classification of specific atmospheric patterns. The MOAR CESM simulation has a horizontal grid spacing of 1.25° longitude by 0.94° latitude, and 30 vertical layers in the atmosphere (Hurrel et al. 2013).

The CESM simulations used in this study include a historical simulation and two future projections. The historical simulation was forced by observed natural and anthropogenic atmospheric composition changes, such as volcanic eruptions and time-varying green-house gas concentrations from 1861-2005 (Bruyere et al. 2015). Despite sharing an overlapping time periods with NARR, year to year comparisons cannot be made. Historical simulations of coupled global climate models should be thought of as an alternative reality, where only average trends in the data can be compared. Factors such as the El Nino Southern Oscillation (ENSO) occur in different years leading to varying interannual variability.

The future projection analysis was completed using model output data from Representative Concentration Pathways (RCPs) 4.5 and 8.5 experiments for the time period 2006-2100. The two RCPs are plausible greenhouse gas concentrations that are based on socioeconomic, environmental, and technological trend research (Moss et al. 2010). RCP4.5 is generally considered a low-to-moderate emissions scenario in which green-house gas (GHG) emissions would be reduced in the future, while RCP8.5 is a high-emissions scenario where little would be done to reduce GHG emissions (Bruyere et al.

2015). The various RCP scenarios used in the IPCC Fifth Assessment Report are shown in Figure 5 (IPCC, 2014), which include the two scenarios used in this study.

Domain of Interest

While the NARR and CESM both include the NGP in their domains, resolution and grid spacing differences prevent a direct comparison. For the classification method to identify atmospheric patterns associated with blizzards, a common domain and resolution must be used. To accomplish this task, the NARR data were spatially averaged to a 16x16, 1.25° (longitude) by 0.94° (latitude) grid centered on the Grand Forks NWSFO CWA and shared by the CESM (Figure 4).

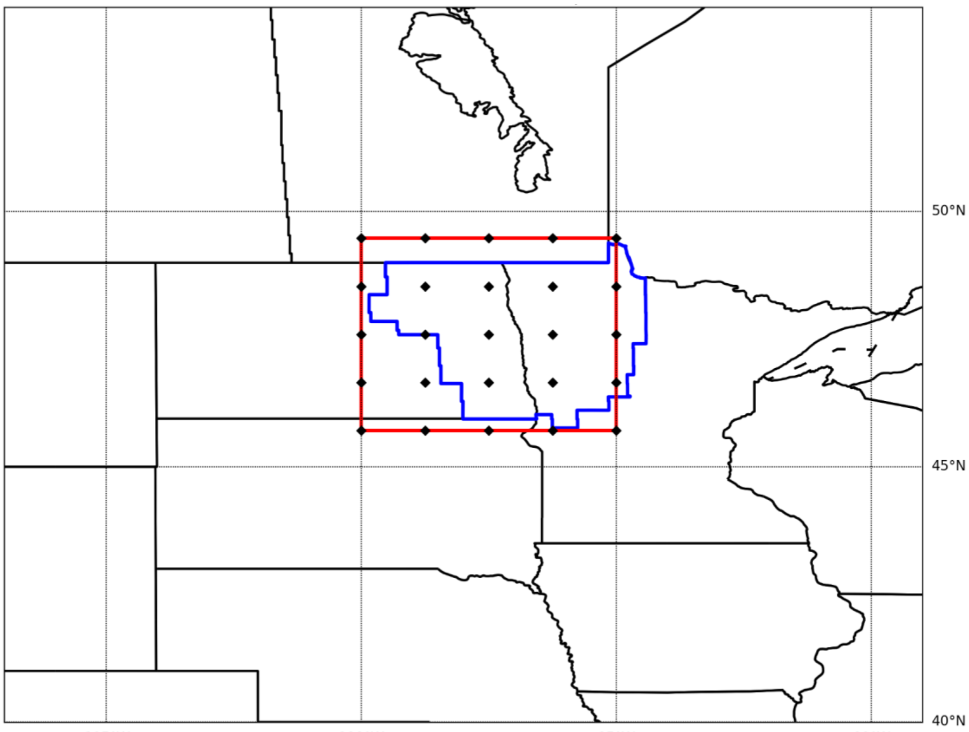


Figure 4. The NGP region of interest for this study. The domain of the plot represents the region for classification of meteorological patterns. The smaller red box denotes the area of main focus, and the black dots represent the grid points from CESM and averaged NARR data. The blue outlined area is the Grand Forks, ND NWSFO CWA.

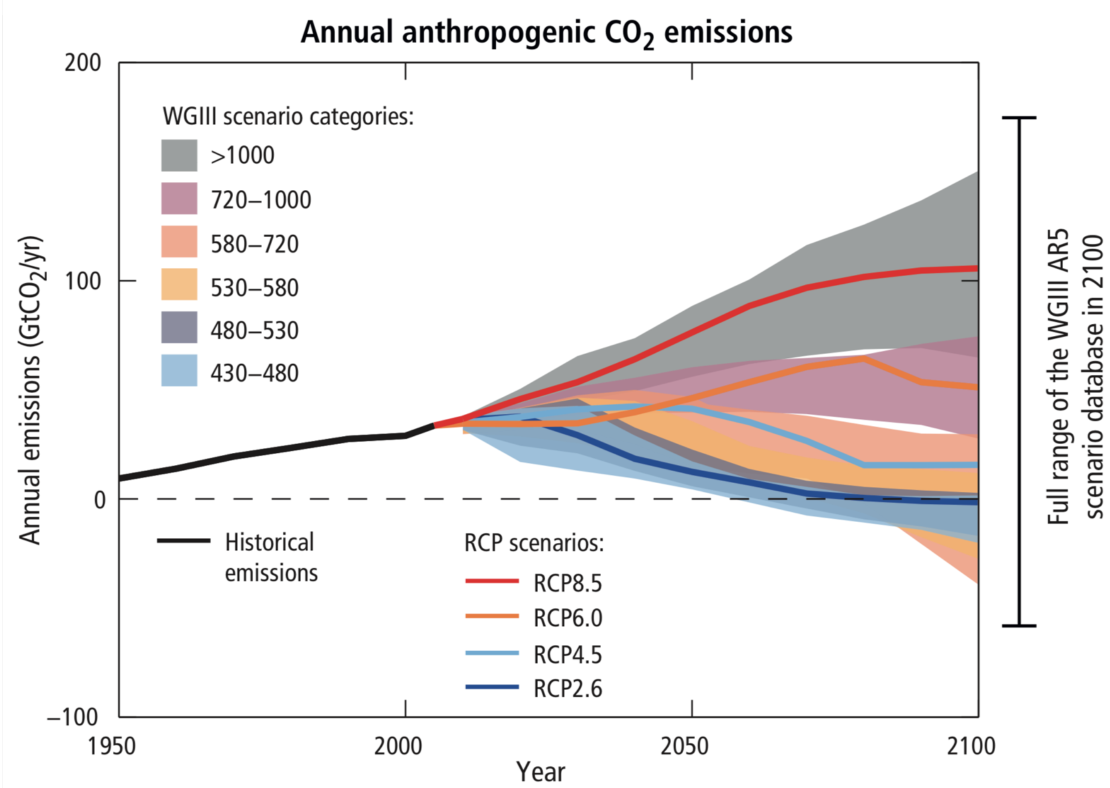


Figure 5. Emissions of carbon dioxide (CO_2) in the Representative Concentration Pathways (RCPs) (lines). Figure and caption from the IPCC 5th annual report (IPCC, 2014).

CHAPTER III

NORTHERN GREAT PLAINS BLIZZARD CLIMATOLOGY

Overview

This chapter provides details about the methodology used to determine characteristics of blizzards as well as the resultant blizzard climatology for the NGP. How the list of events provided by the Grand Forks, ND NWSFO was utilized is discussed, and methods used to identify blizzard properties are presented. The blizzard climatology is then shown and discussed at length.

Methods

Case Selection

Blizzard events from the winters of 1979-1980 through 2014-2015 were identified with the assistance of the event list provided by the Grand Forks, ND NWSFO. Depending on the event, the dataset provided only a date or a range of dates along with other ancillary data that were not consistent across all cases (e.g. peak wind speeds, societal impacts). To properly composite or type synoptic patterns associated with blizzards, more information was needed to isolate times that blizzard conditions were present. The dates and times of blizzard conditions were checked and confirmed using NARR, available surface observations from the Plymouth State Weather Center (http://vortex.plymouth.edu/u-make.html) as well as from the NCAR Mesoscale and Microscale Meteorology Laboratory archive (http://www2.mmm.ucar.edu/imagearchive), and Storm Reports from the NCEI database. These actions actively corrected any mistakes that were found in the blizzard climatology as well as in the NCEI database. Approximate start and end times for each blizzard were determined. Blizzard events that occurred prior to January 1, 1998 no longer had surface analyses readily available, therefore NARR was used exclusively to identify times that blizzard conditions were present prior to that date. The combined use of NARR with observed surface analysis for the more recent cases suggested that NARR was able to determine times that blizzard conditions were present and was further aided by the use of the blizzard dataset provided. However, as NARR provides three hourly output of meteorological data compared to hourly data for archived surface observations, this does introduce a temporal error of plus or minus three hours for start and end times. For the purpose of compositing and for use as training data for SOMs (Chapter 4), the mid-point of each blizzard event was identified.

Creation of Composite Atmospheric Patterns

To understand synoptic patterns associated with NGP blizzard events, composite patterns were generated. Blizzard patterns were originally typed by Dave Kellenbenz into one of four patterns: Alberta Clippers, Arctic Fronts, Colorado Lows, and Hybrid systems. After checking the classifications of these patterns by analyzing time-series of meteorological variables, composite images for the four patterns were created. The variables used to show these patterns included MSLP, surface wind speed, and wind direction, which were composited twelve hours prior and at the center time of the blizzard occurrence. The storm tracks (point of lowest MSLP value) for the low-pressure systems (Colorado Lows, Alberta Clippers, and Hybrid Lows) were composited at -24, -12, 0, and 12 hours with respect to the center point of blizzard occurrence.

Additional Characteristics of Blizzard Events in NARR

Other blizzard properties investigated included surface temperature due to its importance in determining ground blizzard conditions. Minimum surface temperatures and associated maximum wind speeds at 900 hPa within the Grand Forks NWSFO CWA were investigated in NARR as a proxy for surface temperature and wind data. The 900 hPa level was chosen for wind speed because it is frequently utilized in an operational setting and because there is less confidence in the accuracy of surface variables in NARR (Mesinger et al. 2006). NARR precipitation totals, as snow water equivalence (SWE), were also calculated for the 48 hours leading up to the event at individual grid points. The duration of blizzard events was calculated from estimated start and end times, which were determined by looking for winds above 30 knots at 900 hPa coexistent with subfreezing temperatures at the same grid point within the Grand Forks NWSFO CWA (blue outlined area, Fig. 4). Box plots were made for these variables. Box plots were not created for situations where there were fewer than five blizzards (e.g. months at the beginning and end of the season). Rather, only the maximum, minimum, and median values were plotted.

Results

Historical NGP Blizzard Climatology

From 1979-2015, the Grand Forks, ND NWSFO CWA experienced a total of 93 blizzards (about 2.5 per year over 37 years) while Coleman and Schwartz (2017) had identified a maximum of 111 blizzards from 1959-2014 (about 2 per year over 55 years) in Cass and Trail counties (both within the Grand Forks NWSFO CWA). In these studies, a weather event was deemed a “blizzard” and was counted if and only if a blizzard was recorded in the Storm Events database. The annual and bimonthly number of blizzards are shown in Figure 6. There is significant year-to-year variability, with the maximum number of blizzards in a winter season (10) occurring twice in the winters of 1996-1997 and 2013-2014 (Fig. 6a). In the former case (and as noted in the introduction) the number of blizzards in the 1996-1997 winter season contributed to the disastrous Grand Forks Flood of 1997 (North Dakota Department of Emergency Services, 1997). In contrast to these years, the seasons of 1986-1987, 1990-1991, and 2011-2012 had no reported blizzards. On average, 2.5 blizzards occur each year.

Blizzards have a distinct seasonal cycle within the region (Fig. 6b). These events are relatively uncommon early in the season (October-November), before rapidly increasing in December. The second half of December has the highest number of historical blizzards (16), with events then decreasing to a local minimum during the 2nd half of February. This is followed by a 2nd maximum in the first half of March prior to tapering off as the winter transitions to spring. Possible reasons for this feature will be discussed later.

Climatology of Blizzard Patterns

With the yearly and seasonal blizzard climatology established, the synoptic patterns that cause blizzards in the NGP are now discussed. Near-surface, composite synoptic patterns are shown in Figs. 7-8 for each of the respective systems 12 hours prior to and at the center time of blizzard occurrence. Respective plots for 500 hPa analyses are shown in Figs. 9-10. Composite vertical wind profiles for the respective types at the center time of blizzard occurrence in the middle of the blizzard domain are shown in Fig. 11, with general characteristics of the patterns shown in Fig. 12.

Colorado Lows are characterized by a strong low-pressure system that moves from the Nebraska/Colorado border northeast into Minnesota/Wisconsin (Figs. 7-8a). Aloft, this system is associated with a strong shortwave trough or upper-level low that progresses eastward across the domain (Figs. 9-10a). The vertical wind profile for this system reveals increasing winds with height up until ~840 hPa, where the winds begin to weaken (Fig. 11a). The median temperature in NARR for Colorado Lows is -14℃ (Fig. 12a), with wind speeds consistently above 40 knots at 900 hPa (Fig. 12b). The strong forcing with Colorado Lows is associated with widespread advection of moisture that facilitates the highest snow totals of any wintertime system that impacts the region (Fig. 12c). These events are commonly associated with the strongest blizzard events such as the aforementioned Blizzard Hannah.

Originating from Canada, Alberta Clippers feature weaker low-pressure systems that move southeast from Canada and into northern Wisconsin (Figs. 7-8b). Upper-level forcing is weaker with these systems, but a progressive short-wave trough is coincident with an approaching jet-streak at 500 hPa (Fig. 9-10b). The vertical wind profile for this system shows increasing wind speeds throughout the lower layer up to ~840 hPa, with wind speeds remaining constant throughout the upper layers (Fig. 11b). Temperatures are similar to those found within the Colorado Lows, with a median value of -15 ℃ (Fig. 12a), while wind speeds at 900 hPa have a larger range and a higher median wind speed of 44 knots (Fig. 12b). Without large-scale advection of moisture, these fast-moving systems are typically associated with lesser snow totals (Fig. 12c).

The third type of synoptic systems that cause blizzards are known as “Hybrids,” due their characteristics of multiple systems. These characteristics could be caused due to meteorological or time-varying properties. In a composite view, this is a viewed as a low-pressure system with a track between that of an Alberta Clipper and a Colorado Low (Figs. 7-8c). Twelve hours prior to blizzard occurrence the low is centered over Minnesota and is near the eastern edge of the domain during blizzard occurrence (Fig. 7-8c). Aloft, there is a strong shortwave at 500 hPa that strengthens with time (Fig. 9-10c). The vertical wind profile suggests the Hybrid systems are more similar to Colorado Lows than Alberta Clippers, as the wind speeds increase in a similar manner (Fig. 11c). Alternatively, Hybrids can also encompass systems that transition from one type of system to another (e.g., Alberta Clipper to Arctic Front). This can lead to ambiguity that makes subjective classification between patterns difficult. Temperatures for these systems have the largest range, with the lowest median temperature of -19 °C (Fig. 12a). Wind speeds and average precipitation are between Colorado Lows and Alberta Clippers, while they have the highest maximum 900 hPa wind speed (in NARR; Fig. 12b-c).

The final type of pattern that can cause blizzard conditions is Arctic Fronts. Twelve hours prior to blizzard occurrence, the (composite) front stretches from Northeast North Dakota to areas south/southwest of this point as indicated by the shift in wind directions and kink in the isobars (Fig. 7d). The low-pressure system associated with the front is located in northern Wisconsin during blizzard occurrence (Fig. 8d), and aloft there is very strong northwesterly flow at 500 hPa (Fig. 8d). The vertical wind profile indicates that Arctic Fronts have the strongest wind magnitudes when compared to the other systems with winds up to 100 knots at 300 hPa (Fig. 11d). The vertical profile of winds further suggests that downward mixing of these winds aloft is a key ingredient for blizzard occurrence. The temperature range for this pattern indicates it has one of the smallest and coldest ranges for all of the patterns (Fig. 12a). Conversely, wind speeds at 900 hPa have the largest variation of the four patterns, with the weakest lower quartile found (Fig. 12b). Precipitation for these systems is the lowest when compared to the others, with a median value of 1.67 mm liquid water equivalence found prior to blizzard events (Fig. 12c).

These characteristics provide evidence that Arctic Front blizzards are typically ground blizzards. The snowfall associated with these systems typically occurs prior to the frontal passage, and due to the low temperatures, the snow remains loosely on the ground so that once the front has passed the strong winds are able to create and sustain saltation and suspension of snow grains to create low visibility conditions. The variability of the winds suggests that these events are highly dependent on snowpack conditions such as age and temperature.

The four patterns associated with blizzards have distinct periods of occurrence (Fig. 13). The total number of observed patterns by type (Fig. 13a) reveals that Colorado Lows are associated with the highest number of blizzards in the NGP (30). Colorado Lows create blizzards from November through April, with a local maximum in December and their true peak occurrence in March (Fig. 13b). The next most common blizzard creators are the Hybrids with 24 reported. This pattern occurs from October through March and Hybrids are most frequently found in January. Alberta Clippers are responsible for 22 reported blizzards and this pattern occurs from November through March with peak occurrence in January. Lastly, Arctic Fronts have the smallest number of recorded blizzards (18) and occur from December through March, with the highest frequency found in January and February.

Seasonal Characteristics

Properties of blizzards are now discussed from a seasonal perspective. Figure 14 shows three variables that display some of the common blizzard characteristics during a winter season. Figure 14a indicates that minimum temperatures associated with blizzards are lowest in the middle of winter and highest towards the transition seasons. Across all of the months, the highest minimum temperature found during the middle of a blizzard event was 0.2 ℃, an indicator that blizzards need to be able to blow snow around which becomes difficult with temperatures above freezing. While this is important for all blizzard patterns, it is especially so for Arctic Fronts as ground blizzard conditions are more difficult with a warmer snowpack. As indicated in Fig. 13b, Arctic Fronts occur most frequently in December and January, which is when some of the lowest temperatures are observed (Fig. 14a).

Maximum 900 hPa winds show significant variability when separated by month (Fig. 14b). There is a tendency towards weaker winds being associated with blizzard events as the middle of winter is reached. Median values do not show this relationship, and this could be evidence of events being dependent on snowpack conditions (e.g. ground blizzards). Significant variability suggests that snowpack temperature and age play a significant role in the wind speed required to loft snow from Dec-Feb. This implies that cases with weaker winds are probably associated with fresher (and colder) snow that reduces the surface friction velocity needed to cause snow grains to become airborne (Li and Pomeroy 1997). Despite this variability, time periods in the late fall and spring are associated with stronger winds with respect to the minimum (maximum) 900 hPa wind. This suggests that time-dependence of a wind-speed threshold could be used to discriminate blizzard and non-blizzard events. It is important to note that this relationship is more robust than simple comparisons of blizzard temperature vs. maximum wind speed.

Estimated Duration of Blizzards

As duration is part of the AMS definition of a blizzard, estimated calculations of this parameter are illustrated by pattern and month in Fig. 15. It should be noted that blizzard duration in this context means that blizzard conditions were occurring somewhere within the CWA at any given time for a single event, not for a single point. There is no clear relationship between duration and time of year (Fig. 15a). Early and late season events have medians higher than blizzards that occur from December to March, but this property is offset by significant variability during the core winter months. Both Colorado and Hybrid Lows have maximum durations in excess of 40 hours (Fig. 15b), and those two patterns together have occurrences in every month (Fig. 13b). Of the four patterns, Arctic Fronts have the smallest range in duration, with a median of 9 hours (Fig. 15b). As it is known that Arctic Fronts create blizzard conditions from December through March (Fig. 13b), the distinct drop in minimum duration of blizzards can be explained by the appearance of Arctic Fronts in December through March. As an Arctic Front has never created blizzard conditions in April, that month has a larger increase in blizzard durations when compared to March.

Despite the variability in some variables, all four of the synoptic systems that create blizzard conditions in the NGP have some similar characteristics. Temperatures for all of them are all largely well below zero (Fig. 14a), which is to be expected since blizzards require either falling or blowing snow. The surface composite images show that surface winds increase in magnitude from 12 hours prior to the center point of blizzard conditions

(Fig. 7-8c). Observed winds are stronger than the 20 knots found in the composite images and are common over large portions of the NGP. This discrepancy between observed winds and the winds found in NARR within the context of blizzard threshold conditions can be explained by averaging over multiple patterns and the large area as well as biases in NARR surface winds. While the durations between the patterns are similar, the distinction between traditional and ground blizzards are particularly apparent as the Arctic Fronts show ground blizzard conditions do not last as long as traditional blizzards.

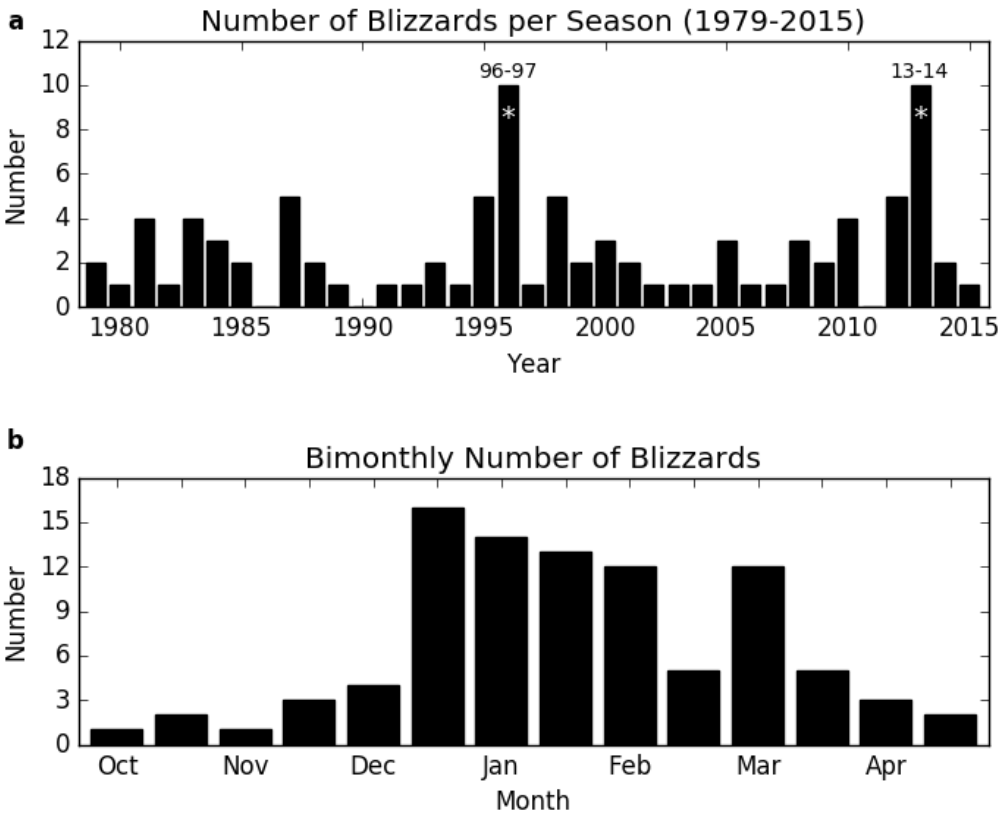


Figure 6. (a) Annual number and (b) bimonthly number of blizzards from 1979-2015.

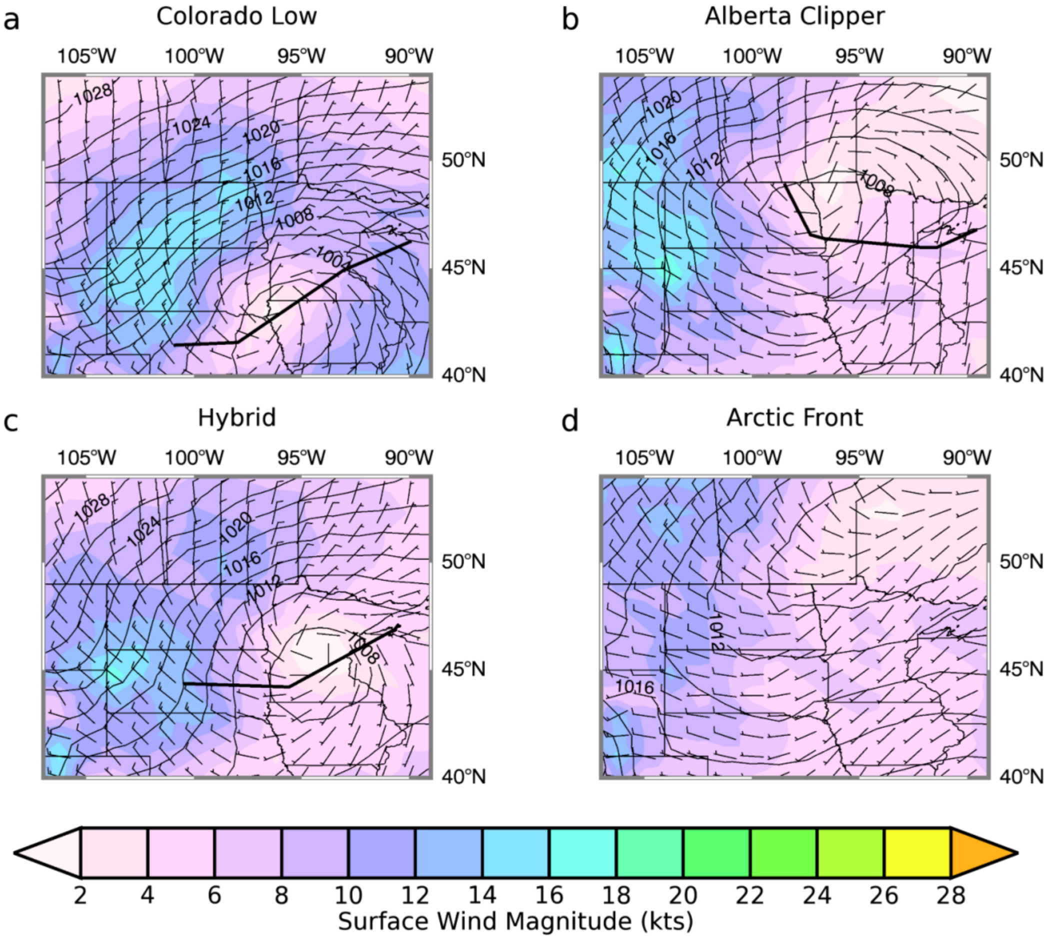


Figure 7. Composite analyses of surface variables 12 hours prior to blizzard occurrence. MSLP in hPa (contoured), surface wind magnitude in knots (color filled), and surface winds in knots. (a) Colorado Lows, (b) Alberta Clippers, (c) Hybrids, and (d) Arctic Fronts. The thick black line denotes the mean storm track from 24 hours prior, to 12 hours post blizzard occurrence in 12-hour intervals.

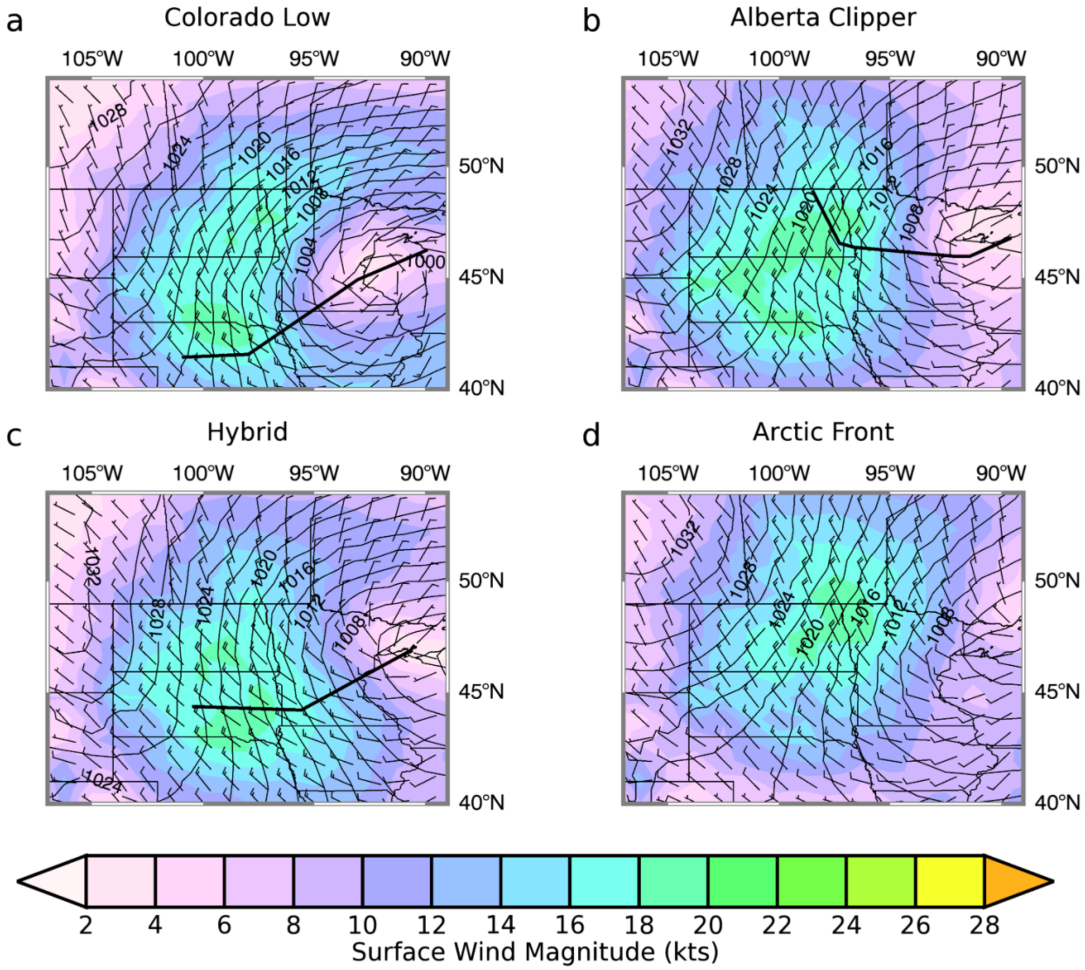


Figure 8. As in Fig. 7, but at the center time of blizzard occurrence.

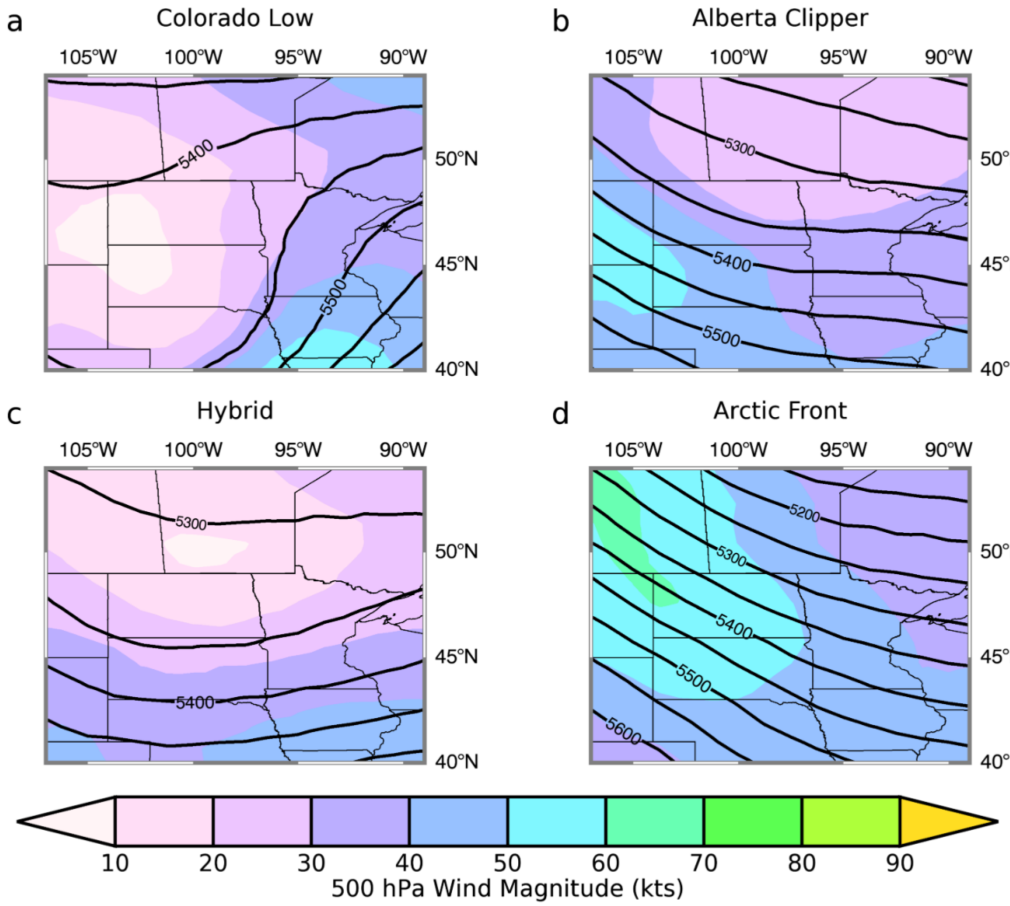


Figure 9. As in Fig. 7, but for upper level variables. Mean geopotential heights at 500 hPa (black contours) and 500 hPa wind magnitudes (color filled).

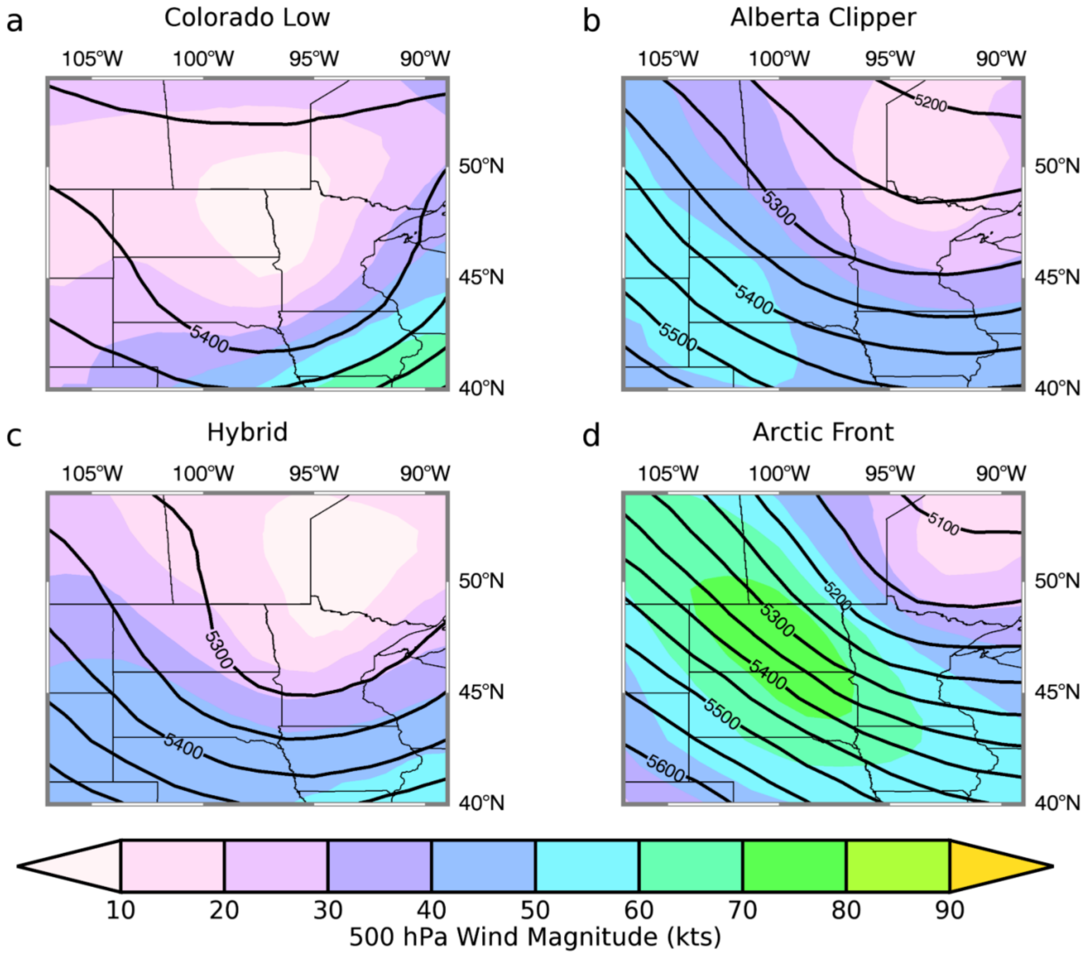


Figure 10. As in Fig. 9, but at center time of blizzard occurrence.

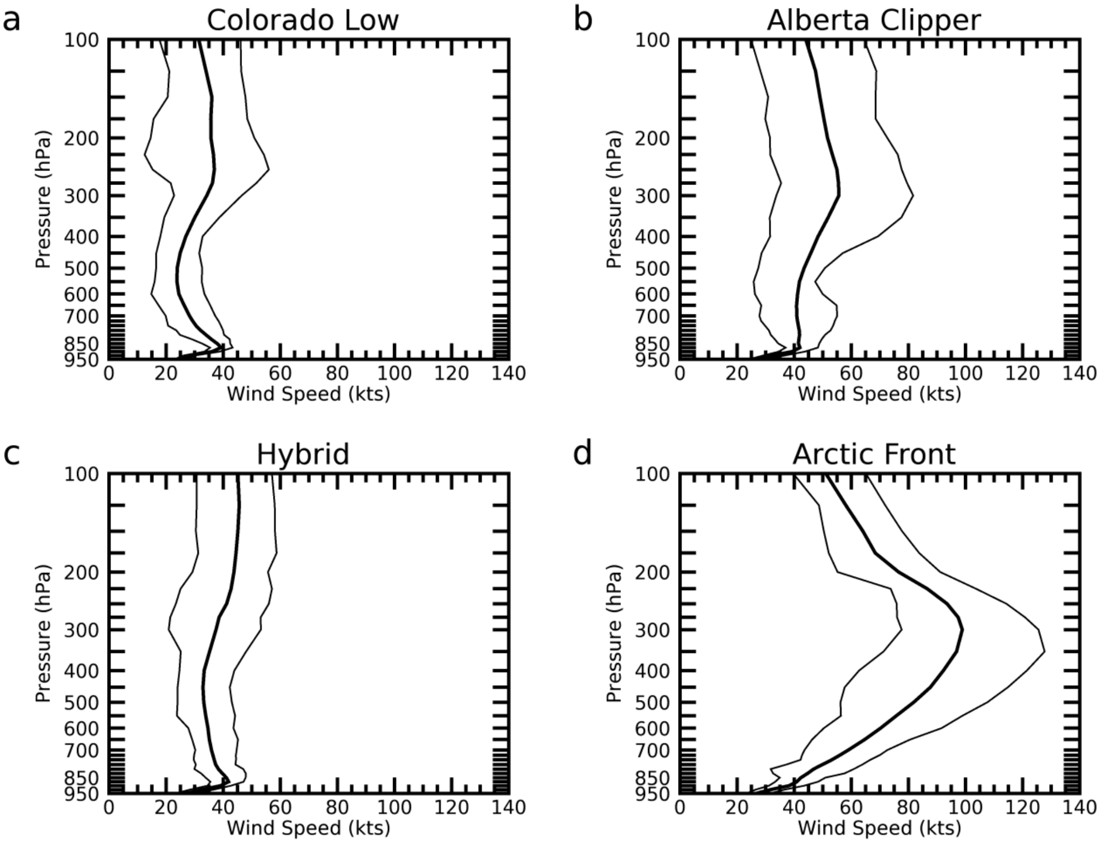


Figure 11. Composite vertical wind profile for magnitude of winds. Thick line in the center denotes the median, thinner lines denote lower and upper quartiles. (a) Colorado Lows, (b) Alberta Clippers, (c) Hybrids, and (d) Arctic Fronts.

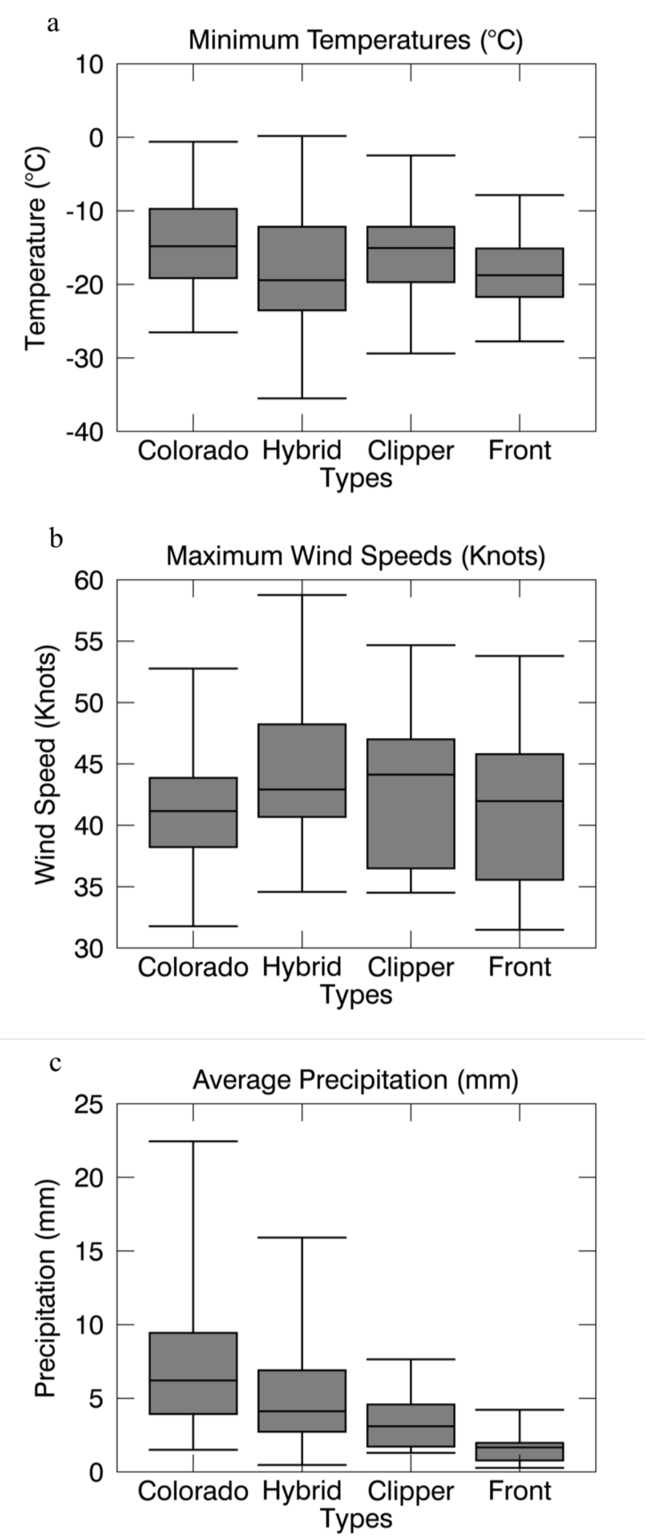


Figure 12. NARR blizzard characteristics by type. (a) minimum temperature, (b) maximum 900 hPa wind speeds, and (c) average accumulated precipitation (SWE) in the 48-hr period prior to the center-point of the blizzard.

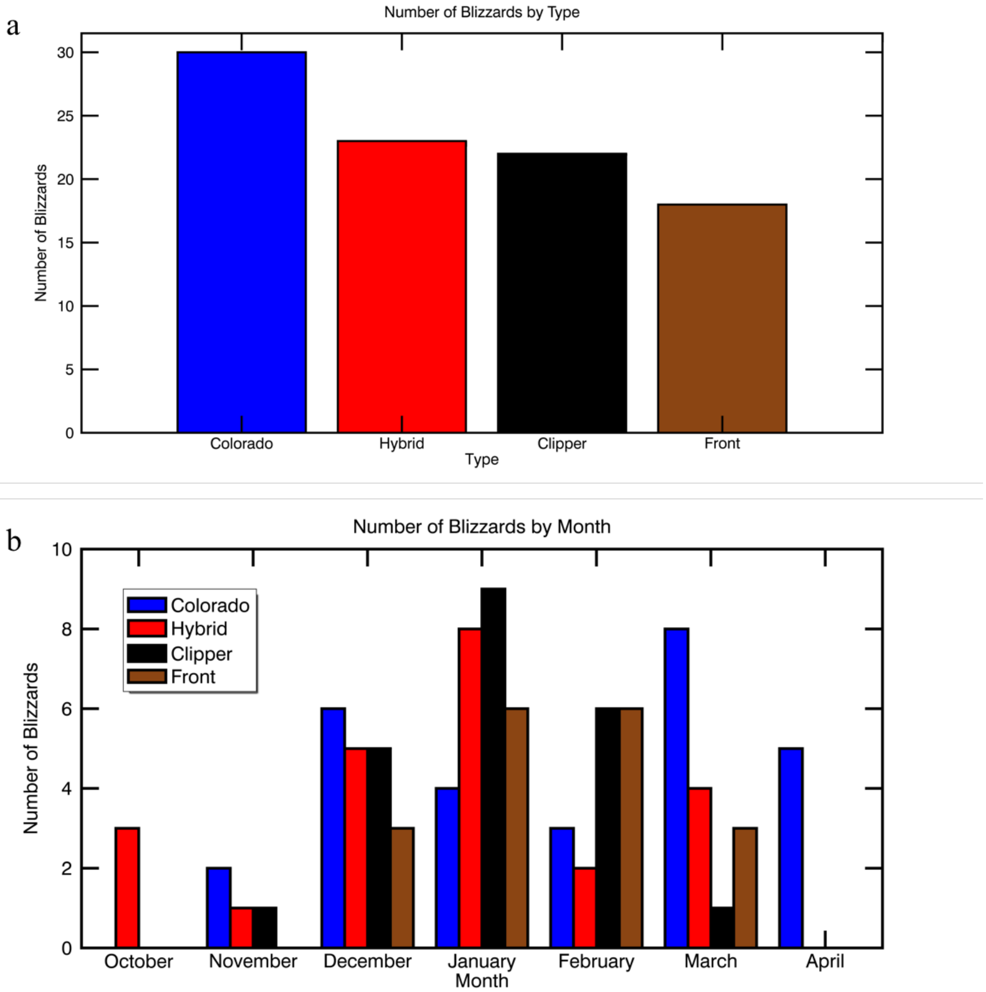


Figure 13. Total number of blizzards by (a) type, and (b) month.

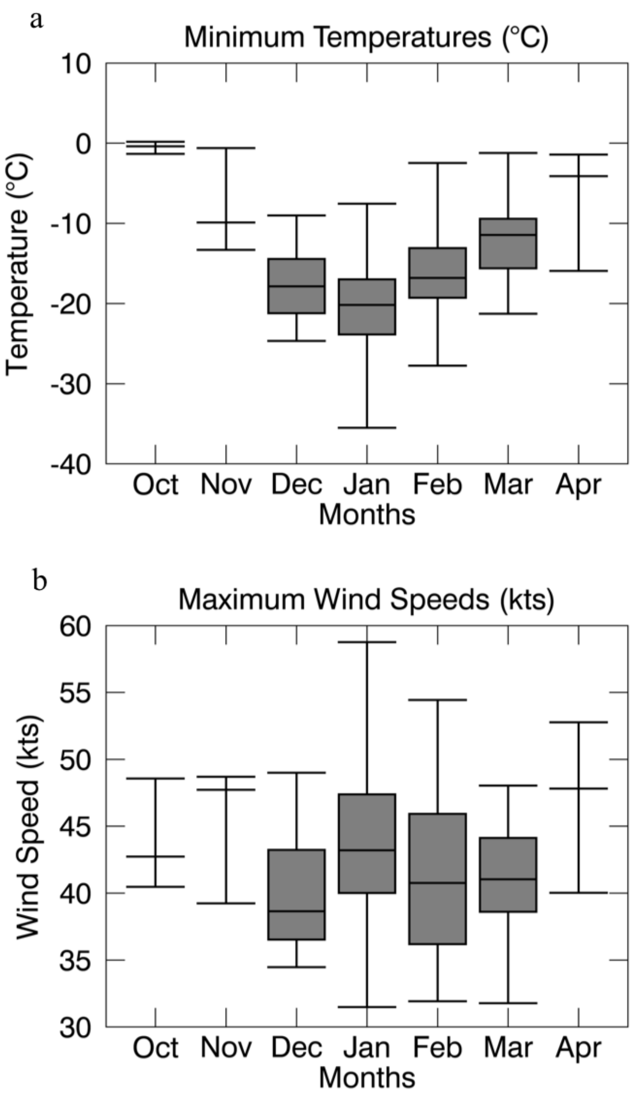


Figure 14. NARR blizzard characteristics segregated by month: (a) minimum temperature, (b) maximum 900 hPa wind speeds.

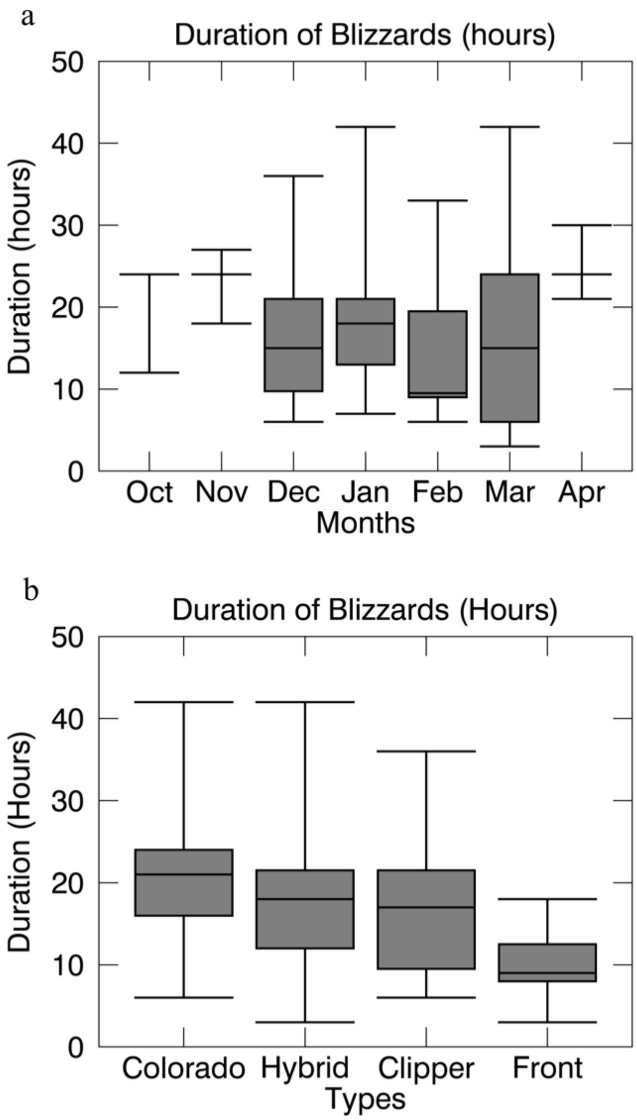


Figure 15. Duration of blizzards segregated by (a) month and (b) type.

CHAPTER IV

OBJECTIVE BLIZZARD CLASSIFICATION METHODOLOGY

Techniques

The methodology used to objectively classify blizzard patterns is described herein. This includes explanation of the SOM technique and how the algorithm was further refined. The objective classification technique is then examined by comparing identified blizzard patterns to the blizzard climatology to verify the skill in using it so that it can be applied to the CESM.

Self-Organizing Maps

Self-organizing Maps (SOMs) were used to automatically/objectively classify atmospheric patterns within the NARR and CESM. A user must first specify the number of nodes within a two-dimensional matrix (e.g. 4 nodes in the horizontal by 2 nodes in the vertical for a total of 8 nodes). A “node” in this context is one classification, and the user is able to specify how many different classifications from their dataset is required. The creation of a SOM then occurs in two steps. First, the SOM is initialized with random values. Training samples (e.g. gridded MSLP data) are then fed individually as input vectors to the SOM. The node whose Euclidean distance is smallest becomes the ‘winning’ node (Hewitonson and Crane, 2002). That SOM node is then modified towards the input vector by a user-defined learning rate, while the surrounding nodes are partially modified towards the input vector through a distance decay function. An example of how this occurs is shown in Figure 16, which displays 7 randomly initialized nodes, and one "winning" node which represents the node the input vector was most similar to. The example (Fig. 16) was created using no distance decay function, while in practice the surrounding nodes would also be weighted to look similar to the "winning" node. This distance component, known as the neighborhood function, sets SOMs apart from k-means clustering, since this acts to smooth the data across nodes allowing them to span the dimensions of the dataset (Kohonen et al. 1996). This process repeats through the training dataset (e.g. the number of blizzard cases) and results in a SOM with a crude organization determined.

The second step of the process then acts to converge to a final solution and decrease the error between the SOM and the training samples. This process is similar to the first step, except each input vector is compared to the SOM multiple times with a smaller learning rate and neighborhood function so the SOM reaches a stable solution (Gutiérrez et al. 2005). This two-step process results in a consistent pattern of solutions where similar nodes are closer together while unrelated nodes are farther apart (Sheridan and Lee, 2011). From the perspective of synoptic climatology, SOMs created with only MSLP data generally results in high and low pressure dominant patterns lying at opposite corners (Hewitson and Crane, 2011).

SOMs created for this study used the SOM_PAK software (Kohonen et al. 1996), a freely available software package available at (http://www.cis.hut.fi/research/som-research/nnrc-programs.shtml). The methodology for generating the SOM using SOM_PAK followed that of Kennedy et al. (2016) and Hagenhoff (2017). In order to determine the SOM map with the smallest average error (based off the classified Euclidean distance), each SOM was given 10 trials. The SOM that had the lowest quantization error was then saved. The “vfind” command includes settings such as training length, learning rates (non-dimensional), and neighborhood radii (the distance via number of nodes away from the “winning” node affected by distance decay function), which are required to create the SOMs. The values used for this study are summarized in Table 1.

Table 1. SOM initialization settings

Initialization Setting	**Value**
Trials	10
Training Length (stage 1)	Number of cases
Learning Rate (stage 1)	0.05
Neighborhood Radius (stage 1)	Horizontal Dimension - 1
Training Length (stage 2)	Number of cases x 100
Learning Rate (stage 2)	0.01
Neighborhood Radius (stage 2)	1

Determining how to use SOMs to objectively find blizzard patterns required testing multiple methods. Two approaches were attempted. First, SOMs were created using only the observed blizzards that were found in the NGP blizzard climatology. It was found that while the ‘blizzard events’ SOMs were able to show a wide range of blizzard patterns, there was no error threshold (e.g. Euclidean distance when compared to observed patterns) that effectively discriminated blizzard versus null events. Alternatively, SOMs were created using all available times in NARR to create a climatology of patterns. These patterns were then used to understand what patterns and variables were associated with blizzard events. This immediately allowed for the elimination of many patterns that were never associated with blizzards. In order to determine the most appropriate ‘climatological’ SOM, multiple dimensions and variables were tested to understand what achieved the best segregation of patterns. This sensitivity testing is described in the next section. To provide context, a climatological SOM is first created to perform gross classification of blizzard vs. null events, and a blizzard SOM is then used to determine the type of blizzard pattern of particular events.

Climatological SOM

The climatological SOM was created using the MSLP anomaly field, which was calculated by determining the mean MSLP for the domain at each time step and subtracting this value from each grid point values in NARR. Anomalies were investigated based on the guidance from Hagenhoff (2017) as it minimizes issues with bias and variability in cyclone strength. MSLP anomalies were then used as the input vector to train the climatological SOM that was calculated twice a day (0 UTC and 12 UTC) from the winters of 1979-1980 through 2014-2015. This resulted in a total of 15,708 cases with each vector being 256 elements long for the 16x16 grid domain.

As mentioned in the background section, SOMs can be created using any variable as well as multiple different types at the same time. One of the benefits of using SOMs is being able to define the number of nodes the user would like their data to be displayed in. Ideally, the number of nodes should be small enough to ensure that every node has at least one case in it, while large enough to show variabilities within the data across the nodes. A sensitivity study was performed by varying the dimension and variables used in the SOM to determine what settings a) performed the best at separating between events that did and did not produce blizzards and b) produced a climatology of blizzard patterns that resembled observed events. The "best" SOM would have the highest correlation between yearly and seasonal observed blizzards and blizzard patterns, thus providing confidence in objectively finding historical blizzard events on both a yearly and seasonal scale.

In order to show examples of the various SOMs tested, a small sample of the number of dimensions and variables used to create SOMs and their outcomes is presented (Table 2). Three dimensions were tested along with three meteorological variables (MSLP, surface temperature, and 500 hPa geopotential heights) resulting in 12 combinations where MSLP was present. The two variables that have not been discussed yet as an input vector for a SOM is surface temperature and 500 hPa geopotential height (both used to create anomaly fields). These was included to investigate their utility in separating out Arctic Front cases, as well as being able to better distinguish between the known synoptic patterns.

Table 2. Characteristics of the twelve SOM sensitivity tests. For variables, "T" denotes temperature, "M" MSLP, and "H" 500 hPa geopotential height. The final SOM selected is emboldened.

SOM Dimensions	**SOM Variables**	**Blizzard Patterns**	**Yearly Correlation**	**Seasonal Correlation**
8x5	M	514	0.51	0.97
9x6	**M**	**440**	**0.66**	**0.97**
10x7	M	452	0.47	0.93
8x5	M, T	541	0.31	0.97
9x6	M, T	481	0.40	0.98
10x7	M, T	536	0.50	0.97
8x5	M, H	636	0.43	0.96
9x6	M, H	648	0.49	0.96
10x7	M, H	592	0.52	0.98
8x5	M, T, H	722	0.39	0.97
9x6	M, T, H	669	0.41	0.98
10x7	M, T, H	603	0.53	0.97

Results demonstrate that no clear pattern emerged as the winner (Table 2). Seasonal correlations only varied slightly from 0.93-0.98, while yearly correlations had more variability ranging from 0.39-0.66. The number of blizzard patterns detected also had large variations (440-722 total patterns) that were closely tied to the yearly correlation. The results from this sensitivity study resulted in the use of the 9x6 SOM using only the MSLP field to isolate patterns that are potentially blizzard events. This SOM displayed the overall best combination of yearly and seasonal correlations, while also resulting in the fewest number of blizzard patterns found. With this SOM, 84 of the total 93 blizzards events were identified, with more details on which events were missed provided in the next chapter.

Blizzard Events SOM

The purpose of this SOM is to distinguish between the known synoptic patterns that create blizzards as was discussed in Chapter 3. To create the blizzard event SOM, MSLP was again utilized along with geopotential height anomalies at 500 hPa, the reason for including the geopotential height anomalies is discussed later. To ensure that each variable provided equal weight to the classification of the SOM, the variables were normalized to a common range. Unlike the climatological SOM, only historical blizzard events that were deemed climatologically relevant were used as the input vectors (see next section). In brief, this eliminated atypical and rare NGP blizzard patterns that are atypical of the patterns typically experienced in the NGP. The input vectors were composed of the middle times of past blizzard events, as well as 12 hours prior and after each event for each of the two variables resulting in a total of 86 cases with each vector being 1,536 elements long.

Methods

Objective Identification of Blizzard Patterns (Blizzard Pattern Detection Algorithm)

In order to objectively identify blizzard patterns, a method was needed to first rule out patterns that, climatologically, rarely produced a blizzard. Once those patterns were filtered out, the remaining potential blizzard patterns were examined to see if they had characteristics similar to historical observed blizzards cases shown in Chapter 3. As blizzard events were defined as a collection of times where blizzard conditions were occurring, consecutive time steps of blizzard pattern characteristics were appropriately considered to be part of one event. The following sections provide details about how each of the above steps were applied in the order listed above.

Step 1: Application of the Climatological SOM

The climatological SOM (Fig. 17) was used to identify patterns that commonly, rarely, and have never produced historical blizzard events. The SOM shows patterns ranging from low pressures systems residing to the east (left side of SOM) and west (right side of SOM) side of the domain. In-between, patterns with weaker gradients (e.g. anticyclones) are seen. Broadly speaking, patterns with stronger winds (as noted by the strong gradients) fall along the perimeter of the SOM except for the bottom center.

To demonstrate how the SOM technique works in classifying patterns, Fig. 18 displays the MSLP and 900 hPa winds that occurred for the 31 December 1996 blizzard event. This event had a low-pressure system on the western edge of the domain, with strong south/southwesterly winds associated with blizzard conditions for the NGP. With respect to the four patterns shown in Chapter 3, this represents an atypical blizzard that is sometimes referred to as a valley wind event by the NWS. When compared to the climatological SOM, good agreement is found; the minimum Euclidian distance and classified pattern features a cyclone to the west with southerly winds at the surface (Fig. 19).

This process was applied to all dates and times within NARR including time periods of blizzards. Figure 20 shows which nodes have historically produced blizzards. The atypical nature of the 31 December 1996 blizzard (Fig. 18) is confirmed; it was the only blizzard associated with that node. Figure 21 reveals where the four known blizzard patterns get classified in the climatological SOM, and most of them occur in the same classes along the left-hand side of the SOM (Fig. 20). The other atypical events are shown as classes where only one or two of them reside in a single node (Fig. 21). By eliminating the patterns with atypical events, southerly (valley) wind events, and a couple of cases where blizzard conditions occurred with easterly winds north of the surface low were removed. For the purposes of identifying climatologically relevant blizzards, it was decided that only those that had at least three historical events associated with them would be considered.

Step 2: Refinement of Potential Blizzard Patterns

Once climatologically rare events were removed, the remaining events were scrutinized further to determine how similar they were to characteristics of historical observed blizzards. The American Meteorological Society's definition of a blizzard has specific wording on what constitutes a blizzard, which can be thought of as a collection of thresholds to separate between a blizzard and non-blizzard event. This same principle was applied to the remaining blizzard patterns, where each of those events were expected to reach "blizzard thresholds" related to the temperature and wind speeds observed in NARR during the historical blizzard events (Fig. 14). Because it was difficult to identify exact locations where blizzard conditions occurred for historical events (e.g. lack of surface observations), a liberal approach was used. Thresholds were only required to be exceeded anywhere within the domain of interest (red outlined box, Fig. 4).

To limit patterns to those that could only produce falling or blowing snow, a temperature threshold was used. This threshold was defined by the warmest minimum 2-

meter air temperature observed with historical blizzard events (0.2°C), which meant that the blizzard pattern within the NARR needed to have temperatures at or lower than this threshold. Sensitivity testing was conducted to understand how this threshold impacted the yearly and seasonal correlations. The threshold was also varied by month, but impacts were negligible for both correlations.

To ensure that the potential blizzard pattern had wind speeds necessary to create low visibility conditions if snow were present, a 900 hPa wind speed threshold was used together with the temperature threshold. Unlike the temperature threshold criteria, this threshold was allowed to vary by month (Table 3) due to the seasonal variability seen in Fig. 14b. This greatly reduced the number of blizzard patterns at the beginning and end of the winter season. As the wind speeds start off higher then decrease through the colder months before increasing again in April, the wind speed threshold essentially varies based off the temperatures that are found in those months. This largely agrees with the results indicated in the study from Li and Pomeroy (1997), as the probability of blowing snow increases for lower wind speeds (5-15 m s^{-1}) as surface temperature decreases. Due to this relationship, it was attempted to create a wind speed threshold based off the observed temperatures from the historical blizzard events, however, there was too much uncertainty in order for that to be done. Presumably, this could be due to the large domain used with this study, as well as the uncertainty of the snowpack conditions. As the wind speed thresholds were created from the lowest maximum wind speeds observed during a historical blizzard event based on the month that the event occurred in, these thresholds can be viewed as a liberal approach.

Table 3. Monthly wind speed thresholds (knots).

Month	October	November	December	January	February	March	April
Wind Speed	40.8	39.2	34.5	31.5	31.9	31.8	39.4

Thresholds herein were applied by interrogating each NARR grid point near the Grand Forks NWS CWA (see black points in Fig. 4) for an identified (potential) blizzard pattern. Events where at least one grid point within the domain of interest met the two thresholds were then considered to be a blizzard pattern. This process was repeated for the entirety of the 3-hourly dataset of NARR from 1979-2015. As it is possible to detect consecutive blizzard patterns, blizzard events were defined as a collection of identified patterns in consecutive order. The time chosen to represent the collection of events was the time when the most grid points had both thresholds met, which is different than using the "center time" which was done when first identifying all of the historical blizzard events in Chapter 3. If, two or more times occurred that had the same number of grid points with the blizzard thresholds met, then the second time that occurred was chosen to represent that blizzard event. As blizzard conditions can exist for extended periods of times, this criterion was relaxed to allow for a gap (null event) of 6 hours, which were then joined into a single event. This prevented identification of multiple blizzard events within a single 24-hr period.

Step 3: Identification of Blizzard Pattern Type

While the climatology SOM was able to distinguish between blizzard and non-blizzard patterns, an additional step was needed to judge which of these nodes best matched the four known blizzard patterns. Figure 21 demonstrates that the four different types occur across the same six SOM nodes of the climatological SOM with no clear segregation by class. In order to better separate between the known synoptic patterns that create blizzards, a 2nd blizzard event SOM was created from blizzards that occurred in the climatological SOM nodes with three or more events. This two-tiered process was used because within the climatological SOM, there is a significant amount of smoothing done by the neighborhood function to accommodate the large range of MSLP patterns. As a consequence of this, the function essentially weakens the stronger MSLP gradients found in blizzard events, making it difficult to differentiate between the known blizzard patterns. By separating out and utilizing the climatologically relevant blizzard cases, the stronger MSLP gradients are preserved and can therefore be used to better separate between the known patterns.

A sensitivity test was completed to determine the variables and size used to create the blizzard event SOM. As this SOM was given fewer input vectors (86 vs. 15,708), smaller maps (4x2, 5x3 and 6x4) were considered. Sensitivity testing of variables determined that the combination of MSLP and 500 hPa geopotential height anomaly fields improved the ability of the blizzard SOM to differentiate patterns. As it is known that the various synoptic patterns take a different path across the NGP, the time dimension was also included in the creation of this SOM. Multiple time steps were considered, but in the end, inclusion of the center point, 12 hours prior, and 12 hours post the blizzard occurrence were used. These were chosen subjectively based upon the segregation of human-identified patterns. The final blizzard SOM had 8 classes (4x2), as attempting to utilize a larger number of classes for the blizzard SOM did not provide additional improvements in performance in separating between synoptic patterns.

The 8-class (4x2) blizzard SOM is shown in Figs. 22-23. This smaller SOM is comprised of low pressure systems that take various tracks across the NGP, as seen by the progression across times (Fig. 22a-c). Figure 22a-b closely resembles the placement of low-pressure systems found in the respective composite maps shown in Figs. 7-8, adding confidence in the ability of the blizzard SOM to differentiate between the known patterns that lead to blizzard conditions. Twelve hours prior to the center point of the blizzard, 500 hPa analyses range from strong westerly/northwesterly flow to an approaching shortwave trough (Fig. 23a). Going forward in time shows that the upper level pattern evolves into a more of a north/northwesterly flow on the left to the deepening of the trough into a closed-off low on the right (Fig. 23b). These troughs and upper-level lows then progress eastward as the event progresses (Fig. 23c). Overall, the upper air patterns in the blizzard SOM (Fig. 23a-b) look like the patterns found in the upper air composite maps (Figs. 9-10), revealing good agreement aloft as was found with the MSLP patterns.

By comparing historical blizzards to the blizzard SOM, it is observed that the SOM objectively separates many of the patterns (Fig. 24). The different classes show that the Colorado Low patterns are generally on the right side of the SOM (Fig. 24a) where the stronger lows are while also having the southernmost cyclone track and are exhibiting the shortwave pattern aloft. The Alberta Clippers (hereafter Clippers) are generally on the left side of the SOM (Fig. 24b) where the weaker lows are displaying a more northerly storm track and (generally) northeasterly flow aloft (with some exceptions). The Arctic Fronts (hereafter Fronts) are also on the left side, especially in the bottom left (Fig. 24d). These patterns exhibit a weak low-pressure system at first, but then have a strong high pressure build in behind the low during the middle of the blizzard event with strong northwesterly flow aloft. By definition, hybrid patterns are a low-pressure system somewhere between a Colorado Low and a Clipper, thus explaining that they are found in all of the classes as they are similar to both the Colorado Lows and Clippers (Fig. 24c).

Application of the Blizzard SOM

The results from the blizzard SOM reveal that it is largely able to objectively distinguish between the subjective classifications of the historical blizzards. As it is known what synoptic patterns lead to blizzards in the NGP, one of the goals of this study is to determine how these patterns may change in the future. This requires the ability to distinguish between the known patterns, which the blizzard SOM is able to do. As the four patterns do not each fall into two classes to easily separate them, the subjective decision was made to represent the right-hand side of the blizzard SOM as the Colorado/Hybrid low patterns, and the left-hand side the Clipper/Front patterns. Therefore, the sole purpose of the blizzard SOM is to classify any given blizzard pattern event determined by the algorithm into either a Colorado/Hybrid low pattern or a Clipper/Front pattern, while providing no influence on the algorithm itself.

Verification Metrics

Performance of the algorithm was assessed with a 2x2 contingency table (Table 4) and linear Pearson correlation coefficients. The 2x2 contingency table describes how the algorithm performs in finding blizzard patterns compared to whether or not a blizzard occurred. The blizzard pattern detection algorithm has two possible outcomes (Yes or No) and this was judged against historical blizzards (Yes) and null events (No). The Probability of Detection (POD) and False Alarm Ratio (FAR) were calculated using

$$POD = \frac{a}{a+c} \tag{1}$$

and

$$FAR = \frac{b}{a+b} \tag{2}$$

While these values are important to understand how often patterns resulted in blizzards or false alarms, the algorithm should also reproduce climatological characteristics of blizzard events. The Linear Pearson correlation coefficient was calculated to assess the fidelity of seasonal and interannual variability of blizzard events.

Table 4. The 2x2 contingency table

		Blizzard Observed	
		Yes	No
Automated Blizzard Pattern	Yes	a (hits)	b (false alarms)
	No	c (misses)	d (correct negatives)

Example of the Blizzard Pattern Detection Algorithm

To demonstrate the results of the algorithm as described in the methods section above, an example is shown for the winter of 1996-1997 with a further subset of cases displayed for January (Fig. 25). Focusing on January, four observed blizzards were documented, and these matched up with objectively identified cases #1, #2, #4, and #5. Two additional null events were identified, cases #3 and #6.

Event #1 appears as a collection of blizzard patterns from 4-6 January (Fig. 25a). This event had a duration of 39 hours with a peak area of ~90%. This was an observed Colorado Low blizzard and was classified to node 7 in the SOM, a common Colorado/Hybrid Low node (Fig. 24a). Compared to the subjective identification of the blizzard center point, the maximum area affected by this event occurred 9 hours later. Event #2 began on 9 January and had a maximum area of 80% lining up closely to the subjectively determined center point (Fig. 25a). An observed Clipper, this event was classified to node 7 in the blizzard SOM, which is an uncommon node for Clippers (Fig. 24b), and had a duration of 54 hours. The odd classification of the event occurred due to the placement of the low pressure over Michigan while it was affecting the largest area. Event #3 on Jan 12 was a short (3 hr) event and only affected one grid point (Fig. 25a). Not surprisingly, this was not an observed blizzard event, but when classified to the blizzard SOM it was determined to be in node 7, most commonly associated with Colorado Lows (Fig. 24a). Analysis of this event determined that this was caused by the remnants of the previous event, which stopped producing winds capable of exceeding the blizzard thresholds for 15 hours.

Continuing chronologically, event #4 was a major blizzard from 15-16 January, affecting 100% of the grid at its peak and lasting a total of 24 hours. This identified event was associated with a historical Arctic Front event and was classified to node 5 in the SOM, the most common Arctic Front class (Fig. 24d). Event #5 is the last observed blizzard event and occurred from 21-22 January, affecting just over 50% of the grid and lasting a total of 21 hours (Fig. 25a). This was a Hybrid low pattern that was classified to node 3, a common Colorado/Hybrid low class (Fig. 24). The final event #6 was a null-event and was associated with a grouping of two events that were separated by 6 hours (Fig. 25a). This event was identified to node 2 in the blizzard event SOM, a node commonly shared by Clippers, Fronts, and Hybrids (Fig. 24).

For the entire winter of 1996-1997, 10 blizzards were observed (Fig. 25b). The algorithm detected 9 of those events, only missing the 31 December 1996 blizzard event that was previously discussed (Fig. 18). Considering this type of event was omitted due to its rarity (as it did not fall in the common blizzard nodes in the climatology SOM), this should be expected. Besides the 9 documented blizzard events, 8 additional blizzard patterns were identified that were not associated with historical events. These are events that had the potential of becoming a blizzard, as indicated by the temperature and wind speed thresholds met, but did not produce a blizzard. Compared to the observed blizzard events during the 1996-1997 winter, these events have shorter durations while one still did produce a 21-hour event, and while most also generally affect a smaller percentage of the grid (Fig. 25b). The Probability of Detection (POD) for this winter resulted in a value of 0.90, with a False Alarm Ratio (FAR) of 0.47. These values are not surprising given the analysis performed.

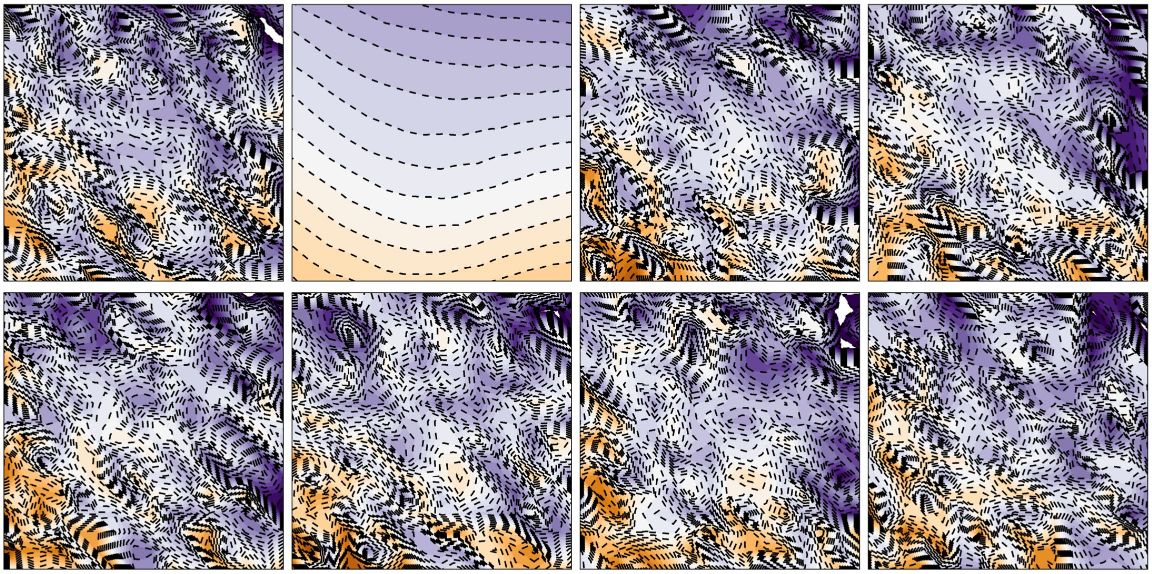


Figure 16. Example 4x2 (8-class) SOM displaying random initialization settings.

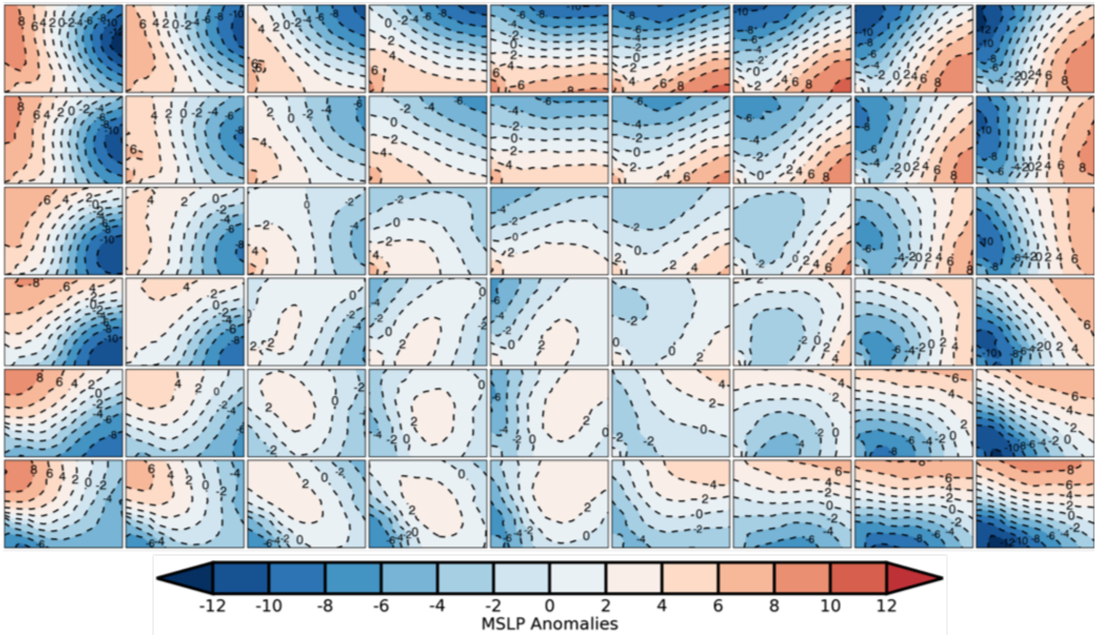


Figure 17. 9x6 (54-class) climatological SOM. Color-filled dashed black lines denote MSLP anomalies. Low (high) pressure is denoted with cool (warm) colors.

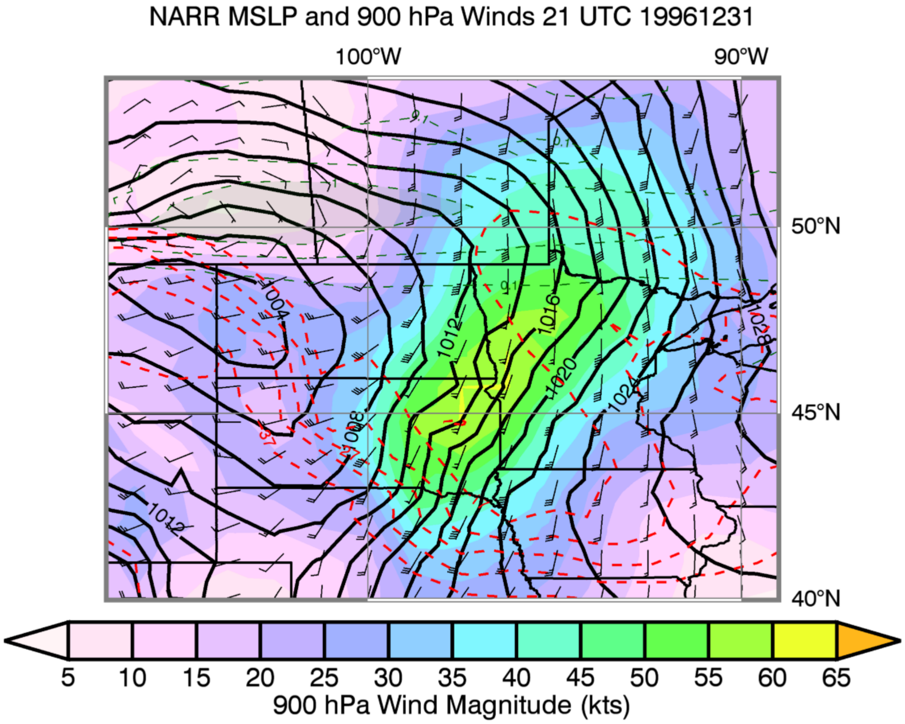
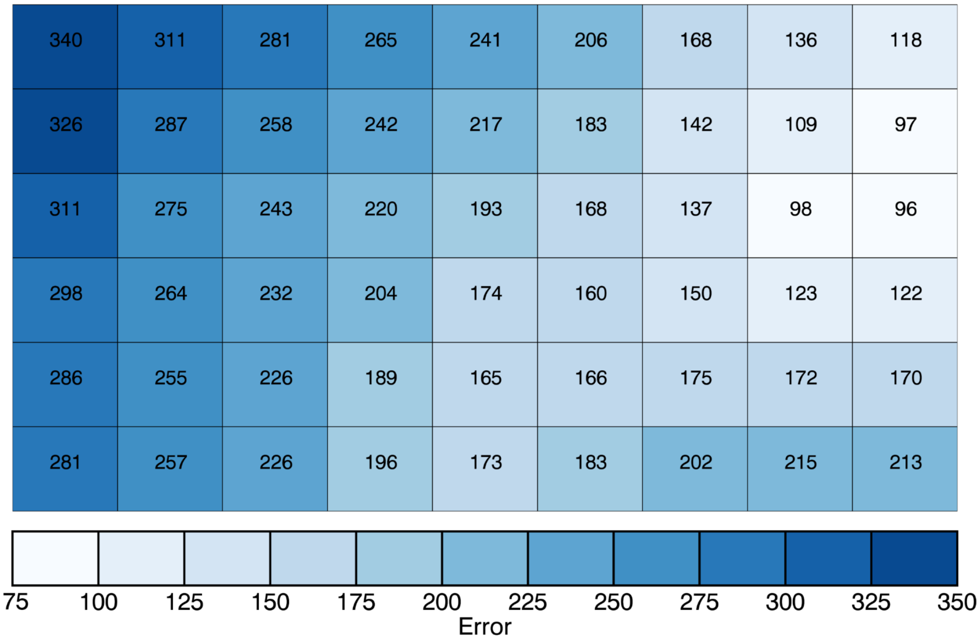
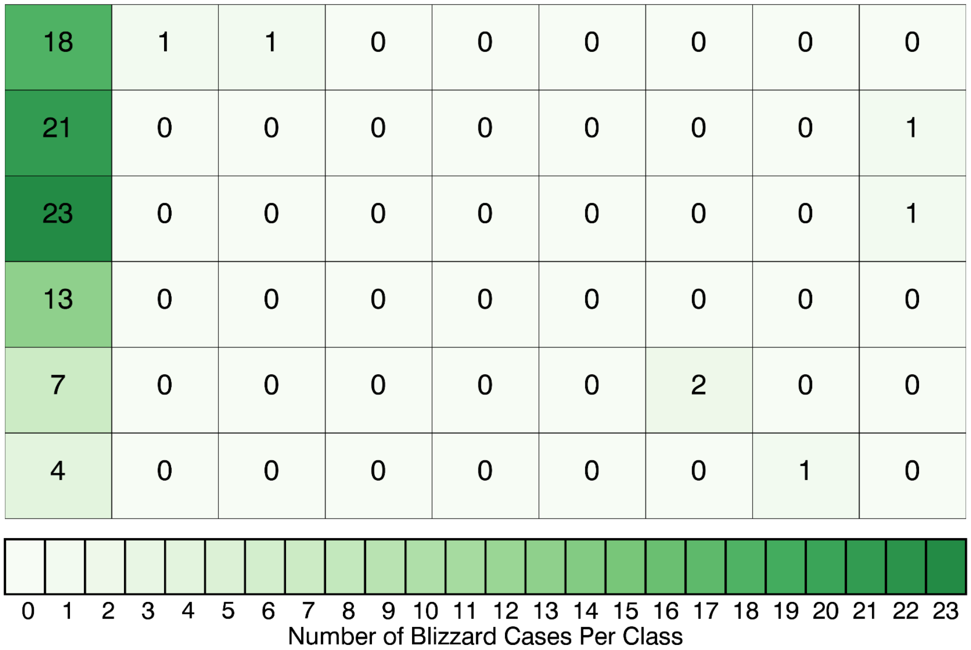


Figure 18. NARR analysis for 21 UTC on 31 December 1996. Solid black lines are MSLP (hPa), red dashed lines are surface temperatures (°F), dashed green lines are accumulated precipitation (mm) with regions shaded for values over 1 mm. Wind barbs are shown with wind speed contoured with shaded colors.



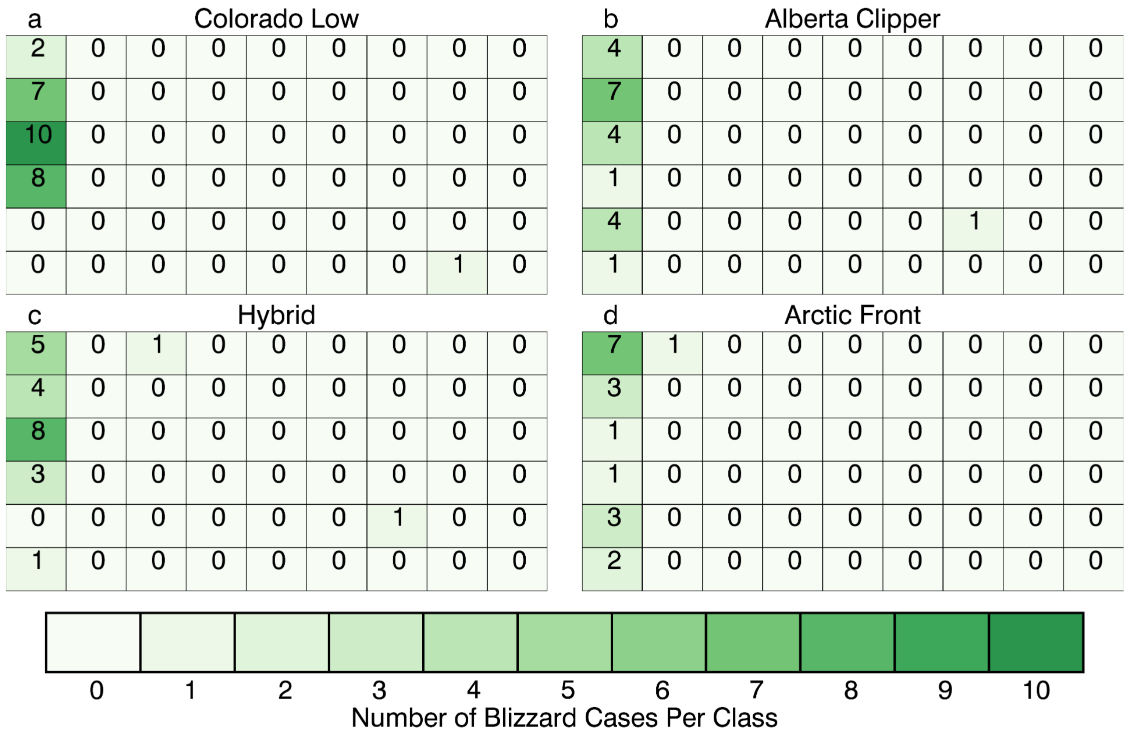
340	311	281	265	241	206	168	136	118
326	287	258	242	217	183	142	109	97
311	275	243	220	193	168	137	98	96
298	264	232	204	174	160	150	123	122
286	255	226	189	165	166	175	172	170
281	257	226	196	173	183	202	215	213

Figure 19. Euclidian distance between the climatological SOM and the 21 UTC 31 December 1996 event. Error values are unitless.



18	1	1	0	0	0	0	0	0
21	0	0	0	0	0	0	0	1
23	0	0	0	0	0	0	0	1
13	0	0	0	0	0	0	0	0
7	0	0	0	0	0	2	0	0
4	0	0	0	0	0	0	1	0

Figure 20. Blizzard case count for the 9x6 (54-class) climatological SOM.



a Colorado Low

2	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0

b Alberta Clipper

4	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
4	0	0	0	0	0	1	0	0
1	0	0	0	0	0	0	0	0

c Hybrid

5	0	1	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0
1	0	0	0	0	0	0	0	0

d Arctic Front

7	1	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0

Figure 21. Blizzard case count for a) Colorado Low, b) Alberta Clipper, c) Hybrid, and d) Arctic Front blizzards for the 9x6 (56-class) climatological SOM.

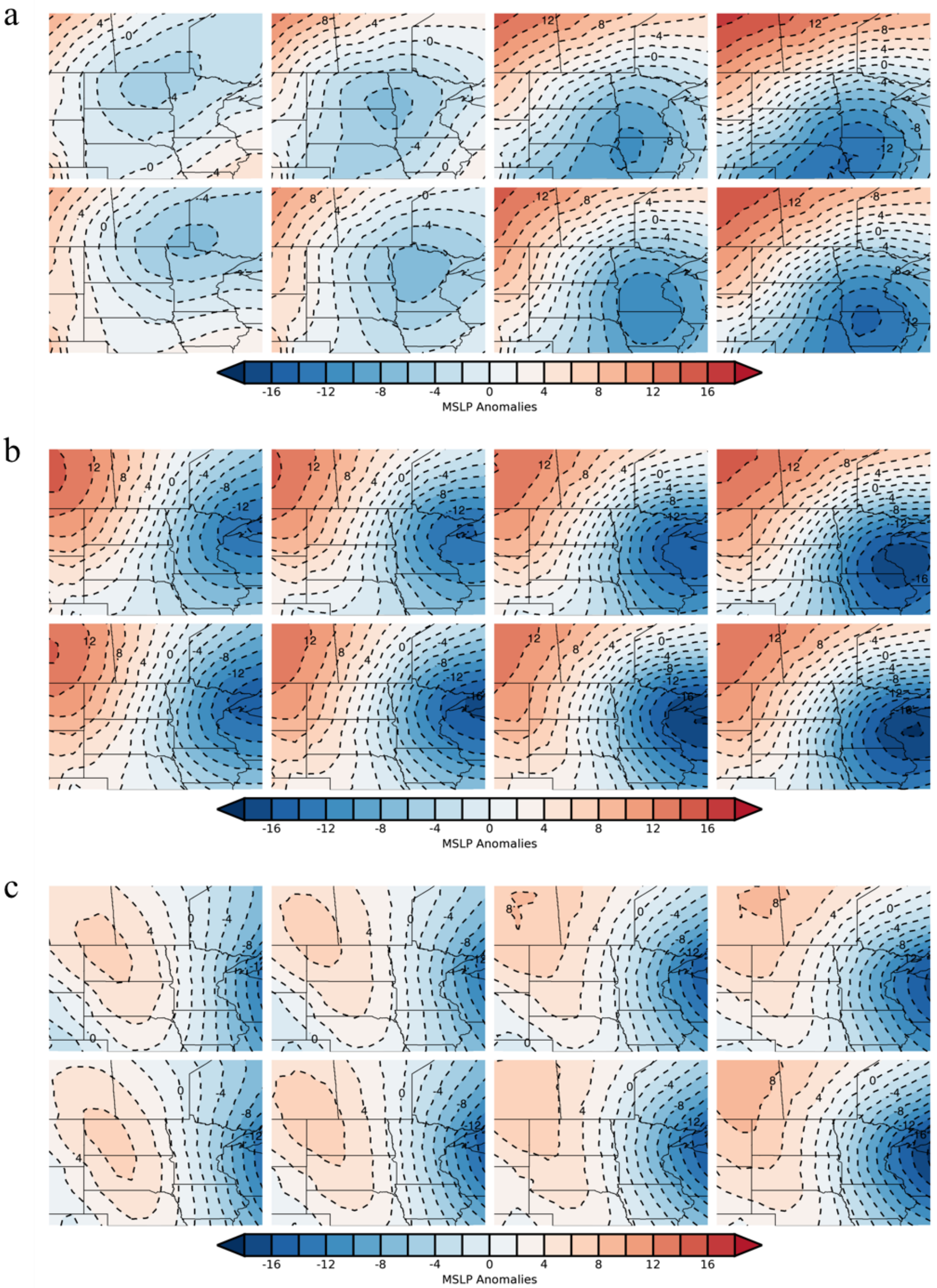


Figure 22. 4x2 (8-class) blizzard events SOM. Color-filled dashed black lines denote MSLP anomalies. a.) 12 – hours prior to middle time of blizzard, b.) middle time of blizzard occurrence, c.) 12 – Hours after middle time of blizzard

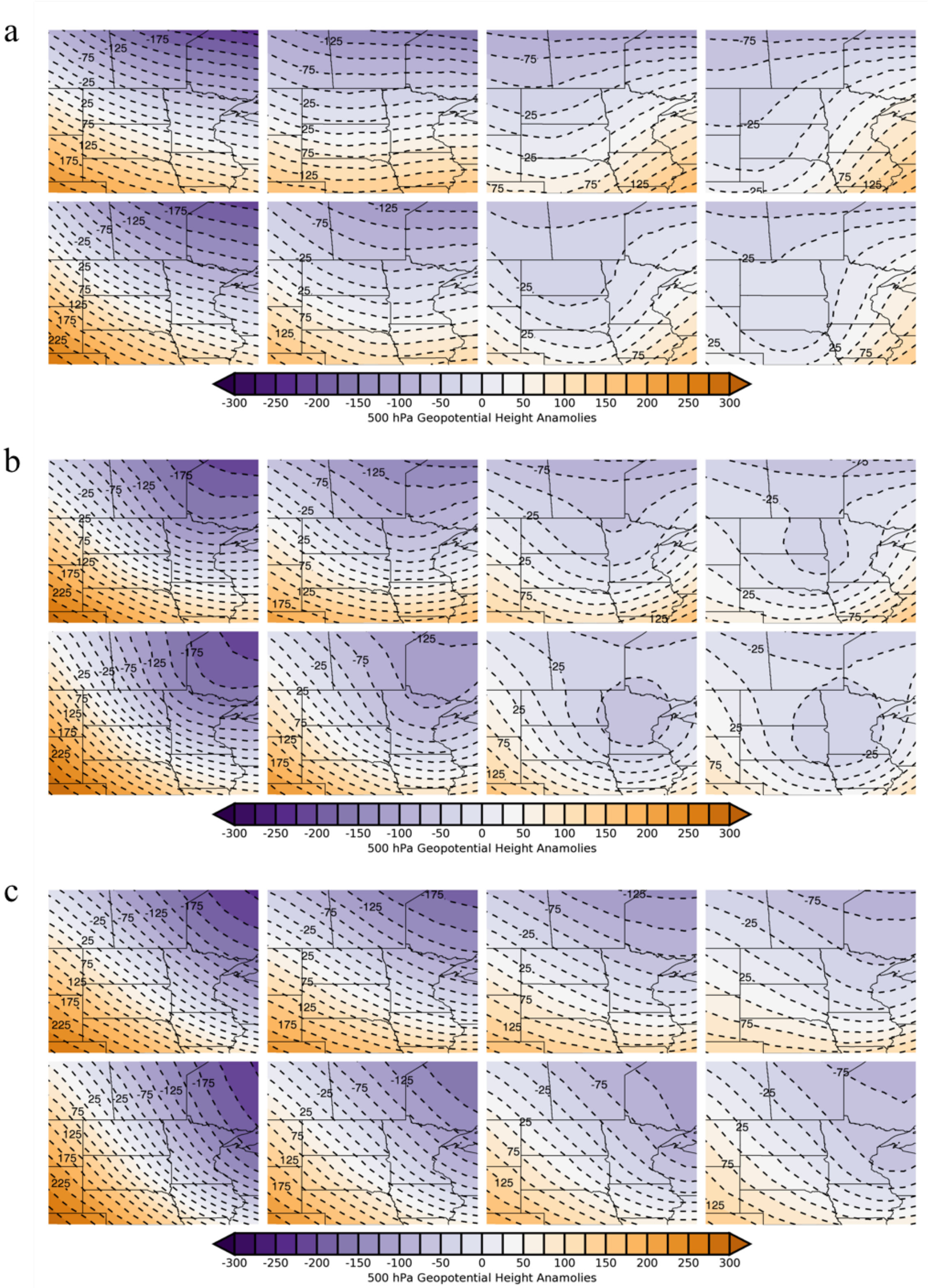
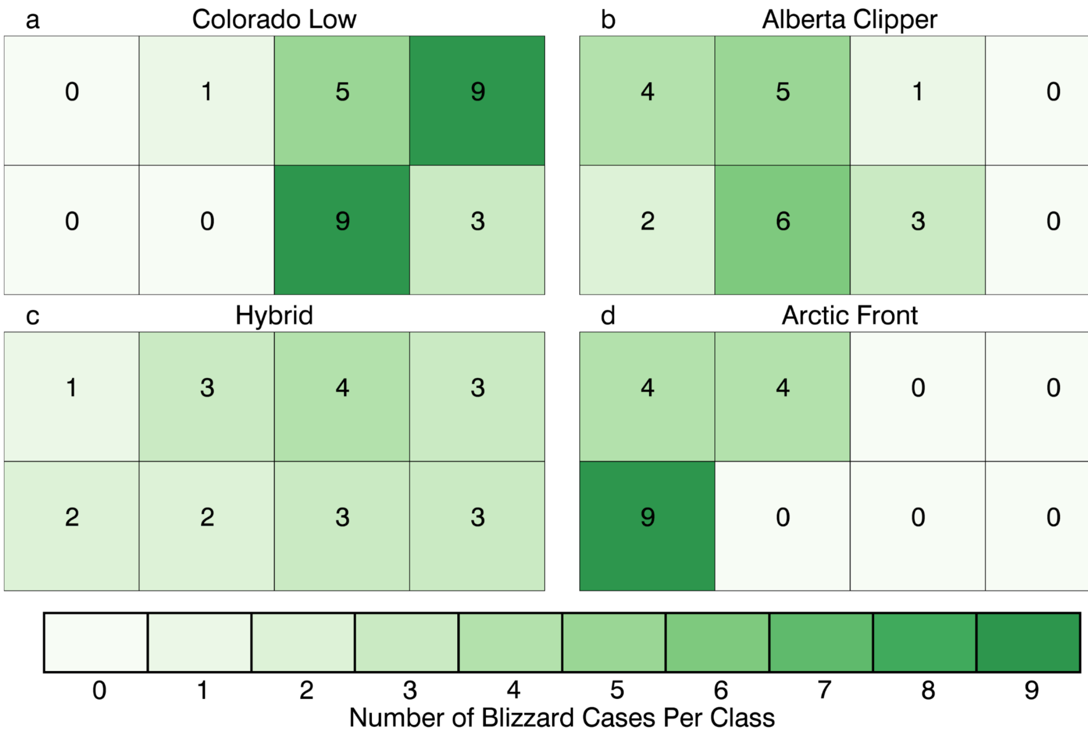


Figure 23. As in Fig. 22, but for 500 hPa geopotential height anomalies.


a Colorado Low

0	1	5	9
0	0	9	3

b Alberta Clipper

4	5	1	0
2	6	3	0

c Hybrid

1	3	4	3
2	2	3	3

d Arctic Front

4	4	0	0
9	0	0	0

Figure 24. Observed blizzard case count for the 4x2 (8-class) blizzard SOM. For reference, node 1 is top left, node 4 top right, node 5 bottom left, and node 8 is bottom right. (a – Colorado Low, b – Alberta Clipper, c – Hybrid, d – Arctic Front).

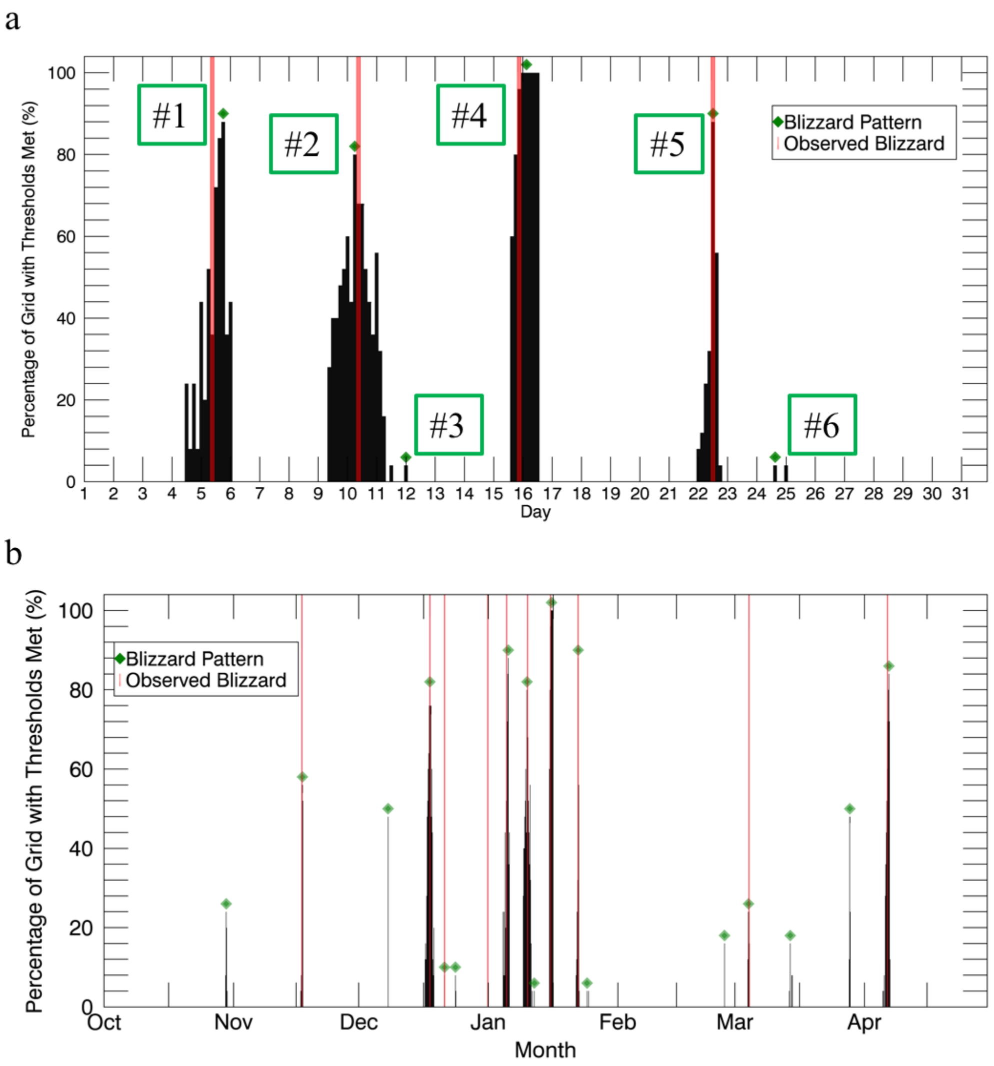


Figure 25. Blizzard pattern detection for the 1996-1997 winter. a) Month of January, b) for the entire Winter. Solid black lines represent events that were identified using the algorithm, and also denote the percentage of grid points with thresholds met. Green diamonds represent the time chosen to represent a blizzard event. Red lines denote observed blizzard events.

CHAPTER V

RESULTS – OBJECTIVELY IDENTIFED BLIZZARD PATTERNS IN NARR

Overview

In this chapter, the results of the objective blizzard classification algorithm are assessed for NARR. Algorithmic performance statistics are presented first, followed by a comparison to the climatology of historical blizzard events.

Verification of the Automated Identification of Blizzard Pattern Algorithm

Climatological properties of the algorithm are shown in Table 5. Throughout the 37-year period investigated, a total of 440 blizzard patterns were identified. 93 observed blizzards occurred during the same time period, which means that the algorithm found 4.7 times as many blizzard patterns as observed blizzards. The POD and FAR of the algorithm are 0.90, and 0.81, respectively. This means the algorithm properly detects the vast majority of known blizzards but also identifies a number of patterns that were not associated with reported blizzards. Generally, the overestimation of blizzard patterns and high FAR are expected; the methodology does not take land-surface conditions or precipitation into account.

Table 5. Characteristics of the blizzard pattern detection algorithm.

Observed Blizzards	Blizzards Detected	Blizzards Not Found	Blizzards Missed	Blizzard Patterns	False Alarms
93	84	7	2	440	356

Next, the algorithm’s ability to “identify” observed blizzards is investigated. A historical blizzard was “found” if it occurred within the time frame of algorithm-detected blizzard patterns. As Table 5 shows, of the 93 observed blizzards, the algorithm found 84 of them objectively, missing a total of 9 cases. Of these cases, seven blizzards were not detected because they were classified to nodes in the climatological SOM where fewer than three blizzards occurred. As a result, these climatologically rare patterns were discounted immediately. The other two cases that were missed did not have the two thresholds met at the same grid point in NARR inside the blizzard domain of interest. Analysis of these events revealed that this only occurred due to a mismatch in time of three hours between the subjectively and objectively classified events. Therefore, the algorithm technically found all of the climatologically significant blizzards that occurred in the past.

Climatology of Blizzard Patterns in NARR

The seasonal blizzard pattern climatology is compared to the observed climatology (Fig. 26a). It is important to note that general trends are assessed in this section rather than comparing actual values. Inspecting the monthly number of blizzards and blizzard patterns (Fig. 26a) reveals that the two climatologies match up nicely, showing similar variability throughout the winter season and subsequently having a correlation of 0.97. Both of the climatologies have very few blizzards and blizzard patterns in the transition months, while also exhibiting the maximum occurrences in January (Fig. 26a). The only month where the two differ is in March, where the number of blizzards stays the same but there is an increase in the blizzard patterns observed (Fig. 26a). The standard deviations (Fig. 26b) follow the same trend for both the number of blizzard and blizzard patterns. The standard deviations are largest for the month of January and smallest for the month of October, indicating that the algorithm has similar seasonal characteristics of variability.

As there was an observed decrease in blizzards during the second half of February (Fig. 6b), the ability of the blizzard pattern detection algorithm to capture this feature is examined. Investigating the bimonthly number of blizzards and blizzard patterns (Fig. 27a) reveals that the two climatologies line up nicely in the late fall and early spring weeks, but the peak of occurrences is shifted between the two, resulting in a correlation coefficient of 0.86. Observed blizzards peak in the second half of December, while the blizzard patterns only depict a local maximum there (Fig. 27a). Blizzard patterns then decrease before reaching the peak in the second half of January. The two climatologies both display a decrease later in the winter before picking up again in March, but this local minimum is shifted between the datasets. Blizzard patterns have a local minimum during the first two weeks of February while the dip for observed blizzards occurs during the second half of February (Fig. 27a). The standard deviations (Fig. 27b) largely follow the same trends that are present in the monthly number of blizzards and patterns, with higher variabilities in the weeks with more occurrences and lower variabilities in the weeks with fewer.

Historical blizzards and patterns were also explored from the perspective of annual totals (Fig. 28). The maximum number of blizzard patterns in a given year occurred during the 2013-2014 winter with a total of 22 events identified. This matched the observed maximum in this year (10), albeit with just over double the number of events. Another maximum occurred in the winter of 1996-1997, with 17 patterns identified vs. the 10 historical events documented (Fig. 28). The standard deviation for blizzards was calculated to be 2.32, while for the blizzard patterns it was 3.47. The larger variability is expected for the patterns since there are more blizzard patterns than observed blizzards. This is encouraging as it indicates the algorithm captures blizzard-pattern variability that is similar to what is observed. Overall, there was reasonable agreement between the two data sets, with a linear Pearson correlation coefficient of 0.66. Despite this agreement, some years had significant discrepancies. Two years that stand out as having significantly more blizzard patterns than blizzards include the winters of 1985 and 2008 (Fig. 28). Presumably, a major factor determining what fraction of patterns produce blizzards is land surface conditions. This warrants future investigation.

Provided that the blizzard event SOM created a continuum of patterns, subjective decisions have to be made when comparing patterns to subjectively identified blizzard types. Given that Colorado/Hybrid and Clipper/Front patterns largely fell on the right and left side of the SOM, respectively, these patterns were grouped together. Unlike observed events, the highest number of blizzard patterns are Clippers and Fronts (Fig. 29a). This implies that while there may be more of these patterns, the percentage of these events resulting in a blizzard is smaller than it is for the respective Colorado and Hybrid patterns. According to these results, 14.0% (34.8%) of the Clipper and Front (Colorado and Hybrid) patterns resulted in a reported blizzard.

Identified blizzard patterns were also investigated seasonally (Fig. 29b). In October, Clipper and Front patterns have a marginally higher occurrence than the Colorado and Hybrid patterns, with the roles being reversed in November (Fig. 29b). For December through February, the Clipper and Front patterns have a much higher occurrence than the Colorado and Hybrid patterns, with January being the month with the highest number of Clipper and Front patterns. In March, the Colorado and Hybrid patterns have their peak occurrence, while producing only slightly more events than the Clipper and Front patterns (Fig. 29b). For the last month of the winter season, Colorado and Hybrid patterns are the most common and occur much more frequently than the Clipper and Front patterns (Fig. 29b).

With the seasonal climatology established, the monthly ratio of blizzard occurrence for each type is now investigated. As mentioned previously, the land surface conditions are perhaps one of the larger determinants in whether blizzard patterns produce a blizzard. Table 6 shows that the highest likelihood occurs from December through February, which makes sense given the snowpack is generally highest during those months. October's perfect ratio for the Colorado and Hybrid patterns is only a result of the algorithm having found all of the patterns that caused those blizzards, of which there were very few. Looking at the other months in Table 6, January has the highest ratio for Colorado and Hybrid patterns resulting in a blizzard, while that occurs in February for the Clipper and Front patterns.

Table 6. Monthly ratio of observed blizzards to blizzard patterns.

Month	**Colorado and Hybrid**	**Clipper and Front**
October	1.00	0.00
November	0.21	0.06
December	0.43	0.12
January	0.54	0.18
February	0.23	0.21
March	0.27	0.09
April	0.36	0.00

The results presented in this chapter indicate that the blizzard pattern algorithm does quite well in capturing the observed blizzard climatology using NARR. Despite high bias and large FAR due to the conservative detection thresholds, the algorithm captures the seasonal variability of blizzards nicely, especially on a monthly timescale (Fig. 26a). On an annual scale, the over detection of events is also seen, but this is expected as land surface conditions were not taken into account. Finally, utilization of the blizzard SOM to distinguish types of patterns proves to be useful, as doing so captures some of the variability observed between the known blizzard. In conclusion, these results suggest that the algorithm can be used to detect blizzard patterns in alternative datasets such as climate model output.

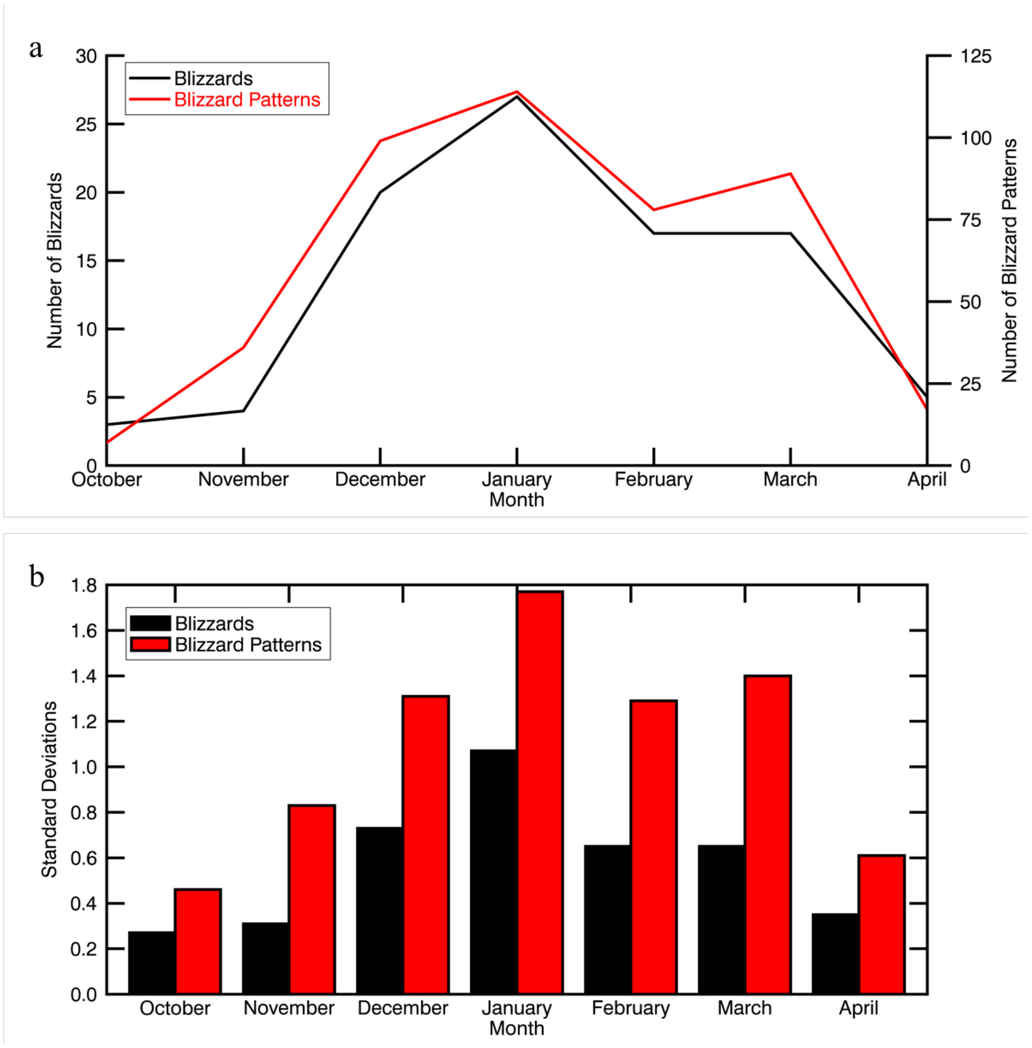


Figure 26. Monthly climatology of blizzards and blizzard patterns for (a) total events, and (b) standard deviations from the mean. The different y-axes should be noted in panel (a).

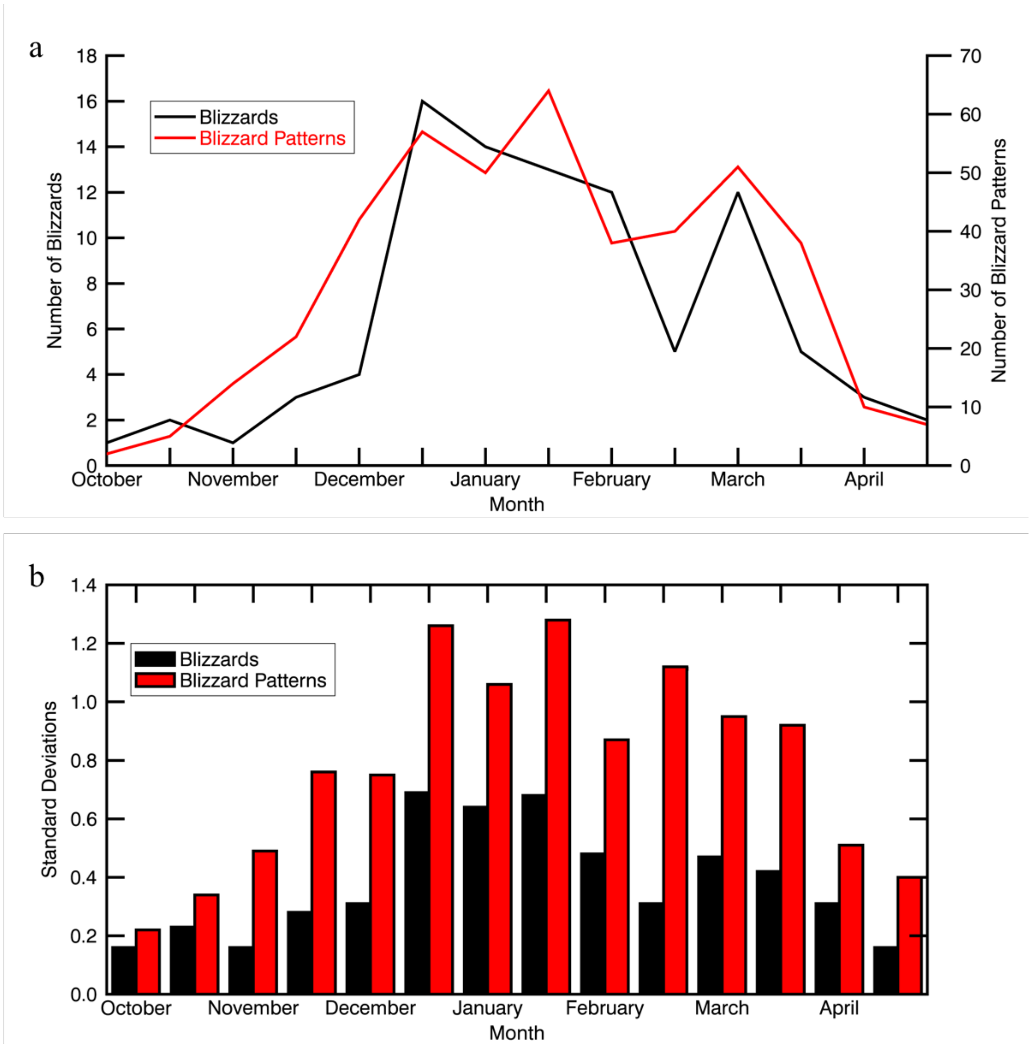


Figure 27. Bimonthly climatology of blizzards and blizzard patterns for (a) total events, and (b) standard deviations from the mean.

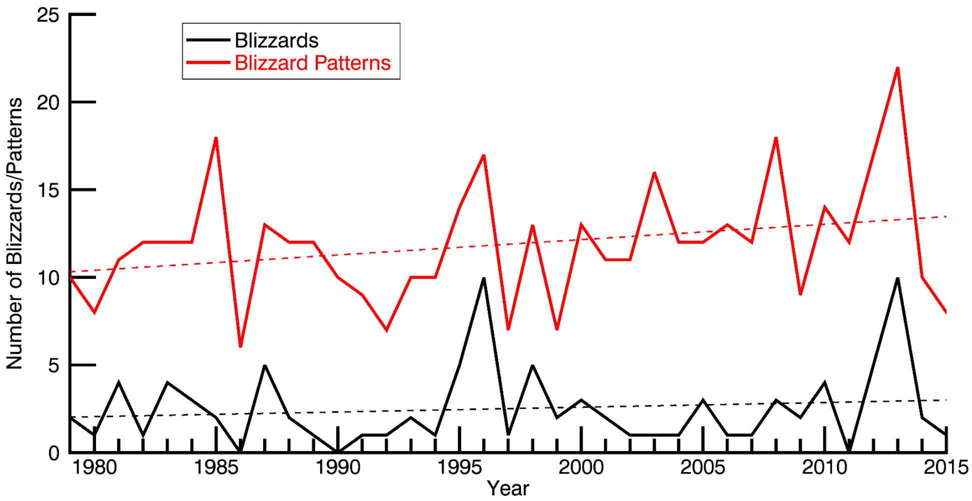


Figure 28. Annual climatology of blizzards and blizzard patterns.

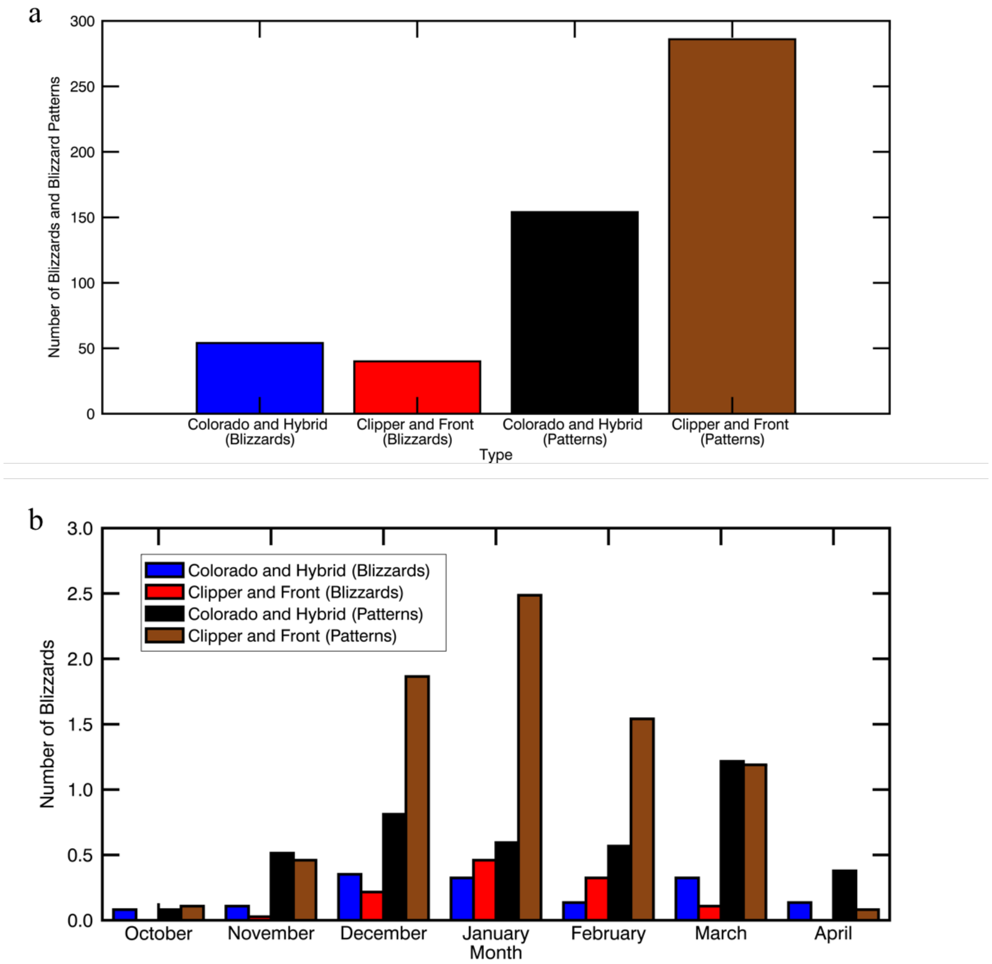


Figure 29. Total number of observed blizzards and blizzard patterns by type (a), and segregated by month (b).

CHAPTER VI

RESULTS – BLIZZARD PATTERNS IN CESM

Overview

The results of objective blizzard pattern detection in CESM are discussed in this chapter. First, historical results from NARR and CESM are compared to understand how capable this model is in reproducing the historical climatology of blizzard events. The occurrence of blizzard patterns in the future is then investigated using two RCP scenarios used to force CESM. These results are compared to historical blizzard events to understand how blizzard patterns may change in the future.

Historical Blizzard Events in CESM and NARR

The results from the previous chapter demonstrate confidence in the algorithm to objectively identify blizzard patterns in NARR that share many characteristics with the NGP blizzard climatology. With this in mind, the algorithm is applied to CESM to determine how well the climate model reproduces the historical climatology of blizzard patterns. As mentioned in Chapter 2, the results from the two datasets cannot be directly compared on a year to year basis. Instead, the historical simulation from CESM is investigated from the perspective of general characteristics such as frequency of occurrence, variability, and trend over the most recent 37-year period.

The average number of blizzards patterns per month is first compared to NARR (Fig. 30a). Overall, NARR has an average of 11.9 blizzard patterns per year, while the

CESM has an average of 13.8 blizzard patterns per year, a 16% relative bias. The seasonal climatology demonstrates that the CESM has this positive bias for all months except March. Another notable characteristic is the lack of a February minimum. Instead, blizzard patterns peak in January then decrease during the second half of the winter months. Breaking down blizzard patterns by year, the CESM has increased likelihood of active years with two-three times as many patterns identified for the right-tail of the distribution (Fig. 31). This results in a negative bias of patterns for the 5-9 patterns per year bin.

Breaking apart the seasonal climatology into known blizzard types, the CESM has biases towards specific patterns (Fig. 30b). Clipper and Front patterns have a positive bias in every month, with the largest bias (6.2 patterns/decade) occurring in February. CESM has a negative bias for Colorado and Hybrid patterns in October, November, and March, and a positive bias in the remaining months (Fig. 30b). The largest positive bias for the Colorado and Hybrid patterns also occur in February (4.6 patterns/decade), with the most negative bias occurring in March (1.3 patterns/decade) (Fig. 30b).

Other characteristics of blizzards such as the duration and area coverage were also investigated (Table 7, Fig. 32). Durations demonstrate CESM has a tendency to produce events that last longer than the NARR (Fig. 32a). Mean values for duration reveal a 3.5-hour increase, which is 26% longer than patterns found in NARR (Table 7). Whereas NARR has 47% of cases lasting less than 12 hours, only 26% are of this duration in the CESM (Fig. 32a). That said, one issue with this comparison is the time steps provided by the datasets. In NARR, 48% of the patterns in the lowest bin are 3-hour events, which cannot occur in CESM since it had 6-hour time steps. Despite this issue, blizzard patterns that last more than 24 hours are also overestimated by the CESM, as shown by higher percentages found for the remaining durations (Fig. 32a). While it is not shown, the CESM did produce one event that lasted longer than 72 hours. Inspection of this event revealed this was an artifact of allowing for a 6-hour gap between events. The algorithm continued to find times when blizzard thresholds were met with lulls in between, creating an event that lasted (unrealistically) 102 hours.

Besides having increased durations, blizzards in the CESM also covered larger areas than NARR (Fig. 32b). On average, the CESM produces blizzard patterns that cover 12% more of the grid than NARR, an increase of 29% (Table 7). These impacts were greater for larger area events. For example, 29% of CESM patterns affected 84-100% of the grid, whereas only 15% of NARR impacted this area (Fig. 32b). This property leads to a smaller fraction of patterns that impact small areas of the domain.

Causes of Biases in CESM

CESM was examined to understand why blizzards were more frequent, longer in duration, and larger in size. Errors may be caused by differences in the frequency of occurrence of blizzard patterns or biases in variables used for thresholds. Use of the climatological SOM indicated that the NARR (CESM) had 10.0% (11%) of all MSLP patterns classified into the climatologically relevant blizzard nodes (the first requirement of the algorithm). This means that part of the bias in pattern frequency is due to CESM having a 10% more MSLP patterns associated with blizzard events. As the climatology of temperatures show, the CESM does not produce significantly colder months when compared to NARR (Fig. 33a). However, the climatology of wind speeds (Fig. 33b) do show that the CESM has a 2.3 knot positive bias, with all of the months having higher median and maximum wind speeds than NARR.

Table 7. Mean (median) values for characteristics of blizzard patterns

	2-m Air Temperature (℃)	**900 hPa Wind Speed (knots)**	**Percentage of Area Affected**	**Duration (hours)**
CESM HIST	-16.6 (-16.1)	42.5 (41.6)	54.8 (56.0)	16.6 (12.0)
NARR	-13.9 (-13.3)	40.0 (39.5)	42.4 (36.0)	13.3 (12.0)

Biases also exist for the subset of blizzard events (Table 7). The mean maximum wind speed for blizzard events in NARR is 40.0 knots while in the CESM it is 42.5 knots, revealing the wind bias carries over to blizzard events. While the temperature ranges are similar between the two, the mean temperature during blizzard events in NARR is -13.9 ℃ while in the CESM it is -16.6℃ (Table 7). Overall, these biases suggest that there is a higher likelihood of any given event being able to reach the blizzard wind and temperature thresholds. This also helps explain why the CESM has a higher occurrence of blizzard patterns than NARR.

Blizzard Climatology: CESM Future Emissions Scenarios

With the caveats known about historical blizzard patterns in CESM, future emissions scenarios can now be investigated to determine how things may change in the future. The decadal number of blizzards in NARR and the various CESM simulations is shown in Figure 34. As was observed previously, the CESM historical simulation overestimates the number of blizzard patterns relative to NARR even on decadal timescales (Fig. 31). Over historical periods, an increase in blizzard patterns is seen in both NARR and CESM. This feature also includes matching of interdecadal variability such as the local minima during 1990-1999 (Fig. 34). Compared to the historical simulation, there is more interdecadal variability observed for RCP4.5 and RCP8.5, and this results in the two scenarios alternating for the highest decadal average of blizzard patterns per year throughout the whole period (Fig. 34). The observed interdecadal variability suggests there could be a minor increase in blizzard patterns before an overall decrease occurs, as seen for the 2020-2029 period in RCP8.5, which has the largest mean number of blizzards (14.6 patterns per year).

Comparing the median values in Table 8, RCP4.5 shows a steady decline in the number of future blizzard patterns when compared to the historical simulation. While also showing a decreasing trend, RCP8.5 shows a larger decrease by the second thirty-year period which stays the same for the third thirty-year period. Comparing the first thirty-year period to the last in the future simulations, RCP4.5 (RCP8.5) has a median number of 12.5 (13.0) at the beginning and the at the end of the simulation runs the median number is 11.0 (11.0), resulting in a decrease of 1.5 (2.0) blizzard patterns per year by the 2070-2099 period.

Table 8. Mean (median) values for number of blizzard patterns per year for thirty-year periods.

	1975-2004	**2010-39**		**2040-69**		**2070-99**	
	HIST	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Number of blizzard Patterns	14.3 (14.0)	13.0 (12.5)	13.4 (13.0)	11.6 (12.0)	12.0 (11.0)	11.7 (11.0)	10.9 (11.0)

Normalized histograms segregated by thirty-year periods also show the decreasing number of blizzard patterns (Fig. 35). RCP4.5 shows a shift towards the lower number of occurrences per year, demonstrated by having a higher percentage of patterns producing 5-14 patterns per year vs. those associated with 15+ per year (Fig. 35a). CESM RCP8.5 shows a similar shift towards the lower occurrences per year, almost doubling the occurrences of 5-9 patterns per year when compared to RCP4.5 (Fig. 35b). RCP8.5 no longer produces more than 20 blizzard patterns per year (Fig. 35b), and RCP4.5 does the same after 2040 (Fig. 35a).

The seasonal distribution of blizzard patterns is now compared for thirty-year periods (Figure 36). In both scenarios, the decrease in blizzard patterns seen on a yearly scale is distributed variably across all months. Despite decreases in total blizzard patterns, RCP4.5 surpasses the historical period for November, January, and March in the 2010-2039 period (Fig. 36a). For the remainder of the times, only the period from 2070-2099 surpasses the historical period in March, with the rest having fewer occurrences (Fig. 36a). In RCP8.5, only the time period from 2010-2039 has a higher occurrence when compared to the historical period, which occurs in February and March (Fig. 36b). In both simulations, there is a distinct shift in peak blizzard patterns from January into February starting in the 2040-2069 period for RCP4.5 (Fig. 36a) and for all periods in RCP8.5 (Fig. 36b). For 2040-2069, the distribution of blizzards in both scenarios is bimodal with a local maximum in December and a peak in February (Fig. 36). There is also a notable reduction in blizzard patterns that occurs during the early and late winter months, with RCP8.5 showing a greater reduction than observed in RCP4.5 (Fig. 36).

Changes in blizzard patterns by pattern type reveal that the decrease in blizzard patterns is closely shared amongst the two pattern types (Fig. 37). The outlier occurs in RCP8.5 for the 2070-2099 period, where the Clipper and Front patterns have a decrease of more than twice that of Colorado and Hybrid patterns (Fig. 37b). Otherwise, both scenarios display that the smallest decrease for pattern types occur during the 2010-2039 period, and more than double the decrease going into the 2040-2069 period before largely levelling off for the last period (Fig. 37).

Characteristics of Future Blizzard Patterns

With the future climatology of blizzard patterns in the CESM established, characteristics of these events are now examined. Comparing the durations found in the historical period to all three periods in RCP4.5 and RCP 8.5, it is observed that duration distributions remains largely the same (Fig. 38). There is a small increase in the number of events that are 12-hours long or less, taken largely from the events that are 18-24 hours long (Fig. 38). Interestingly, both scenarios depict a 1-2% increase in events that last 66-72 hours long (Fig. 38), and both also have one event per decade that lasts longer than 72 hours. As depicted in Table 9, there is a slight increase in mean durations from 16.9 hours in the historical simulation to the 17-hour range throughout all the future scenarios.

Table 9. Mean (median) values of blizzard pattern characteristics segregated by thirty-year periods.

	Temperature (℃)		**Wind Speed (kts)**		**Area (%)**		**Duration (hrs)**	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
1975-2004	-16.6 (-16.2)	-16.6 (-16.2)	42.3 (41.5)	42.3 (41.5)	54.2 (56.0)	54.2 (56.0)	16.9 (12.0)	16.9 (12.0)
2010-2039	-15.5 (-14.7)	-14.4 (-13.0)	41.2 (40.3)	42.3 (21.7)	50.8 (46.0)	56.0 (56.0)	17.3 (12.0)	17.8 (12.0)
2040-2069	-14.1 (-13.2)	-14.5 (14.2)	41.9 (41.0)	41.2 (40.3)	54.8 (52.0)	50.0 (48.0)	17.1 (12.0)	17.1 (12.0)
2070-2099	-13.0 (-12.3)	-10.2 (-9.4)	41.2 (40.8)	41.8 (40.8)	51.2 (48.0)	50.0 (44.0)	17.0 (12.0)	17.5 (12.0)

As another indicator of strength, areas impacted by blizzard patterns are compared (Fig. 36, Table 9). Overall, mean values decrease 3-4% for the two projections (Table 9). Only minor variations exist in distributions for RCP4.5 for the periods 2010-2039 and 2040-2069 (Fig. 39a). Interestingly, there is an increase for 2010-2039 for the largest bin in RCP8.5 that creates a slightly more bimodal distribution (Fig. 39b). For the other two periods, this disappears and the clear shift is towards smaller blizzards.

Future projections also show changes in meteorological properties associated with blizzard patterns. Mean temperature values in Table 9 show a shift towards higher temperatures, starting at -16.6 ℃ and increasing to -13.0 ℃ in RCP4.5 and -10.2 ℃ in RCP8.5 for the final period. Minimum temperature distributions associated with the events also show an increase in median values for both RCP4.5 and 8.5 as periods further in the future are reached. Although there is a consistent warming of blizzards, individual events can still occur at low temperatures. For example, there is an increase in events in the coldest temperature ranges (-45 ℃ to -36 ℃, Fig. 40a) for RCP4.5, while the same occurs in RCP8.5 but for slightly higher temperatures (-35 ℃ to -31 ℃, Fig. 40b). Overall, there is a distinct warmer shift for both scenarios. The highest percentage of patterns for the historical simulation is in the -25 ℃ bin and this increases to -15 ℃ for the final period (2070-99) in RCP4.5 (Fig. 40a). In RCP8.5 this shift is even more pronounced, with 26% of the blizzard patterns occurring within the -15 and -5°C bins- (Fig. 40b).

The last parameter investigated is maximum 900 hPa wind speeds (Fig. 41, Table 9). Mean wind speed values reveal little change in future scenarios (Table 9). Neither of them have an increase over the historical run. The largest decrease is from 42.3 knots in the historical run to 41.2 knots, which occurred from 2040-2069 in RCP 8.5 (Table 9). Wind speed distributions associated with blizzard pattern events reveal bin to bin variability in both future scenarios (Fig. 41). The wind speeds in RCP4.5 have a shift towards the 35-40 kt bins, with small decreases observed for the higher 50+ kt bins (Fig. 41a). RCP8.5 shows similar properties but has a maximum for the 40-knot bin (Fig. 41b). The number of events in the 60 kt bin increases in RCP8.5 from 2070-2099, but only 1% of the patterns occur in this range making results statistically insignificant (Fig. 41).

Overall, wind speed distributions do not reveal a noticeable shift in wind speeds associated with blizzard patterns.

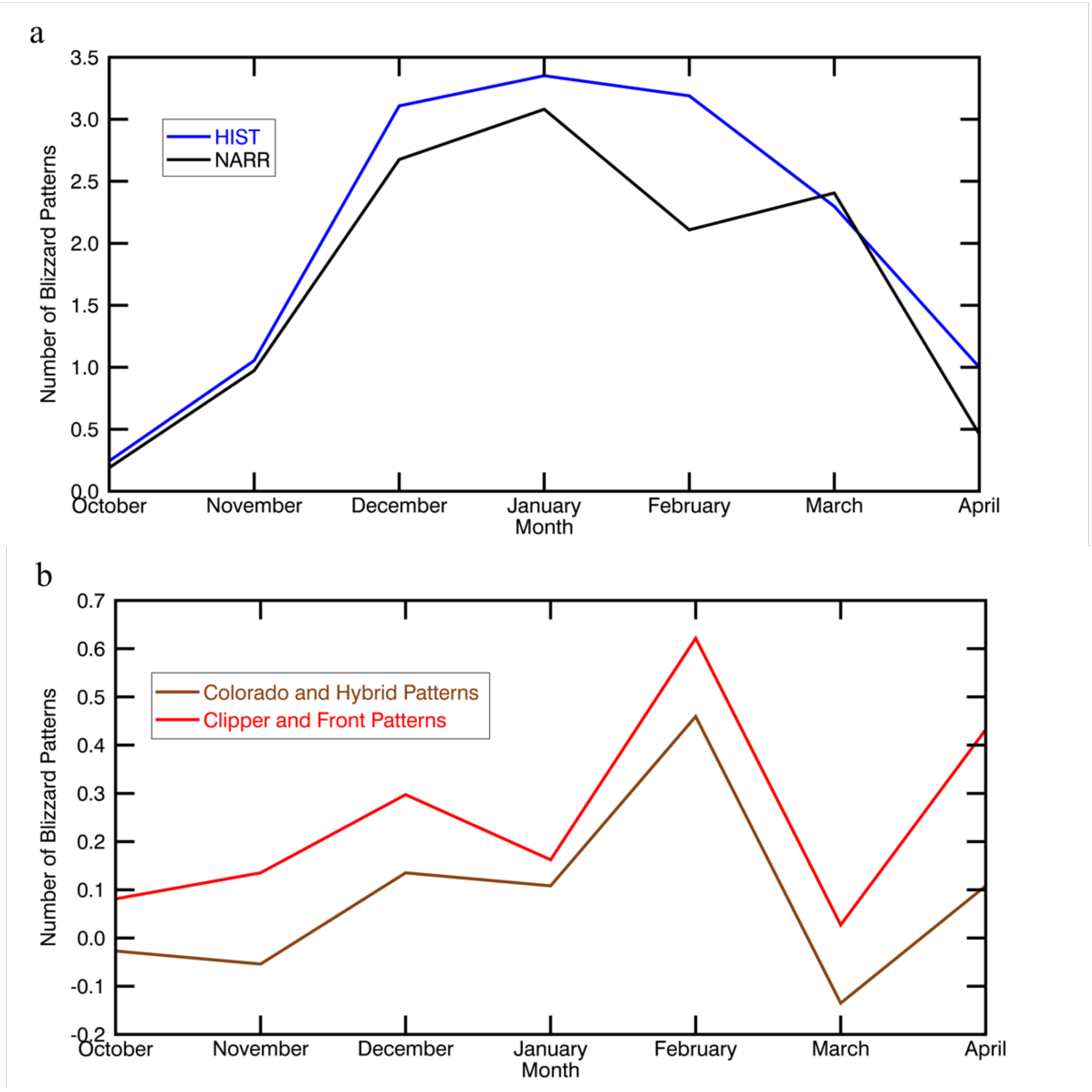


Figure 30. Seasonal climatology of blizzard (a) for NARR and CESM-HIST, and (b) CESM-HIST bias for Colorado and Hybrid, as well as Clipper and Front Patterns.

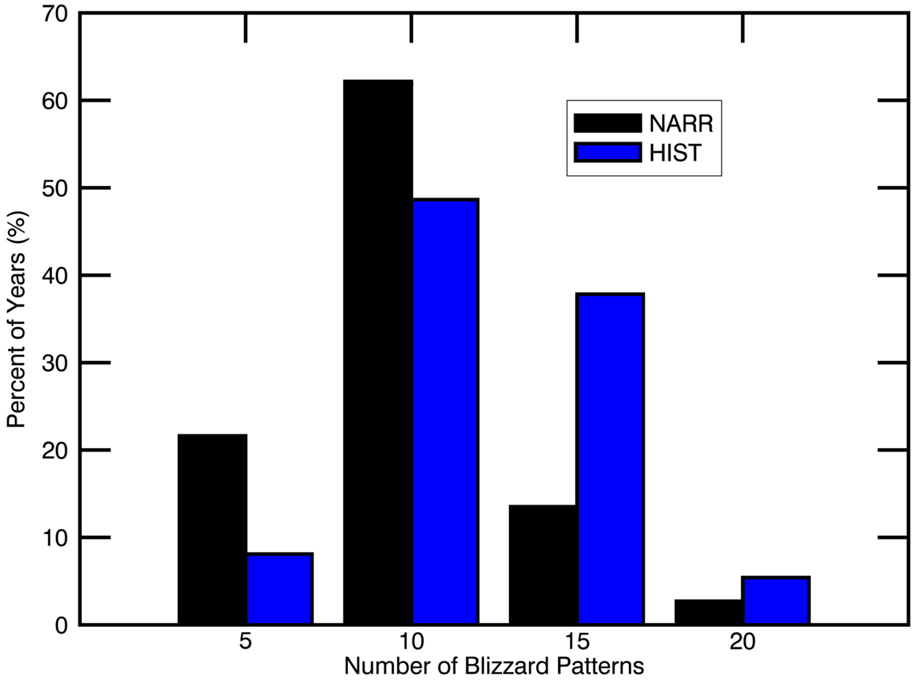


Figure 31. Normalized histogram of annual blizzard count in NARR and CESM-HIST.

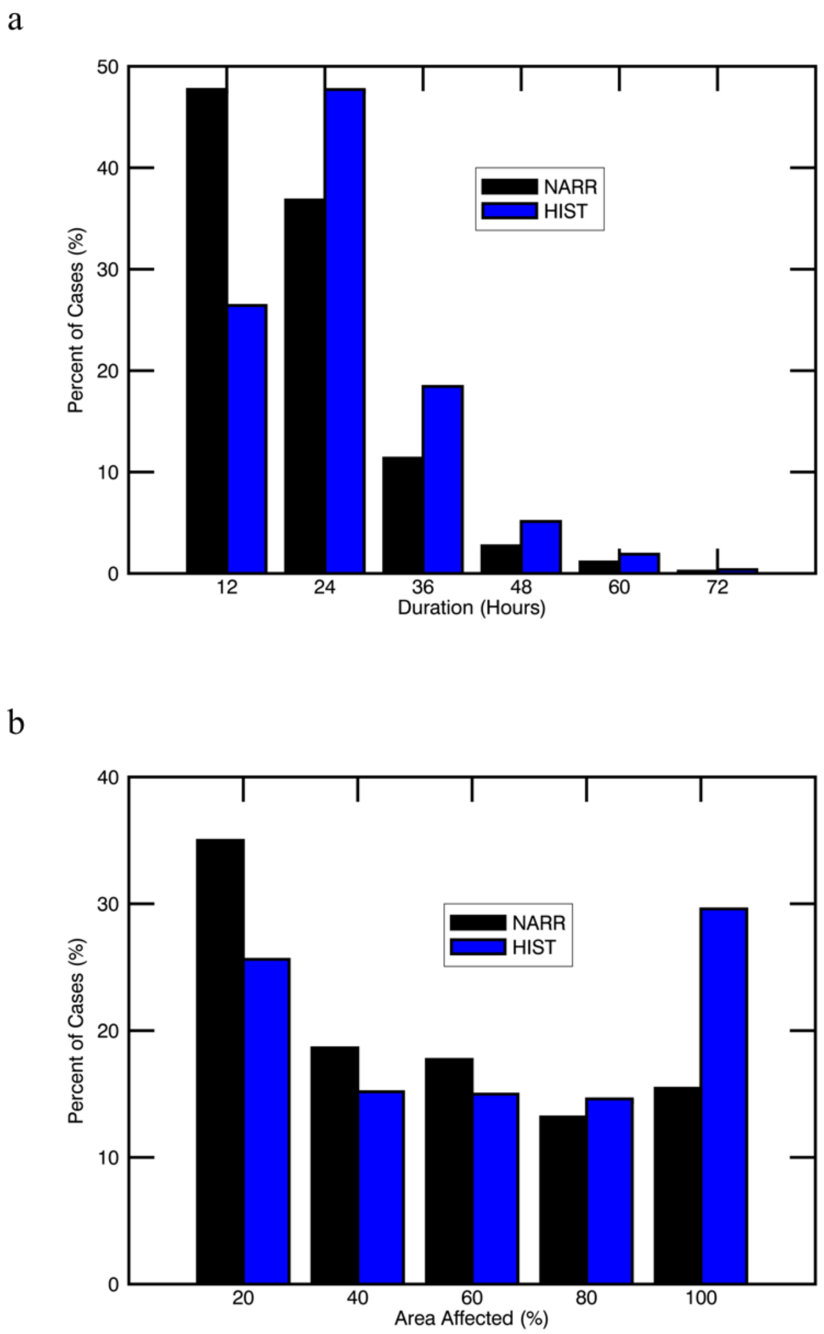


Figure 32. Normalized histograms of blizzard (a) duration and (b) area affected for NARR and CESM-HIST.

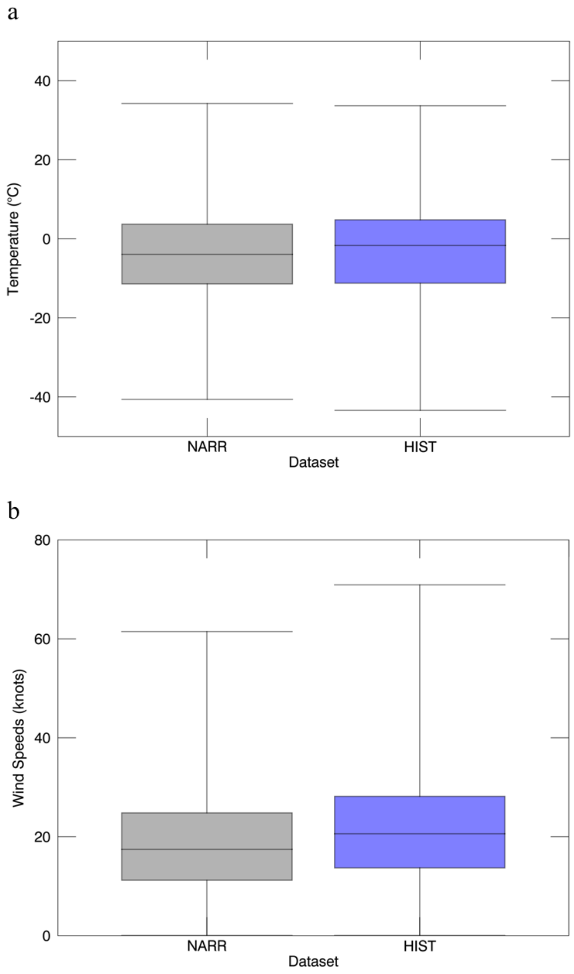


Figure 33. Boxplots of NARR and CESM-HIST for wintertime (a) temperatures, and (b) 900 hPa wind speeds.

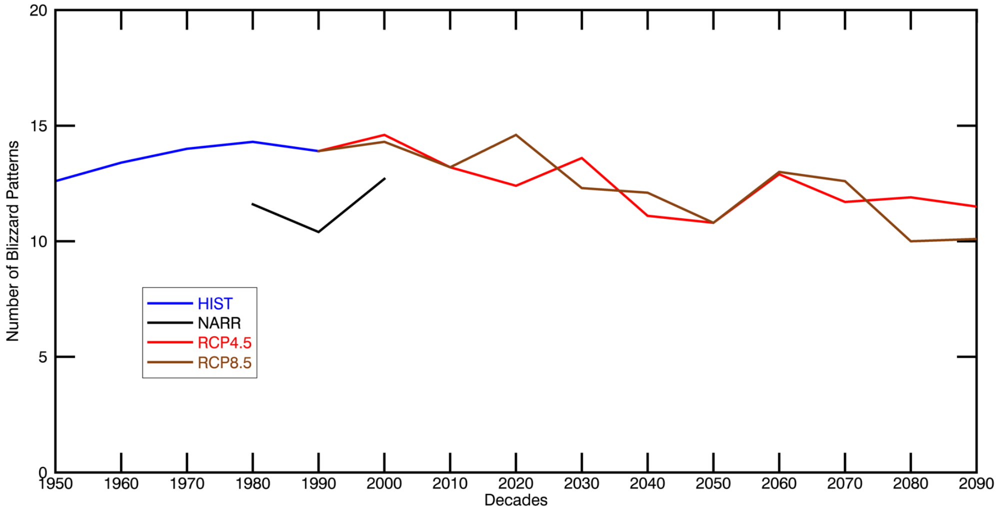


Figure 34. Mean number of annual blizzard patterns per decade.

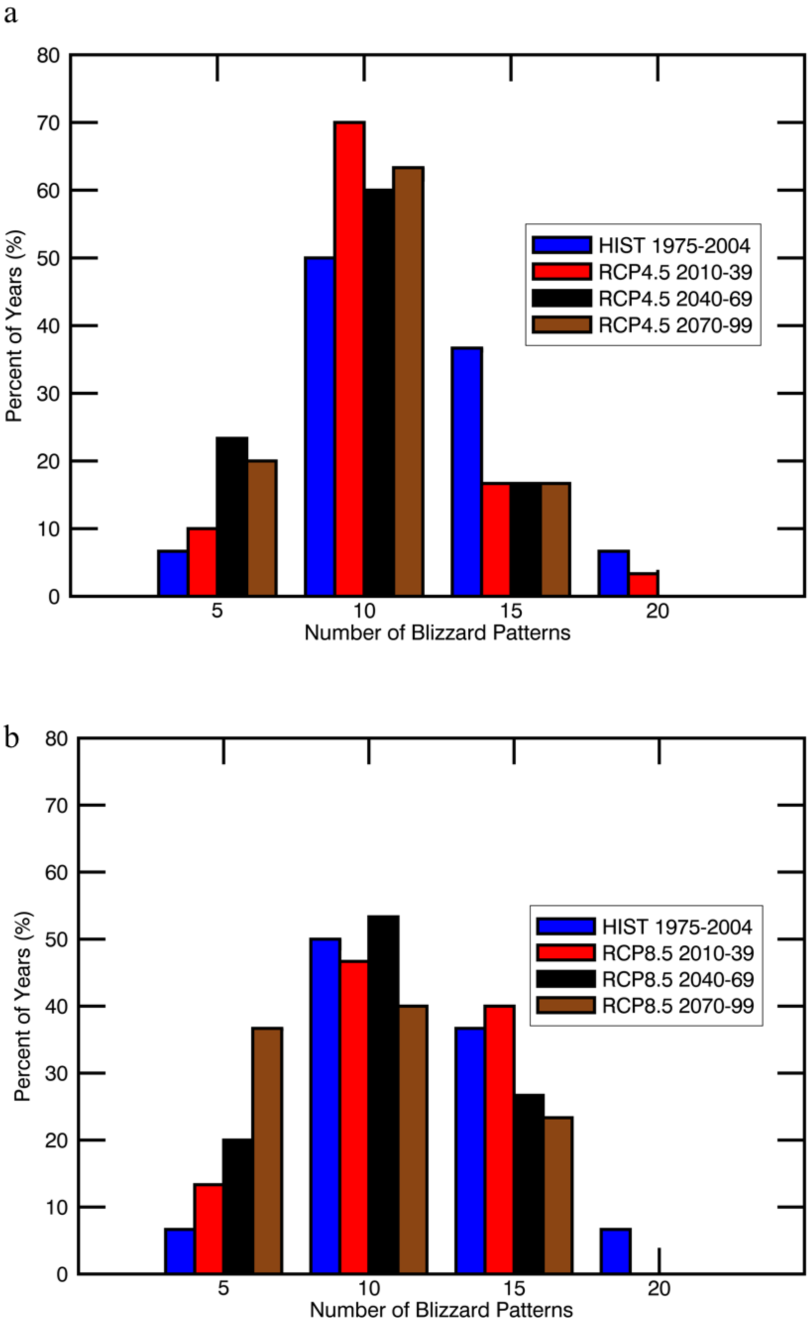


Figure 35. Normalized histograms of annual number of blizzard patterns for (a) RCP4.5 and (b) RCP8.5.

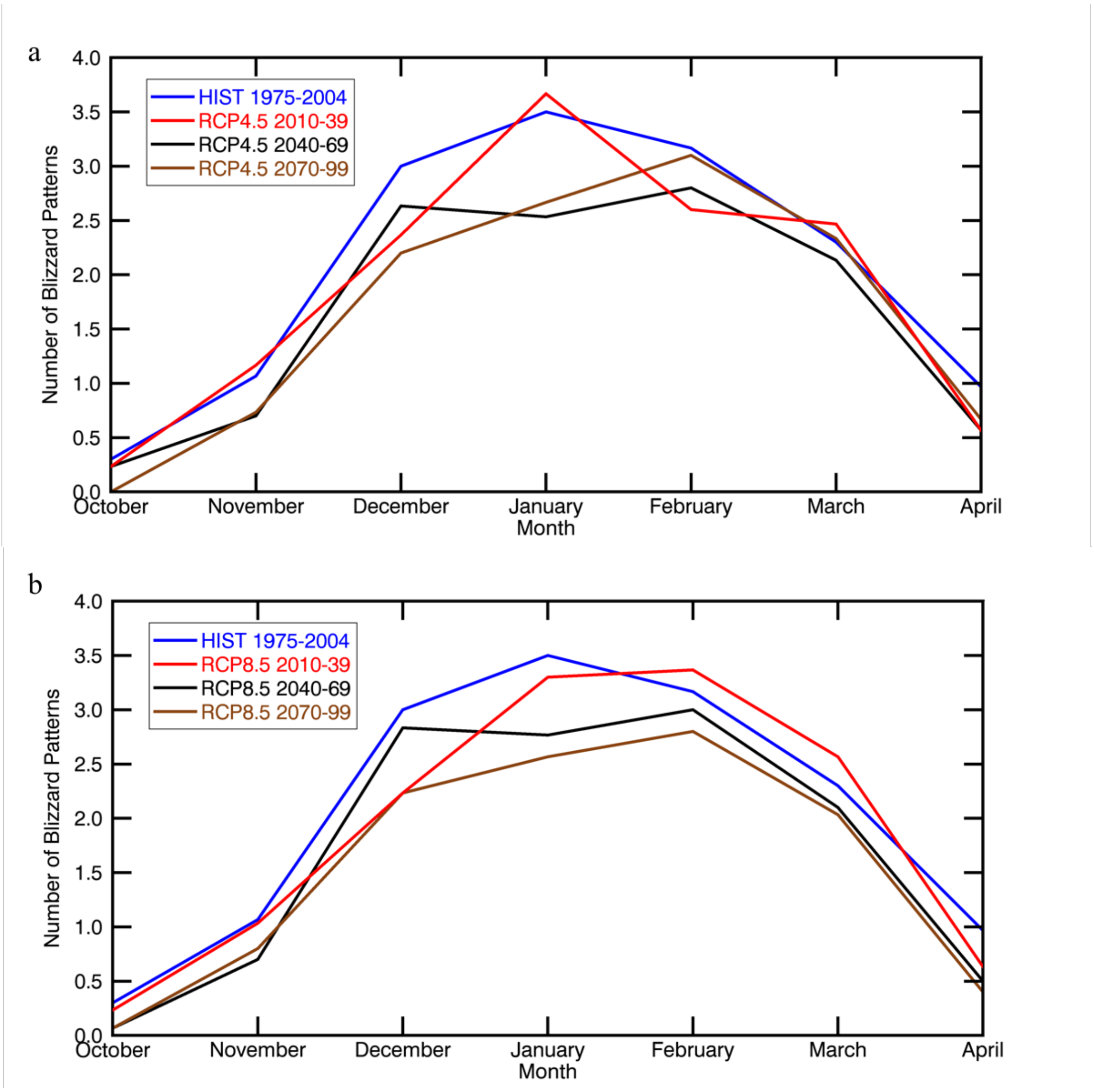


Figure 36. Seasonal climatology of blizzard patterns for historical and (a) RCP4.5 and (b) RCP8.5 simulations.

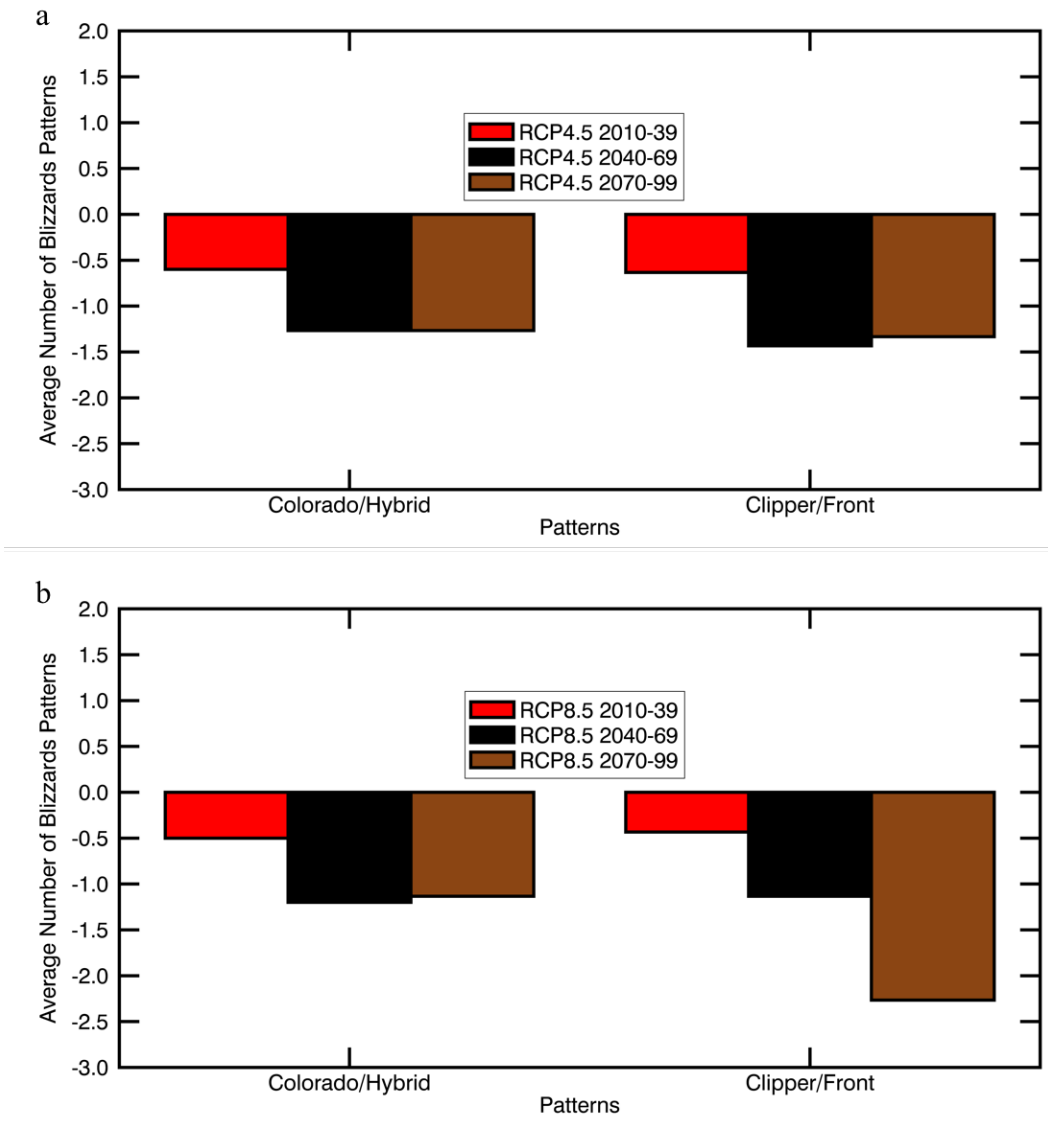


Figure 37. Change in Colorado/Hybrid and Clipper/Front patterns for (a) RCP4.5 and (b) RCP8.5 simulations. Values are calculated with the historical simulation as the baseline (RCPX.X – Historical).

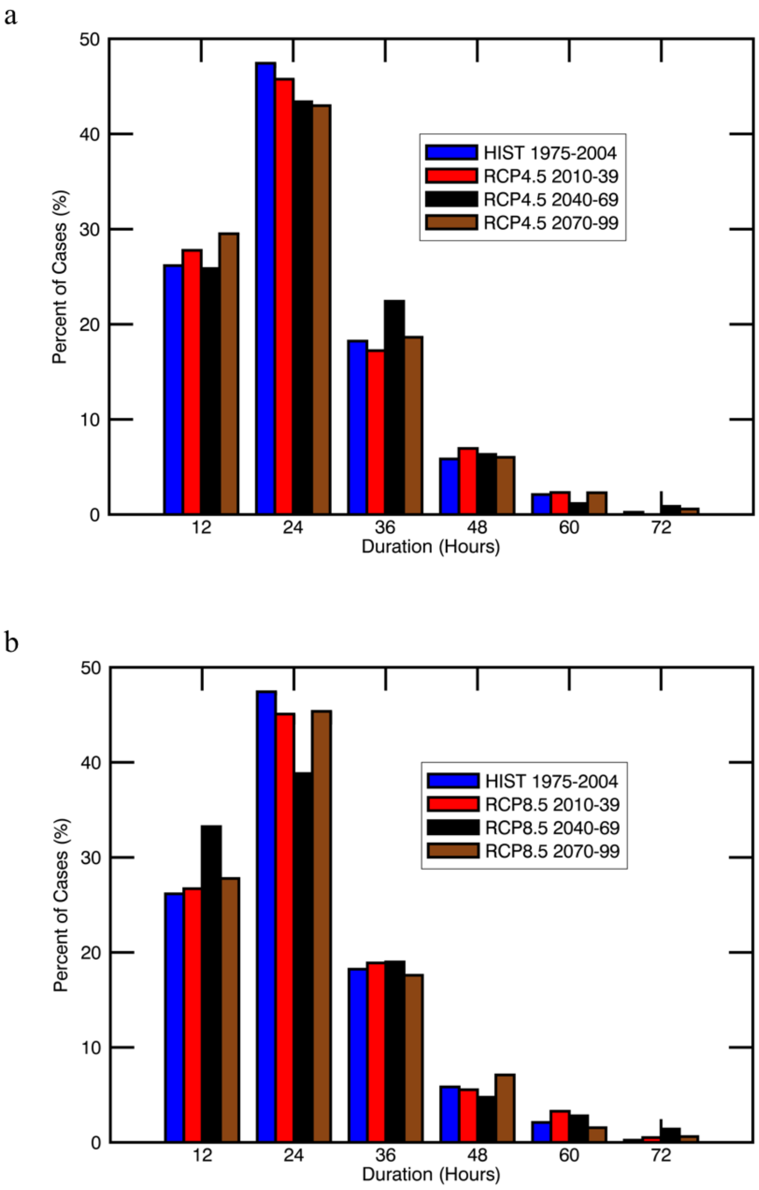


Figure 38. Normalized histograms of blizzard pattern duration for (a) RCP4.5 and (b) RCP8.5.

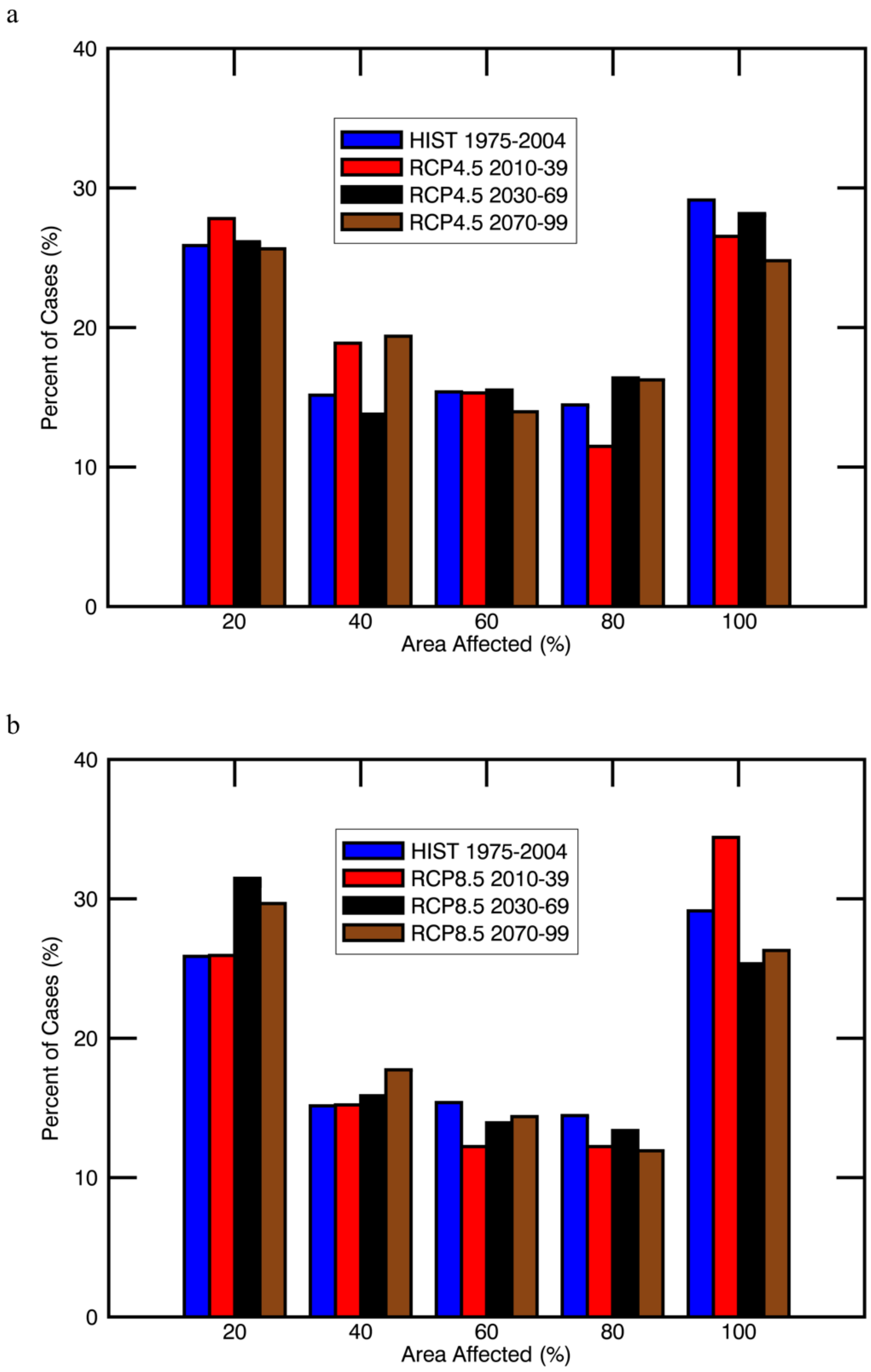


Figure 39. As in Fig. 38 except for blizzard event area.

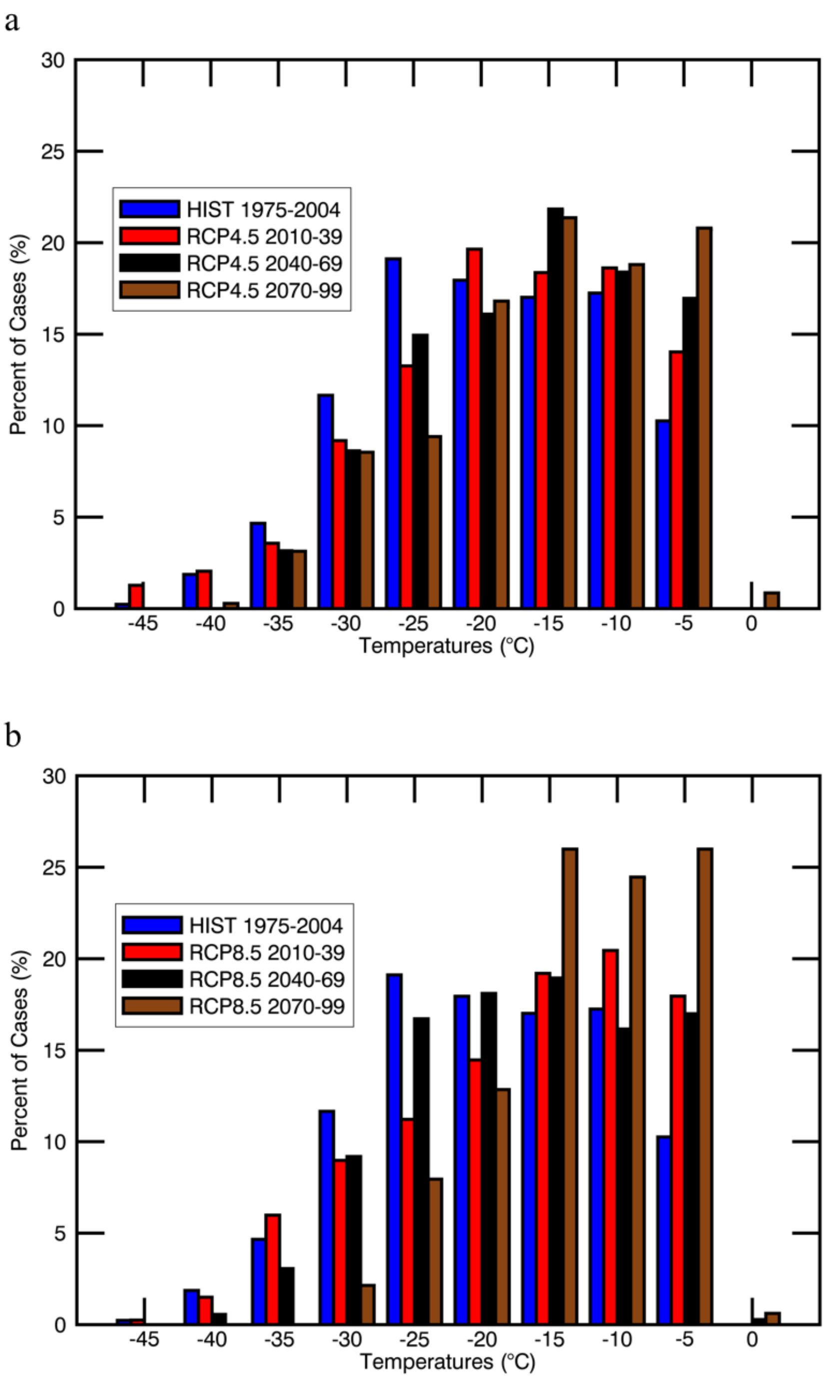


Figure 40. As in Fig. 38 except for minimum surface temperatures associated with blizzard events.

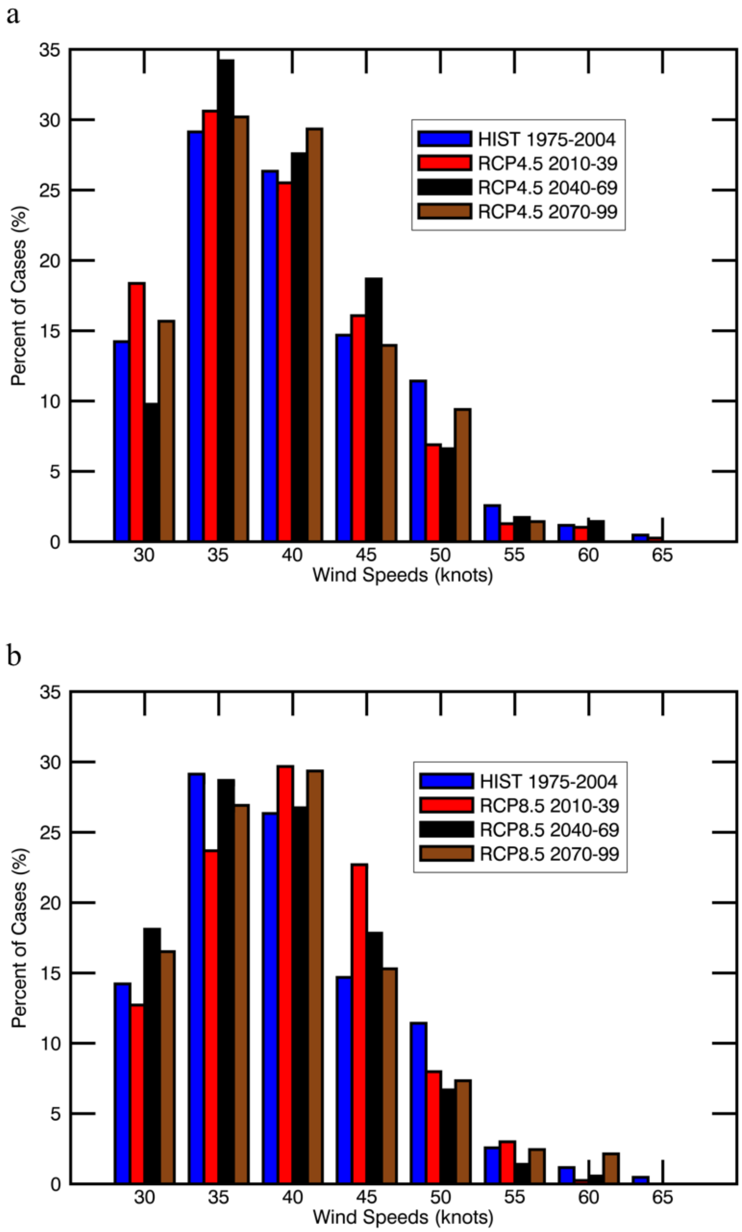


Figure 41. As in Fig. 38 except for maximum 900 hPa wind speeds associated with blizzard events.

CHAPTER VII

DISCUSSION

Overview

Discussion is split into four sections within this chapter. First, the results of the observed Northern Great Plains blizzard climatology are examined. Then, using the blizzard pattern detection algorithm on NARR, the automated blizzard pattern climatology is compared to observed events and the historical CESM simulation. Results for the two future scenarios are then discussed. This information is then used to determine a projected change of blizzard events for the NGP. Included is a discussion of the limits and assumptions used by this study, followed by future work.

NGP Blizzard Climatology

The NGP blizzard climatology has good agreement with studies by Schwartz and Schmidlin (2002) and Coleman and Schwartz (2017). Despite the analysis being completed using different time periods, the 93 blizzards in the NGP from 1979-2015 documented herein is comparable with the maximum number of 111 blizzards found for Cass and Traill counties in 1959-2014 described in Coleman and Schwartz (2017). The seasonal pattern of blizzards in the NGP (Fig. 6b) also agrees with the results established by that study, wherein it was determined that blizzards start in October, peak in January, and no longer occur after April.

Four main synoptic patterns are responsible for the majority of blizzards in the NGP; Colorado Lows, Hybrid Lows, Alberta Clippers, and Arctic Fronts. As the first three collectively occur in every month (Fig. 13b) and generally bring moderate to high snowfall totals with them (Fig. 12c), these events create blizzard conditions via falling snow with high wind speeds. As the falling snow accumulates loosely on the ground, the high winds can also cause saltation and subsequent suspension of snow grains adding lofted snow to the already falling snow. As Arctic Fronts only occur from December through March (Fig. 13b) and are not associated with high snowfall totals (Fig. 12c), it is inferred that these events require an already existent snowpack to create ground blizzard conditions via blowing snow. Further, the snowpack must also be conducive to allow for blowing snow to occur with low shear stress values permitting winds to start the saltation and suspension of snow grains into the air. Li and Pomeroy (1997) found that colder and fresher snow allowed for the occurrence of blowing snow more easily than warmer and older snow, indicating that snowpack conditions are important when determining whether or not blowing snow can occur. A lack of studies about blizzards prevents detailed discussion about these results. Instead, the occurrence of patterns largely matches climatological studies wherein the frequency of specific mid-latitude cyclones such as Colorado Lows and Alberta Clippers (Kapela et al. 1995, Thomas and Martin 2007) were considered. Results are also consistent with the experience of local forecasters (personal communication, Grand Forks NWSFO).

NARR Blizzard Pattern Climatology

The blizzard pattern detection algorithm produced a NARR-based blizzard pattern climatology with many similar characteristics to those associated with observed blizzard events in the NGP. While it was difficult to fully capture the seasonal climatology on a bimonthly scale (Fig. 27a), the algorithm did well for monthly intervals (Fig. 26b). Overall, the algorithm overestimates the number of blizzard patterns when compared to blizzards events (Fig. 26), identifying 4.7 times as many patterns as there were blizzards. These issues are largely attributed to the lack of knowledge of land surface conditions, as well as the conservative approach used with thresholds that were applied to identify potential blizzard patterns. The discrepancy for bimonthly blizzard and blizzard pattern frequencies (Fig. 27) could be due to the lack of synoptic patterns that impact the area. In the beginning of February for instance, patterns that do occur could be associated with low snowfall events. This raises the potential for an older snowpack that does not create ideal conditions for blizzards to occur from the remaining patterns that affect the area during the second half of February (Fig. 27).

Snowpack conditions are considered indirectly via time-varying wind speed thresholds. Ideally, a wind speed threshold should be tied to the temperature and age of the snowpack vs. time of year as these conditions control the probability of blowing snow (Li and Pomeroy, 1997). Although this was attempted, results from NARR had too much uncertainty to produce such a function. In order for this to be achieved, current snowpack conditions need to be known, and there is no gridded snowpack record (with age, temperature, etc.) that dates back to the 1970's. Even if the gridded snowpack record did exist, calculating all of the necessary variables to predict blowing snow would also prove to be difficult over a large domain such as the Grand Forks NWSFO CWA, as this would require developing and verifying parameters with known blowing snow events. This type of threshold would also only account for blowing snow, while it is known that falling snow can also commonly create blizzard conditions. An entirely different threshold would need to be designed (e.g. precipitation rate) in order to incorporate low visibility conditions due to falling snow.

With the lack of detailed visibility observations across the area and subjective nature of human classifications, objectively classified patterns beg the question of which record is correct. As was indicated, there is no clear cut-off in nodes that capture each type of subjective blizzard classification (Fig. 24). This is because the blizzard SOM only has three time periods (12 hours prior to blizzard occurrence, center time, and 12 hours post blizzard occurrence), as well as only two variables in order to determine what type of blizzard pattern was occurring. Human forecasters, given the proper datasets and tools, can utilize a variety of data sources, variables, and time periods to subjectively determine their type. Overall, results from the blizzard SOM indicate that there are a wide variety of tracks that the various systems follow across the NGP, which makes it difficult to match subjective classification with objective classification. Neither of the classification schemes are wrong, but it is likely that the objective scheme is less biased and would produce a more consistent classification scheme than a similar subjective scheme would. The gradient in subjectively determined blizzard types is encouraging and suggests that both methods have merit.

The overall bias of blizzard patterns vs. observed blizzards raises the concept of blizzard producing efficiency. Results indicate that some patterns are more likely to produce blizzards than others (Fig. 28b). Overall, 14.0% of the Alberta Clipper and Arctic Front patterns resulted in a blizzard, whereas 34.8% of the Colorado Low and Hybrid patterns were associated with blizzards. This can largely be explained by what was discussed earlier--Colorado and Hybrid Lows are able to create their own blizzard environments due to juxtaposition of falling snow (with higher snowfall rates) and strong winds, while Alberta Clippers and Arctic Fronts are more likely to be associated with lesser snow totals as well as dependence on a preexisting snowpack that increases the probability of blowing snow.

Probability of blizzard occurrence also varies by time of year (Table 6). In January there was a 54% chance that any given Colorado and Hybrid low pattern was associated with a reported blizzard (Table 6). Given that January produced the coldest blizzard pattern events (Fig. 33a), the snowfall associated with the Colorado and Hybrid patterns during this month are likely to be light and fluffy, which are the easiest type for wind speeds to create low visibility conditions. Surface properties in January are also generally snow-covered, which means that any snow being blown around by the wind is less likely to be stuck to the surface. In February, there is a 21% chance for a Clipper and Front pattern to create a blizzard (Table 6), which is more likely to be tied to the surface properties than temperatures. The lower temperatures that occurred in the previous month and into February (Fig. 33a), allow for the snowpack to remain most conducive for blowing snow conditions to occur. As Clipper and Front patterns create the lowest snowfall totals, they are more dependent on the snowpack conditions.

Based on these results, some conclusions can be drawn regarding which future forecasting research should be completed. As the chance for a Colorado and Hybrid pattern to produce in a blizzard is higher in every month than it is for the Clipper and Front patterns (Table 6), skilled forecasters have a high chance of correctly identifying when Colorado and Hybrid patterns can create blizzards. This is largely due to the heavy snowfall rates associated with these patterns, which when combined with high wind speeds has a high chance of creating low visibility conditions. As for the Clipper and Front patterns, knowledge of the snowpack is needed to determine if these patterns can result in blizzard conditions via blowing snow. As has been discussed earlier, determining if all the necessary variables to predict blowing snow are favorable for an event to occur is challenging, and further research is needed.

Linear regression analysis of blizzards and blizzard patterns per year revealed that there was a positive trend of the annual number of blizzards (0.27 per decade) and blizzard patterns (0.87 per decade, Fig. 28). While neither of the slopes are statistically significant, it does indicate that the number of blizzard patterns increased faster than actual blizzards in the NGP. Coleman and Schwartz (2017) found larger annual blizzard counts since the 1990s and hypothesized the occurrence of this was largely due to more consistent blizzard reporting parameters, as well as the modernization of the NWS and its capabilities in detecting blizzards. The higher positive slope of blizzard patterns, when compared to blizzards, suggests this may not be entirely the case. Rather, the findings indicate that a smaller fraction of the blizzard patterns are resulting in an observed blizzard.

Comparing the provided blizzard climatology to the objective blizzard pattern climatology further allows for a discussion on which record is more accurate, as the yearly climatology of blizzards and blizzard patterns (Fig. 28) indicates that the two don’t entirely agree. The climatology reveals some years with high number of blizzards and blizzard patterns (e.g. 1996, 2013), while others show a high number of blizzard patterns and no blizzards recorded (e.g. 1990, 2011) (Fig. 28). As has been discussed, land-surface conditions and precipitation have big impacts on whether or not a blizzard pattern results in a blizzard, but it is also possible that some blizzard events were simply not recorded/observed. The definition of a blizzard has also undergone changes over the past decades, previously including variables such as temperature and snowfall expected to reach respective thresholds, with implications on how that affects the number of historical blizzards remaining unknown. Use of the current definition of a blizzard in declaring whether or not a blizzard has occurred can also be viewed as a subjective decision, mainly due to the problem of not having continuous spatial coverage of automated surface observation stations. Due to this problem, the Grand Forks NWSFO does allow for a more lenient use of the visibility threshold (personal communication, Grand Forks NWSFO), as well as the use of trained weather spotters, in declaring whether or not a blizzard has occurred. Lastly, as blizzards are declared at the discretion of local NWS offices, it is unclear how the change in personnel at each office affects the detection and reporting of blizzards. In conclusion, it remains possible that some detected patterns were associated with unreported blizzard events.

Climatology of CESM Blizzard Patterns

Results from the CESM historical simulation show that it overestimates the number of blizzard patterns when compared NARR. On a monthly scale, the CESM had more patterns in every month except for March, and it did not have the decrease of patterns in February (Fig. 27a). Results demonstrate that this feature is independent of biases (e.g. wind speed) or land surface properties which were not considered in the algorithm. Instead, this lack of the local minimum is attributed to the increased number of both Alberta Clipper/Arctic Front and Colorado Low/Hybrid patterns that have the largest positive bias in February (Fig. 27b).

The overall positive bias of patterns is attributed to two factors. First, there is an increased number of patterns identified in CESM (10% increase over NARR) classified to the common blizzard nodes in the climatological SOM. Comparison of 900 hPa wind speeds showed that CESM wind speeds were 2.3 knots higher than NARR on average and this also led to an increased number of patterns identified as blizzard patterns.

Other characteristics of CESM blizzard patterns with respect to NARR included longer durations (Fig 32a) and increased area of the domain impacted (Fig. 32b). These results should not be surprising considering the positive bias of wind speeds in CESM. This led to an increased probability of a pattern at each time interval hitting the required thresholds to be classified as a blizzard pattern. To investigate the differences in duration, output from NARR was used every 6 hours rather than every 3 hours, with the results shown in Table 10. It is observed that by using NARR as 6 hourly data, the durations do resemble the output from the CESM more similarly, while the CESM still does produce longer lasting blizzard pattern events than are observed in the NARR for all of the bins except for the 72-hour bin (Table 10).

Table 10. Percentage of cases for durations in 12 hourly bins.

Bin	**NARR (3 hourly)**	**NARR (6 hourly)**	**CESM (6 hourly)**
12	47.8	36.1	26.4
24	36.8	43.2	47.7
36	11.4	15.8	18.4
48	2.72	3.52	5.13
60	1.11	0.502	1.90
72	0.23	0.754	0.38

Blizzard Events in the Future

Regardless of emission scenario in CESM, a decreased number of blizzard patterns is predicted. Comparing the first decade of interest (2010-29) to the last (2090-99), RCP4.5

(RCP8.5) displayed an average decrease of 3.1 (4.2) blizzard patterns per year (Figs. 34-35). Investigation of events by month demonstrates that both future scenarios have the largest decrease in patterns during the beginning and end of the winter season. This is largely caused by an increase in surface temperatures during this time period. Even during the remainder of winter, both scenarios show a shift in temperature associated with blizzard patterns. This, in part, causes a shift in peak occurrence from January into February, while also decreasing the number of events in their peak month (Fig. 36). The decrease in patterns is almost equally shared amongst the two types (Fig. 37), except for the 2070-99 period in RCP8.5 which has Alberta Clipper/Arctic Front patterns decreasing twice as much as the Colorado Low/Hybrid patterns (Fig. 37b). Interestingly, Eichler et al. (2013) suggested that the NGP would experience a decrease (increase) in Alberta Clipper (Colorado Lows), while the results from this study suggest a fairly even decrease in both, at least in regard to their ability to produce blizzard conditions.

In order to provide statistical confidence for the decrease in blizzard patterns observed in the future simulations, Bayesian estimation was performed. In brief, Bayesian estimation provides a method which yields comprehensive distributional information about the averages between two datasets, and also shows the comparative credibility of every possible difference for the averages (Kruschke, 2013). The latter is achieved by calculating the 95% highest density interval (HDI), which provides a useful measure of determining where the majority of the most credible values fall. Comparing the years of 2070-99 in RCP4.5 to the years of 1975-2004 in the historical simulation, the difference of means reveals that RCP4.5 has on average 2.62 fewer blizzard patterns per year (Table 11). The 95% HDI shows that a difference of zero is not amongst the most credible differences, and that the two averages are different as 99.9% of the credible differences are less than zero. Performing the same comparison using RCP8.5 displays that this simulation has on average 3.39 fewer blizzard patterns per year (Table 11), with the 95% HDI also not including a difference of zero, and similarly revealing that the averages are different as 100% of the credible differences are less than zero. RCP scenarios were also intercompared. Unlike the comparisons to historical blizzards, a difference of zero fell within the 95% HDI meaning that there is not statistical significance between these simulations at this level.

Table 11. Bayesian estimation values for the number of blizzard patterns per year comparing CESM-HIST (1975-2004) to the future emissions scenarios (2070-99).

	RCP4.5 (2070-99)	**RCP8.5 (2070-99)**
Difference of Means	-2.62	-3.39
95% HDI	-0.94 to -4.29	-1.52 to -5.22

Overall, the decrease in blizzard patterns largely agrees with the results from other studies using CMIP5 models that show a decrease in wintertime NH cyclone frequency in future emissions scenarios (Lambert and Fyfe, 2006; Zappa et al. 2013). Both of those studies revealed increases in cyclone intensities, and as blizzard patterns can be considered amongst the most intense cyclones due to their high wind speeds, their observed decrease is explained by the fewer number of cyclones experienced in the NGP rather than decreasing intensities. The observed wind speeds during blizzard events (Fig. 41) also support this argument that cyclones are not getting weaker, as their wind speeds remain largely unchanged in the future scenarios. Other aspects of these events such as duration and area coverage do not show conclusive evidence of change.

With the observed shift towards higher temperatures experienced during blizzard pattern events in future scenarios, the use of thresholds to distinguish blizzard events needs to be addressed. The wind speed threshold was calibrated using the lowest maximum 900 hPa wind speeds observed per month in NARR during a blizzard event. This threshold acts as a proxy to land-surface conditions as warmer months are tied to stronger wind speed thresholds. While there is observational basis for this decision as stronger winds are necessary to cause blowing snow at higher temperatures (Li and Pomeroy 1997), the per-month delineation in wind speeds used means that the wind threshold would likely need to be raised to account for the higher temperatures. As a consequence of this, the results from this study are considered to be conservative as the wind speed threshold is arguably too low. Further supporting this conclusion are other factors that determine whether a blizzard pattern produces blizzard conditions. As has been discussed throughout, whether or not a blizzard pattern results in a blizzard depends upon many different factors such as snowpack conditions. The results from Krasting et al. (2013) suggest that the NGP will experience a decrease in annual snowfall, with most of this reduction experienced in the transition months. With these months already experiencing a decrease in blizzard patterns, the percentage of those patterns resulting in a blizzard could be reduced significantly. As the peak occurrences of blizzard changes towards the month of February, perhaps the blizzard patterns in the middle of winter would remain unaffected in their ability to produce blizzard conditions. However, with the shift towards higher temperatures impacting the snowpack, this could require a higher shear stress in order for saltation to occur (Li and Pomeroy 1997). The ground blizzard process might therefore be impacted greatly in a warmer climate.

In order to investigate how much the observed increase in blizzard pattern temperatures impact the number of blizzard patterns, a sensitivity study was performed. As the thresholds used to determine whether or not an event was a blizzard pattern included both temperature and wind speed, the temperature threshold was removed and the difference in doing so was compared. Figure 42 reveals that the biggest changes occur during the transition seasons of winter, most notably in April where both RCP4.5 and RCP8.5 have almost one extra blizzard pattern per year occurring on average. In January, it is shown that this is the month where the smallest change occurs for RCP8.5, and in RCP4.5 it is where there is no change by removing the temperature threshold (Fig. 42). Compared to the historical period, both future projections show similar trends while displaying a larger increase in blizzard patterns every month except for October. This indicates that the increase in temperatures is a major cause for the reduction of blizzard patterns. As the transition months show the biggest changes due to the removal of the temperature threshold (Fig. 42), this suggests that the ability for the strong Colorado Low and Hybrid systems to produce snow may be inhibited, as the increase in temperatures above freezing may create more rain events than snow events. However, as Figure 36 shows, there are still some blizzard patterns for both future scenarios during the transition months, which means that the chance for blizzards to occur from these blizzard patterns during these months remains.

With these thoughts in mind, a conservative estimate of future blizzard occurrence is calculated for each thirty-year period. Blizzard events are estimated by multiplying the number of future blizzard patterns by the historical percentage of patterns associated with blizzards (21.1%) found by using NARR. Table 12 reveals a decrease of 0.6-0.7 blizzards may occur in the future climate. Applying this decrease to known number of blizzards that occur on average per year (2.5 blizzards per year), reveals that the NGP may experience 1.8-1.9 blizzards per year for the time period of 2070-99.

Table 12. Estimated mean number of blizzards in CESM for each time period.

	1975-2004	**2010-39**		**2040-69**		**2070-99**	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Blizzard Patterns	14.3	13.0	13.4	11.6	12.0	11.7	10.9
Blizzards	3.0	2.7	2.8	2.4	2.5	2.4	2.3

Future Work

As the blizzard pattern and observed climatology did not exactly match, the dataset could be used to investigate the patterns that were not associated with reported blizzards. While some events were inspected to ensure the thresholds were being applied properly, these blizzard patterns could be looked at more closely to investigate surface observations during the events. As was discussed earlier, it is possible that some blizzards occurred without them being recorded.

Further work is also required to understand the impacts of thresholds when applied to CESM, to first account for the bias that was observed, and also to account for changing temperatures. Ideally, a function should be developed to create a wind speed threshold based off the temperature experienced during any given event. Additionally, a visibility parameter could be created in NARR/CESM that would account for both falling and blowing snow and how this relates to observed visibility conditions. This requires knowledge of land surface conditions wherein snow accumulation is tracked. In doing so, the age and condition of the snowpack could also be calculated. This type of variable does not exist but would prove to be beneficial to blizzard research.

Lastly, while this study has been completed using the historical simulation as well as two future emissions scenarios from the CESM, the rarer nature of events results in uncertainty that limits the significance of detectable variability and trends, especially for specific characteristics. Ideally, the algorithm should be applied to either multiple models or multiple ensemble members as this would increase confidence in the results. For example, the CESM includes a Large Ensemble (LENS) project with 30 separate members. Such work will further examine the CESM model and provide a greater range of results regarding how blizzard patterns may change in the future climate of the Northern Great Plains.

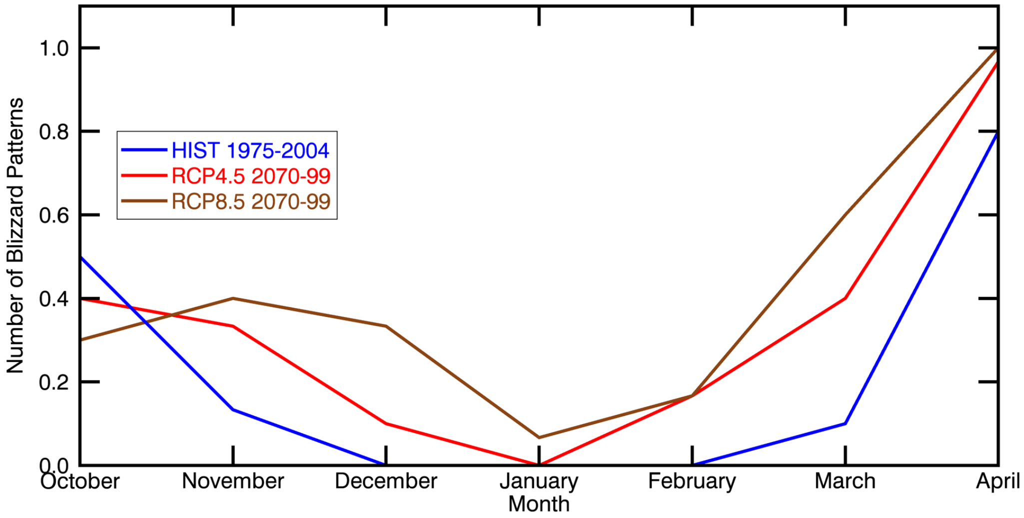


Figure 42. Change in average number of blizzard patterns by removing the temperature threshold for the time periods of 1975-2004 and 2070-99.

CHAPTER VIII

CONCLUSIONS

This thesis had two primary objectives. The first objective was the investigation and classification of the types of atmospheric patterns associated with blizzards in the NGP, which was aligned with the suggestions of Schwartz and Schmidlin (2002) and Coleman and Schwartz (2017). The second objective was the identification of blizzard-associated atmospheric patterns, which was accomplished by using SOMs to identify those patterns over the NGP within NARR from 1979-2015. This classification was then used to identify atmospheric patterns associated with blizzards in the CESM to understand its capability to produce a historical climatology of events as well as to investigate how they may change in the future. Results of this work are now summarized.

Part I: Historical NGP Blizzard Climatology

It was determined that the NGP experiences on average 2.5 blizzards per year, climatologically starting in October and ending in April. The most common month for occurrence is January, and the highest number of blizzards that occurred for one winter season is 10. These blizzards are largely caused by four distinct synoptic patterns; Colorado Lows, Hybrid Lows, Alberta Clippers, and Arctic Fronts. The first three patterns generally create blizzard conditions through a mixture of falling snow and high winds that create low visibility conditions. Arctic Fronts typically create them via ground blizzard criteria, which requires snow to already be on the ground to be lofted into the air by the high wind speeds creating low visibility conditions.

Part II: Automated Detection of Blizzard Events

Comparing the automated blizzard climatology using NARR data to the observed blizzard climatology yielded good agreement. All of the climatologically common blizzards were successfully detected, and a similar blizzard climatology was created on both a monthly and yearly scale. This method revealed that roughly one in five blizzard patterns create blizzard conditions. The development of the blizzard SOM proved to be useful in determining the known blizzard pattern types objectively. The blizzard SOM revealed that a distinction could be made about which patterns have a higher chance of creating blizzard conditions when they occur, with 34.8% (14.0%) of Colorado and Hybrid (Clipper and Front) patterns resulting in a blizzard.

Part III: Blizzard Events in CESM

Blizzard patterns were identified in historical and future CESM simulations. When the algorithm was used with the historical simulation of the CESM, it resulted in overestimation of the number of blizzard patterns compared to NARR. The CESM was shown to produce too many cyclones, with the tendency to create wind speeds higher than observed in NARR. In the future emissions scenarios, an overall decrease in blizzard patterns was found. During the transition seasons, the observed increase in temperatures was determined to be the main cause for the decrease in blizzard patterns. For the time period of 2070-99, the NGP will be experiencing 1.8-1.9 blizzards per year, a decrease from the current 2.5 blizzards per year. Due to the thresholds chosen and their implications for blizzards in the future climates, this is likely a conservative estimate and could be even lower than expected. Future decades were also shown to have their peak occurrence of blizzard patterns move from January to February. Further testing beyond overall trends in this study is prevented as blizzards are relatively rare events. Blizzard characteristics do have slightly variations while remaining largely unchanged in both of the future scenarios, but the temperatures experienced during these patterns noticeably shift towards higher values. Due to the combination of fewer blizzard patterns and the expected decrease in snow coverage, there will be even fewer blizzards created from the already decreasing number of blizzard patterns in the NGP.

APPENDIX

NGP Blizzard List

Year	Month	Day	Time (UTC)	Duration (Hours)	Type
2016	2	8	9	33	Clipper
2015	1	8	21	18	Clipper
2015	1	3	12	17	Clipper
2014	3	31	21	24	Colorado
2014	3	21	15	12	Front
2014	3	6	0	6	Ground
2014	2	26	21	10	Front
2014	2	13	12	7	Clipper
2014	1	26	18	16	Clipper
2014	1	22	12	9	Front
2014	1	16	12	15	Front
2014	1	4	6	13	Clipper
2013	12	28	21	15	Front
2013	3	18	9	27	Hybrid
2013	2	18	21	22	Hybrid
2013	2	11	3	20	Colorado
2013	1	19	18	12	Front
2013	1	12	3	24	Colorado
2011	3	12	6	18	Clipper
2011	1	1	9	21	Colorado
2010	12	30	21	30	Colorado
2010	10	27	9	24	Hybrid
2010	1	25	18	22	Clipper
2009	12	26	3	36	Colorado
2009	3	10	21	19	Colorado
2009	1	12	15	9	Clipper
2008	12	14	15	30	Colorado
2008	2	9	18	18	Front
2007	3	3	0	11	Hybrid
2006	1	24	15	7	Front
2005	11	16	3	27	Clipper

2005	10	6	3	12	Hybrid
2005	1	22	6	15	Clipper
2004	2	11	18	9	Clipper
2003	2	11	18	6	Front
2001	12	23	0	16	Colorado
2001	10	25	0	24	Hybrid
2001	2	25	12	12	Colorado
2000	12	21	3	18	Clipper
2000	12	16	15	15	Hybrid
2000	3	9	3	6	Colorado
1999	12	19	18	16	Clipper
1999	4	1	18	9	Colorado
1999	3	17	18	6	Hybrid
1999	2	12	12	9	Front
1998	12	18	21	10	Clipper
1998	11	10	21	18	Colorado
1998	3	13	18	3	Front
1997	4	6	12	30	Colorado
1997	3	4	9	6	Colorado
1997	1	22	12	14	Hybrid
1997	1	15	21	13	Front
1997	1	10	9	30	Clipper
1997	1	5	9	18	Colorado
1996	12	31	21	7	Valley
1996	12	21	12	6	Front
1996	12	18	0	36	Clipper
1996	11	17	9	24	Colorado
1996	3	25	0	24	Colorado
1996	2	27	21	18	Hybrid
1996	2	10	21	21	Clipper
1996	1	18	12	27	Hybrid
1995	12	9	0	15	Hybrid
1995	2	10	6	9	Clipper
1994	4	26	15	21	Colorado
1993	12	22	0	9	Clipper
1992	12	25	6	12	Front
1991	12	14	3	12	Hybrid
1990	1	11	12	18	Clipper
1989	2	1	6	9	Front

1989	1	7	21	42	Hybrid
1988	3	12	3	30	Colorado
1988	2	14	15	6	Clipper
1988	1	24	21	9	Hybrid
1988	1	12	15	21	Hybrid
1987	12	31	3	6	Colorado
1986	4	15	3	21	Colorado
1985	11	19	3	21	Hybrid
1985	3	4	6	42	Colorado
1985	1	25	0	9	Front
1984	12	16	18	6	Colorado
1984	3	10	15	9	Front
1984	2	5	6	9	Front
1983	12	25	0	21	Hybrid
1983	12	15	9	12	Hybrid
1983	3	8	21	18	Colorado
1982	4	3	12	24	Colorado
1982	3	8	15	3	Hybrid
1982	1	23	15	18	Colorado
1982	1	10	18	21	Hybrid
1981	2	1	12	9	Colorado
1980	1	11	15	21	Hybrid
1980	1	7	3	18	Hybrid

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