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Article

A Climatology of Atmospheric Patterns Associated with Red River Valley Blizzards

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Abstract: Stretching along the border of North Dakota and Minnesota, The Red River Valley (RRV) of the North has the highest frequency of reported blizzards within the contiguous United States. Despite the numerous impacts these events have, few systematic studies exist discussing the meteorological properties of blizzards. As a result, forecasting these events and lesser blowing snow events is an ongoing forecast challenge. This study presents a climatology of atmospheric patterns associated with RRV blizzards for the winter seasons of 1979-1980 to 2017-2018. Patterns were identified using subjective and objective techniques using meteorological fields from the North American Regional Reanalysis (NARR). The RRV experiences on average, 2.6 events per year. Blizzard frequency is bimodal with peaks occurring in December and March. The events can largely be typed into four meteorological categories dependent on the forcing that drives the blizzard: Alberta Clippers, Arctic Fronts, Colorado Lows, and Hybrids. Objective classification of these blizzards using a competitive neural network known as the Self-Organizing Map (SOM) demonstrates that gross segregation of the events can be achieved with a small (8-class) map. This implies that objective analysis techniques can be used to identify these events in weather and climate model output that may aid future forecasting and risk assessment projects.

Keywords: Blizzards; blowing snow; climatology; self-organizing maps; synoptic typing

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1. Introduction

The United States (US) National Weather Service (NWS) currently defines blizzards as events that have sustained winds or frequent gusts ≥ 35mph (16 m s^{-1}) and considerable falling and/or blowing snow that reduces visibilities to < ¼ mile (400 m) for periods of three hours or longer. These events are recorded within the National Centers for Environmental Information (NCEI) *Storm Data* publication that is reliant on submissions by the Warning Coordination Meteorologist (WCM) at each NWS forecast office. This publication serves as the official archive of storm events for the country [1,2].

Within the contiguous United States, reported blizzards are most common over the Northern Great Plains (NGP) including the region centered on North and South Dakota [1,2]. At a county level, the highest frequencies are found along the border of North Dakota and Minnesota which topographically, makes up the Red River Valley (RRV) of the North (Fig. 1). To some extent, this is impressive considering population related reporting biases noted for warm-season hazardous weather events such as tornadoes [3-6]. Alternatively, reporting biases could exist by NWS County Warning Area (CWA) as noted for warm-season hazards such as hail [7] and wind [8].

Regardless of potential biases in *Storm Data*, the high frequency of blizzards in this region makes physical sense and can be attributed to factors including the topography/land cover, climatology of snow cover, and frequency of high-wind events. A lake plain leftover from the receding Glacial Lake Agassiz 8000 years ago, the shallow Red River of the North flows northward to Lake Winnipeg before eventually emptying into the Hudson Bay [9]. The RRV is largely devoid of

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trees except within the immediate vicinity of the river and in shelterbelts (tree rows) planted due to agricultural activity. Although the RRV is on average only a few hundred meters deep over a 100 km width, there is evidence that winds are enhanced within this region. For example, blowing snow plumes are sometimes seen only within the RRV, typically in regimes with cold-air advection (Fig. 2). While there are numerous studies that document topographic influences of valleys on winds in other locations, the authors are unaware of any existing studies for the RRV.

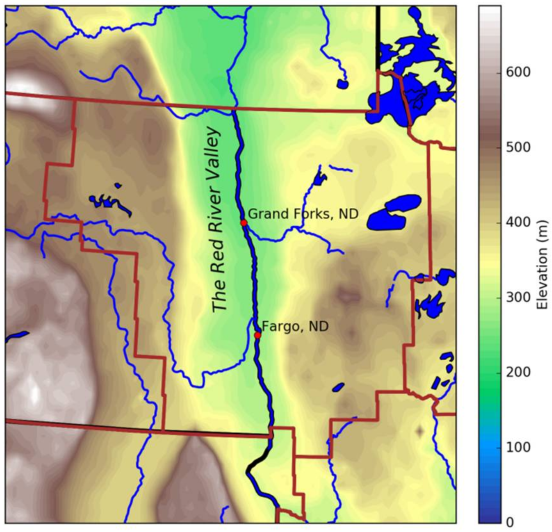

Figure 1. Topography of the Red River Valley (RRV) of the North. Elevation (ASL) is shaded while NWS CWAs are denoted by the dark red polygons. Larger water bodies and rivers are highlighted in blue.

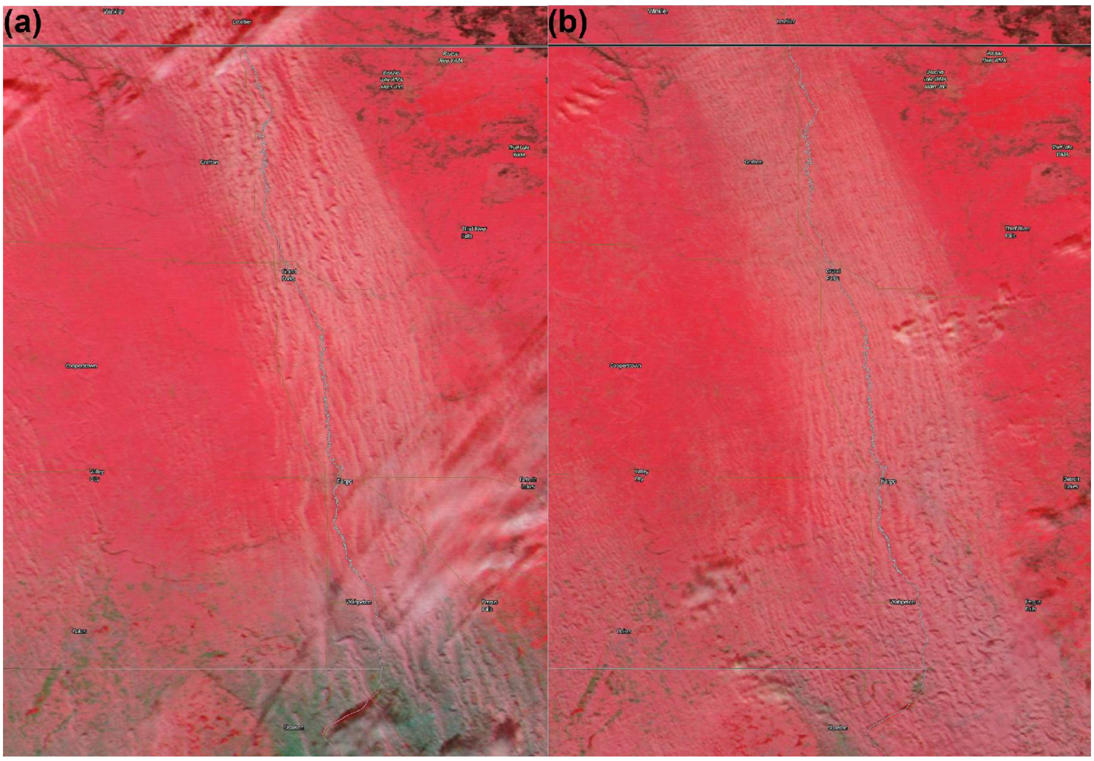

Figure 2. False color imagery (M3-I3-M11) from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi satellite during the daylight (~1:30pm local time) overpass on (a) 11 Jan. 2018, and (b) 15 Jan. 2018. Snow cover is denoted by pink/red, cloud cover and blowing snow by white, and bare landscape by green (bare ground) or dark (forest) areas.

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With a latitude of 45-49° N in the center of the North American continent, the RRV is the coldest non-mountainous region within the CONUS [10]. Although the region only receives on average 80-100 cm of snow in a year [11], the cold temperatures facilitate an environment that supports an average snow cover extent >85% during the winter months [12]. Snowfall events responsible for this cover have been tied to several meteorological patterns including extratropical cyclones that form due to lee cyclogenesis such as Colorado Lows and Alberta Clippers [13-17].

As the name implies, Colorado Lows originate due to cyclogenesis near its namesake. Historically, these types of systems have been associated with a number of impactful blizzards including events such as the Children's Blizzard on 12 Jan. 1888 [18]. The strength of these cyclones can advect a significant amount of moisture northward and as a result, these systems are responsible for the heaviest (and largest scale) snowfalls in the RRV and southern Manitoba and Ontario [16]. The more progressive cousin of these systems include Alberta Clippers that propagate rapidly east-southeast from Canada into the upper-tier of the US [18]. Precipitation for these events typically comes in the form of mesoscale snow bands. Overall, snow totals are lower due to lack of available moisture, but these systems can still produce significant winds capable of reaching blizzard criteria [16,20]. While Colorado Lows and Alberta Clippers are colloquial terms for common North American mid-latitude cyclones, blizzards can also be forced by systems that originate in other areas (e.g. Montana). Historically, these events have been given the moniker 'Hybrids' by the Grand Forks NWSFO, and as such, this term is used herein to describe systems that do not conform to stereotypical patterns, but have a defined low pressure center. Depending on the event, snowfall can be meso- or synoptic-scale in nature, with high variability for totals.

While blizzards are often thought of as large-scale events associated with the juxtaposition of winds and snowfall associated with mid-latitude cyclones, the RRV also experiences events known as ground blizzards that are frequently driven by strong winds behind Arctic (Cold) Fronts [16,21]. For these cases, winds greater than 4-7 m s^{-1} impart a force on already fallen snow, rolling it on the surface before being bounced and lofted into the atmosphere [22,23]. As demonstrated in Fig. 2, these events can often occur under otherwise clear skies, and in some cases, are confined solely to the RRV providing evidence of topographic enhancement of winds.

Historically, the Grand Forks NWS Forecast Office (NWSFO) has subjectively classified blizzards within their CWA (see Fig. 1) into the four aforementioned categories (Alberta Clippers, Arctic Fronts, Colorado Lows, and Hybrids), and has maintained a local database of these blizzards from 1974-present. These events are identical to the reported blizzards in *Storm Data* although additional meteorological information is sometimes included within the local dataset vs. what is officially provided in Storm Data. While this is considered the official dataset for blizzard events, the events are of such importance that the local newspaper (The Grand Forks Herald), has independently kept track of and named impactful events since the winter of 1989-1990.

The purpose of this work is two-fold. First, the climatology of blizzards within the Grand Forks NWSFO CWA will be described for the winters of 1979-1980 to 2017-2018. Besides investigating when and how often blizzards occur, this abbreviated time period will allow for composite patterns to be generated using the North American Regional Reanalysis (NARR) [24]. Given the limitations and known human biases of subjectively defining atmospheric patterns, the second goal of this work is to demonstrate that atmospheric patterns associated with these events can be objectively defined. To do so, a competitive neural network known as a Self-Organizing Map (SOM) [25] will be used.

The efforts of this work will add to the limited body literature that discuss blizzards in continental regions such as the Northern Great Plains. The climatology and demonstration of an objective technique to classify these patterns described herein will pave the way for future studies that will seek to identify these events in reanalyses, Numerical Weather Prediction (NWP) models, and climate simulations. This will allow for questions to be investigated that range from best forecasting practices for these events to how blizzards may change in a warming climate.

2. Materials and Methods

As noted in the introduction, the climatology of blizzard events in this study comes from the publically available NCEI *Storm Data*. For the purposes of this project, only blizzards contained within the Grand Forks NWSFO CWA (Fig. 1) were investigated (see Appendix). These events are referred to as RRV blizzards due to the majority of the CWA encompassing this topographic feature, although a few counties within this region are on the periphery of the valley. To compare events to NARR data, the time period was limited to the winter seasons of 1979-1980 to 2017-2018. Subjective classifications of these events were made by Grand Forks NWSFO meteorologists using available observations, model, and reanalysis output.

2.1. Composite analysis

Composite surface and upper-air patterns were generated using the NARR [24]. Although on a native 32 km horizontal grid, this dataset was averaged to a lower resolution, 16×16, 1.25° (longitude) by 0.94° (latitude) grid centered on the Grand Forks NWSFO CWA. This was done to reduce the computational cost of the SOM and to facilitate future comparisons to other datasets (e.g. weather or climate model output). While a number of reanalyses are now available, NARR was chosen due to the authors' familiarity with this dataset, along with prior studies that demonstrated favorable performance over the region [25-27]. Given the variables and resolution used, it is anticipated that similar results would be found if other current generation reanalyses were used (e.g. ERA-Interim [28]).

Using *Storm Data*, available surface observations, and the NARR, midpoint times were estimated for each blizzard event. Patterns were composited for the four primary patterns using midpoint times, and for 12-hr periods before and after these points. For patterns that contained a mid-latitude cyclone, the minimum Mean Sea Level Pressure (MSLP) within the domain was identified and tracked over this time.

2.2. Objective classification using a SOM

To objectively classify atmospheric patterns, the Self-Organizing Map (SOM) [29] technique was used. A competitive neural network, SOMs are most similar to a K-means clustering algorithm used in conjunction with a neighborhood function during the training process. The result of this process is a topological map (feature map) that allows clusters (nodes) to a) span the data space and b) relate to each other in a two-dimensional matrix. This latter property allows users to be less concerned with the exact number of clusters to choose and instead, focus on clusters that are relevant for their analysis purposes. While this alone makes it a useful algorithm for pattern recognition, SOMs hold other advantages over other traditional techniques such as Component Analysis (PCA) or Empirical Orthogonal Functions (EOFs) [30-32]. As a result, SOMs are now commonly used in the fields of meteorology and oceanography. For additional information, the reader is referred to earlier surveys of SOM studies [33-34].

The process of creating a SOM follows the strategy employed in earlier work by the author [35], and the reader is referred to this study for more details on the nuances of SOM creation. To summarize the process, a user must first select data for input, then reduce the multi-dimensional meteorological data into input vectors that the SOM performs the clustering on. SOMs are trained in a two-step process that first determines the orientation of the feature map, then iterates to a final solution that seeks to minimize the error between the training dataset and the final classification of nodes [29]. These stages require the selection of user parameters such as the map size, training length, learning rate, and the neighborhood radius. After the SOM is created, training samples are compared to each node within the feature map and classified to the node with the minimum Euclidean distance.

Consistent with the generation of composite patterns in the previous section, the spatially averaged 16×16, 1.25° (longitude) by 0.94° (latitude) NARR was used to train the SOM. Based on the results of the compositing process, variables that showed significant variability across patterns were

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used, and these included 500 hPa geopotential heights, MSLP, and surface temperatures. Other combinations of variables were tried, but the inclusion of 500 hPa geopotential heights made the largest difference in the ability of the SOM to segregate patterns. Identical to [35], variables were computed as anomalies from the field mean at each given time step. This allowed the SOM to focus on the gradients in variables, minimizing the issues of biases or variability that vary by season or exist when patterns are compared across multiple datasets (e.g. NARR vs. climate model data) which is useful for future studies. To capture the progression of systems across the domain, each training sample included time steps at the midpoint and +/- 12 hrs. With three total variables, a 16×16 region, and three times for each case, input vectors used to train the SOM had a length of 2304 elements. All variables were normalized to a common scale to contribute equally to the SOMs. In total, 93 blizzard cases were used as input vectors (winters of 1979-2018 to 2015-2016) due to the availability of NARR data at the time the SOM was created and goal to classify future patterns. Errors (Euclidean distances) for classified patterns in the latter two seasons were similar to the trained data. This suggested that 1) training the SOM with all 100 patterns would not significantly alter the results, and 2) ample variability was captured in the SOM and the methodology is useful for pattern recognition purposes.

A key parameter of the SOM (and other objective classification techniques) is the number of classes chosen. For classifications of atmospheric states, these decisions will be dependent on the purpose of the study as well as the number of samples being used to train the SOM. Too few classes can smooth out the details of patterns, while too many will lead to situations where some SOM nodes have no observed patterns classified to them [35]. With a relatively small number of cases (~90-100), and the purpose of comparing the SOM to subjectively classified classes, a rectangular 8-class (4×2) is presented. Larger maps were also created, but did not provide further insight to the results shown herein.

The SOM was generated using SOM_PAK software which is freely available [29]. Within this package, the ‘vfind’ program was used which randomly initializes a SOM feature map a specified number of times, and selects the map that minimizes the lowest quantization error. Following the guidelines of SOM_PAK [29], settings for ‘vfind’ included a training length that increased and learning rates and neighborhood radii that decreased between the two steps in the training process (Table 1).

Table 1. SOM Settings used with the SOM_PAK command ‘vfind’.

Parameter	Value
Topology	Rectangular
Neighborhood Function	Bubble
Trials	10
Training Length (stage 1, stage 2)	93, 93000
Learning Rate (stage 1, stage 2)	0.05, 0.01
Neighborhood Radius (stage 1, stage 2)	3, 1

3. Results and Discussion

3.1. General characteristics

During the 39-year period, 100 total blizzards were reported, averaging 2.6 events per year. An annual and seasonal breakdown of these events is provided in Fig. 3. RRV Blizzards are highly variable with seasons varying from 0-10 events (Fig. 3a). Record years (10 events) included the infamous 1996-1997 winter that concluded with the catastrophic RRV flood [36,37] and the 2013-2014 winter that did not have significant flooding. On the other end of the spectrum, three seasons (1986-1987, 1990-1991, 2011-2012) did not have any recorded blizzards. Out of curiosity, named blizzards from the Grand Forks Herald were also compared for annual totals. Over the shorter

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period (1989-1990 – 2017-2018), the paper named 63 (vs. 76) blizzards, and the datasets had a correlation of 0.77. Provided that the distribution area for the paper is smaller than the CWA, these results are expected. While some specific years had more events recorded by the paper vs. *Storm Data*, this is attributed to events that were stronger winter storms but did not meet official blizzard criteria.

Blizzards have been reported from Oct.-Apr., with the bulk of the events occurring from the 2nd half of Dec. to the 1st half of Mar (Fig. 3b). The most frequent period of occurrence was the 2nd half of Dec. with a total of 17 blizzards over the 39 year period. A unique aspect of the seasonal cycle is the bimodal distribution with a well-defined lull in late February. This is in agreement with North American cyclone climatologies that indicate a relative minima of cyclones during February [38].

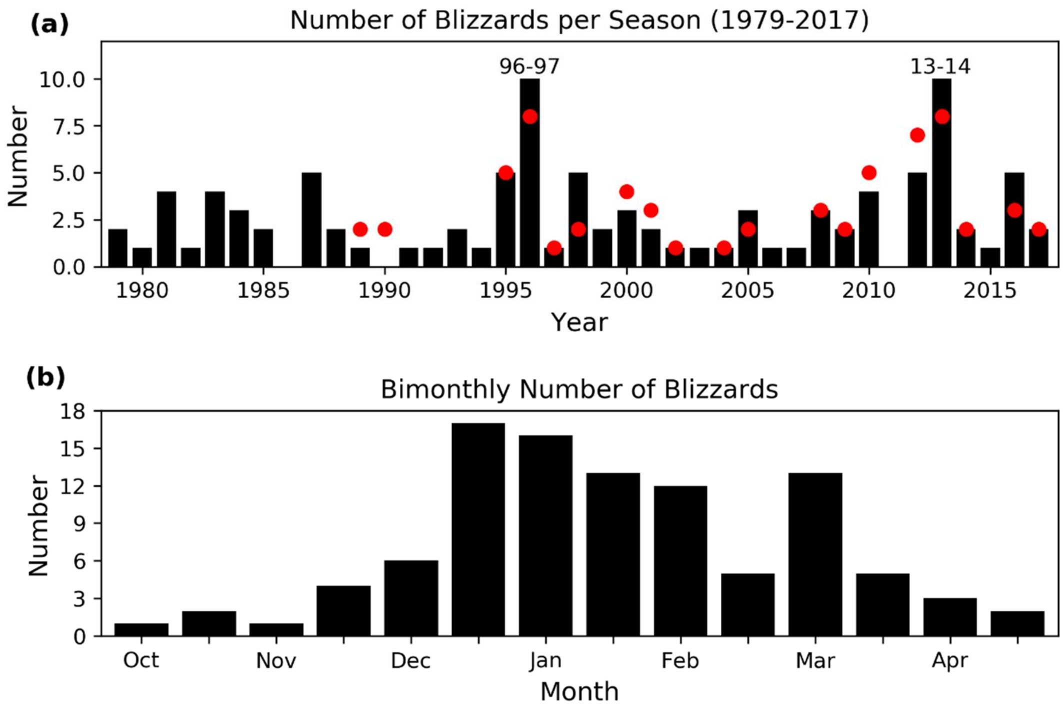

Figure 3. (a) Annual and (b) bimonthly number of *Storm Data* blizzards for the winter seasons of 1979-1980 to 2017-2018. Named blizzards by the Grand Forks Herald are provided by the red dots in panel (a).

3.2. Composite analysis

Classifications of the 100 classified blizzards were used to generate composite patterns from the NARR. Of the 100 patterns, two patterns were sufficiently different that they did not fit any of the four categories, and these were omitted from the composite analysis. These included two events driven by southerly winds well ahead of weaker mid-latitude cyclones on 6 March 2014 and 31 December 1996. The remaining composite patterns are now described.

Of the four patterns, Colorado Low blizzards feature the strongest mid-latitude cyclone (Figs. 4-7a) and resemble prior composites of this type [39]. Tracking from NE Colorado to N Wisconsin, the composite minimum MSLP decreases from 1002-1000 mb from 12 hours prior to the midpoint of the event. With a storm track south of the RRV, the region is predominately under northerly surface winds that strengthen and shift from ENE to NW as the cyclone progresses eastward. While not shown (and noted earlier), these systems are responsible for the highest snowfall totals as the region falls within the precipitation shield north of the cyclone track [40]. Aloft, these events are associated with the progression of a well-defined trough that deepens over the region (Figs. 5,7a). In response to the passage of this trough, strong 500 hPa height falls are found leading up to the event, with the maximum decrease located just northeast of the surface low. In some cases, these troughs are

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associated with an upper-level closed low, although this definition has been lost to some extent during the compositing process.

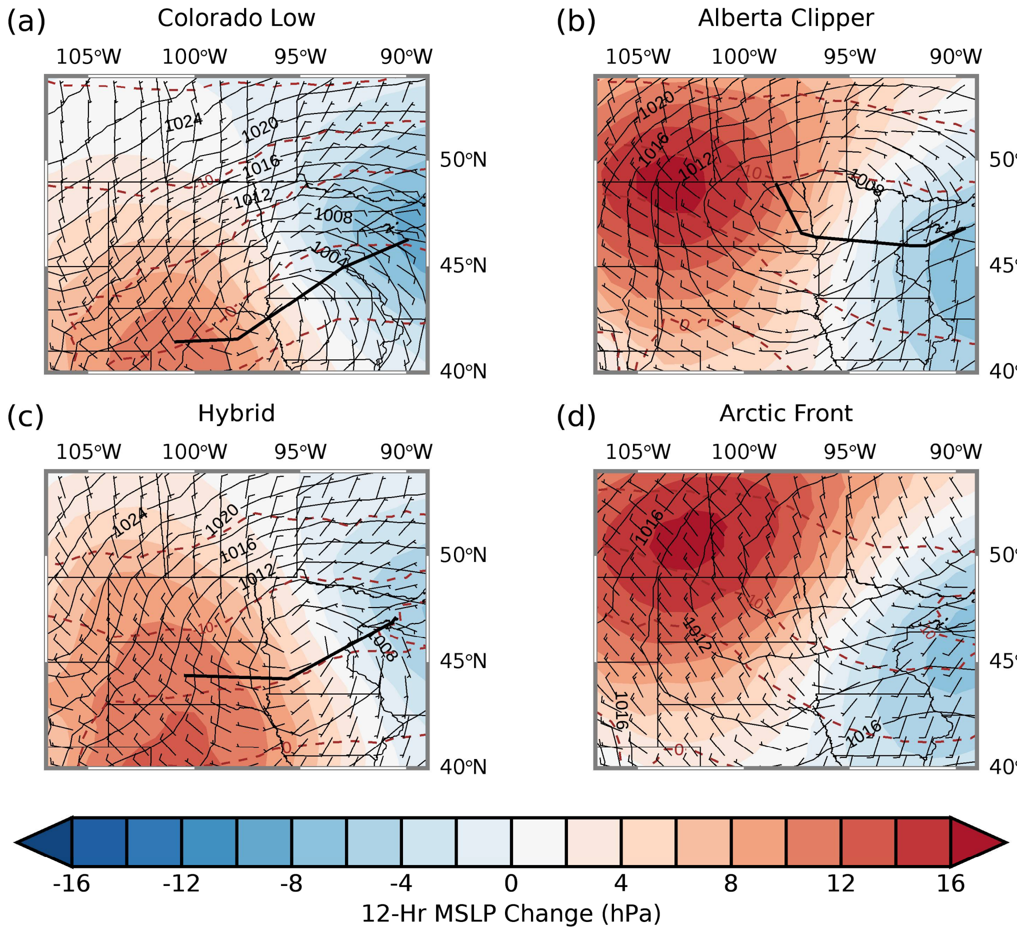

Figure 4. NARR Composite plots of MSLP (mb), surface wind barbs (kts), and surface temperatures (° C) 12 hr prior to the midpoint of (a) Colorado Low, (b) Alberta Clipper, (c) Hybrid, and (d) Arctic Front blizzards. 12-hour MSLP change (midpoint – 12 hr prior) is provided by shaded contours while composite mean cyclone tracks are denoted by the thick black lines for select classes.

Blizzards associated with Alberta Clippers also feature a well-defined, albeit weaker (1008-1006 mb) mid-latitude cyclone (Figs. 4-7b). Consistent with the name and prior composites [19], these systems track ESE from southern Canada across the RRV with the cyclone center eventually reaching NE Minnesota and N Wisconsin. One should note that the composite cyclone tracks appear to be shifted east compared to the Colorado Low, and barely encompass the passage of the low out of Canada. Because these tracks were identified symmetrically around the midpoint of the blizzard conditions, this implies that poor visibility primarily occurs after the passage and development of the surface cyclone (Fig. 5b). Aloft, conditions leading up to the event feature stronger WNW 500 hPa flow with maximum height falls located over MN, just ahead of a developing short-wave trough (Fig, 4b). By the midpoint of the blizzard, this trough has amplified and progressed eastward across the domain with 500 hPa winds shifting to the NW.

As noted earlier, the Grand Forks NWS defines Hybrid events as those with characteristics of multiple patterns, and this is also true of the composite patterns (Figs. 4-7c). At the surface, this class manifests itself as a mid-latitude cyclone track that begins farther north (south) of a Colorado Low (Alberta Clipper). Minimum pressure and intensity of the wind field are similar to that of the Alberta Clipper, but with weaker 12-hr pressure rises/falls (Fig. 6c). This latter property can be attributed to the slower progression of Hybrids vs. Alberta Clippers. At 500 hPa, Hybrids are associated with weaker, near-zonal flow 12 hours prior to the midpoint of blizzard conditions (Fig.

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4c). Compared to the Alberta Clippers, the short-wave trough is in a similar position, but the orientation of the flow leads to a more neutral tilt. Unlike the aforementioned pattern, Hybrids feature more deepening of the upper-level low/trough by the midpoint of the blizzard, similar to what is seen for Colorado Lows.

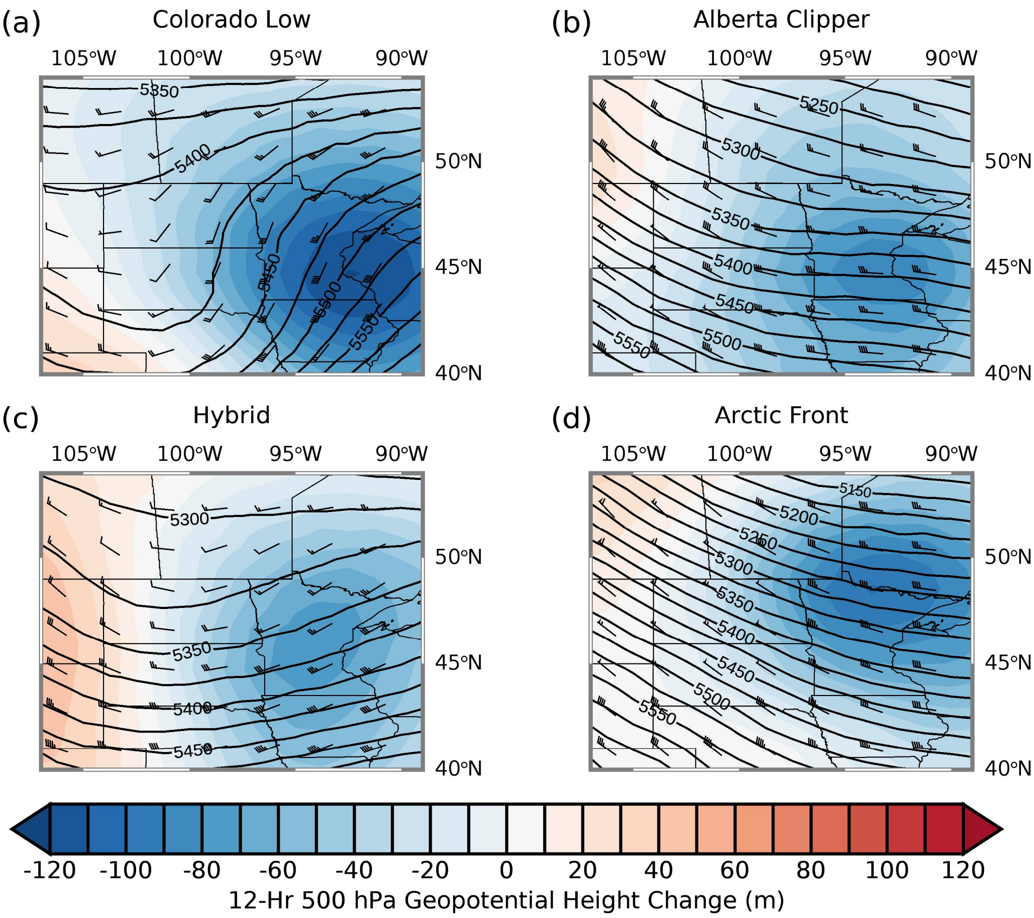

Figure 5. As in Fig. 4. Except for 500 hPa Geopotential heights. 12-hr height change is provided by the shaded contours and 500 hPa wind barbs (kts) are overlaid.

Arctic Fronts are the final, and arguably most unique composite pattern identified with RRV blizzards (Fig. 4-7d). Unlike the other patterns, no centralized region of low-pressure is seen at the surface. Instead, this pattern features an elongated SW to NE oriented surface trough associated with the developing Arctic Front (Fig. 3d). As the event progresses, surface pressures rapidly rise and northerly winds strengthen behind the front, as the Arctic High develops to the NW, increasing the gradient in MSLP and Cold Air Advection (CAA). Because the surface trough / Arctic Front is often associated with a more distant cyclone, 500 hPa patterns are more dissimilar from the other patterns (Figs. 4,6d). These events are characterized by strong NW flow that eventually develops a SW trough (passing vorticity maxima) in the eastern half of the domain by the mid-point of the event. As a result, the region ends up residing under large (60 m) height rises associated with a strengthening jet stream and implied Anticyclonic Vorticity Advection (AVA). Compared to the Alberta Clippers and Hybrid events, 500 hPa winds associated with Arctic Fronts are approximately double in magnitude (80 vs. 40 kts). This leads to a vertical wind profile (not shown) that implies downward transfer of momentum in a regime of subsidence is a key mechanism for reaching blizzard criteria for winds. The presence of CAA, AVA, and subsidence matches many of the checklist items for impactful post-cold frontal winds [21].

Meteorological patterns responsible for blizzard events have preferred periods of occurrence (Fig. 8). Early and late season events (Oct., Nov., and Apr.) are primarily due to Hybrid and

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Colorado Lows, with only one (Alberta Clipper) event not fitting these categories. These classes have bimodal distributions with Colorado Lows (Hybrids) peaking in Dec. and Mar. (Jan. and Mar.),

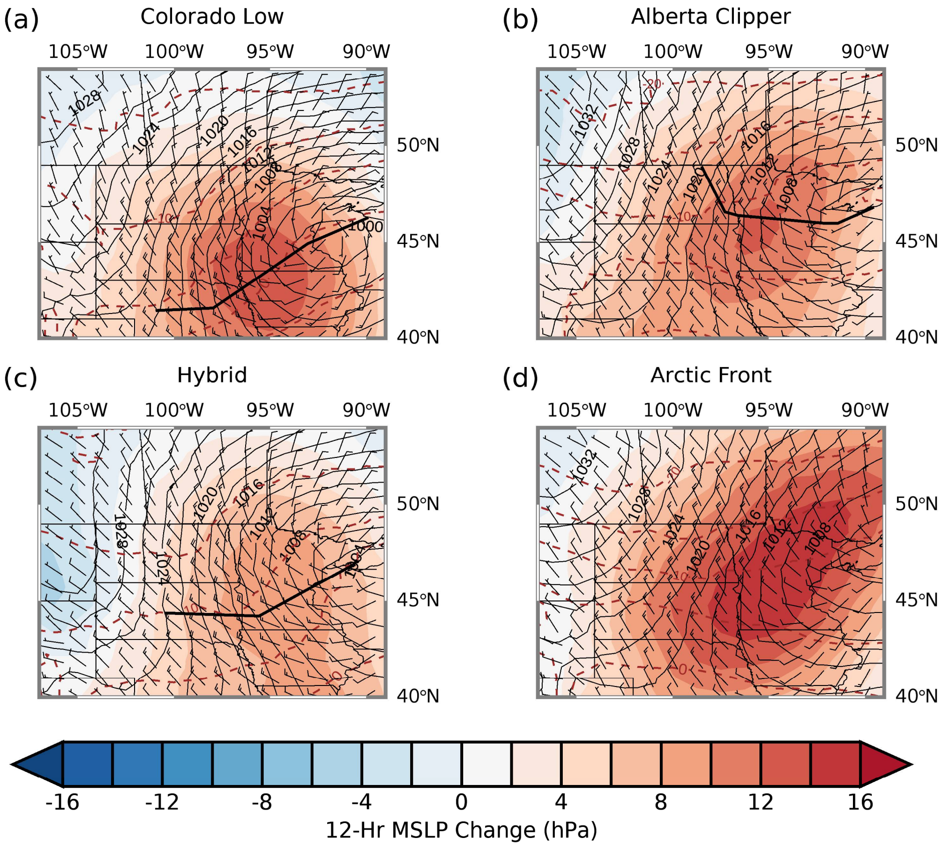

Figure 6. As in Fig. 4 Except for the midpoint of the blizzard.

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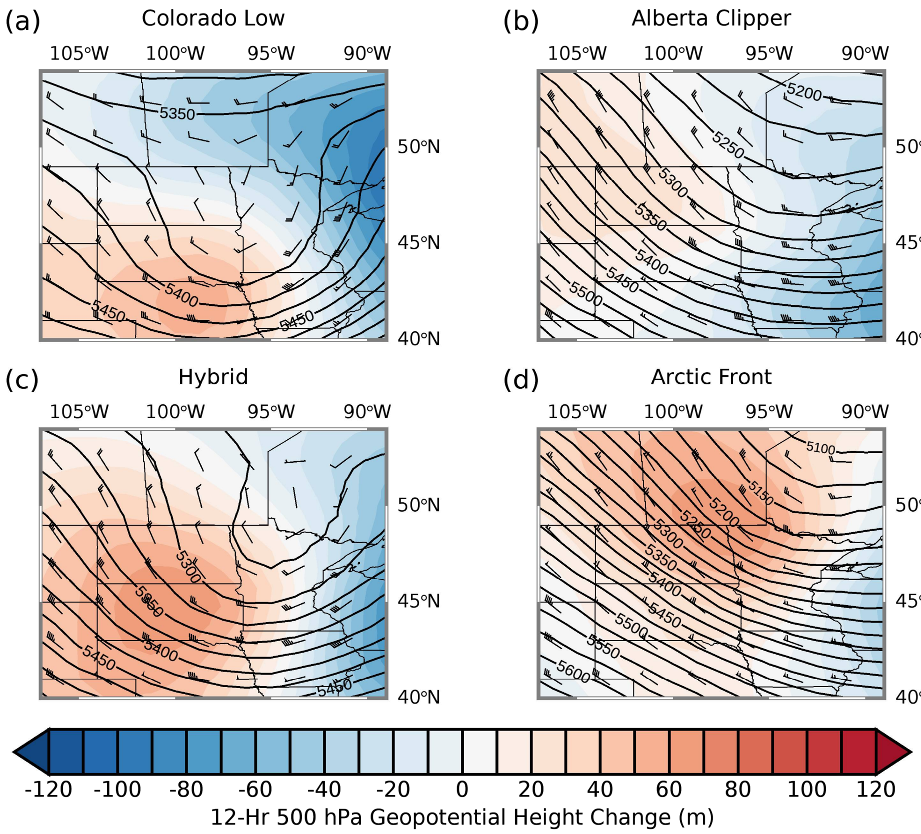

Figure 7. As in Fig. 5 except for the midpoint of the blizzard.

respectively. Alberta Clippers occur from Dec. to Mar. with the majority of the events occurring during Jan. and Feb., consistent with [19]. Arctic Fronts, commonly responsible for ground blizzards, are more common during the late winter with events between Dec. to Mar and a maximum in Jan. As a result of these distributions, Jan. ends up being the most diverse month with relatively constant fractions (0.2-0.3) across the categories (Fig. 8b). As noted earlier, the lull in February is consistent with extra-tropical cyclone climatologies, and this is seen in Fig. 8 as a reduction of Colorado and Hybrid lows in this month.

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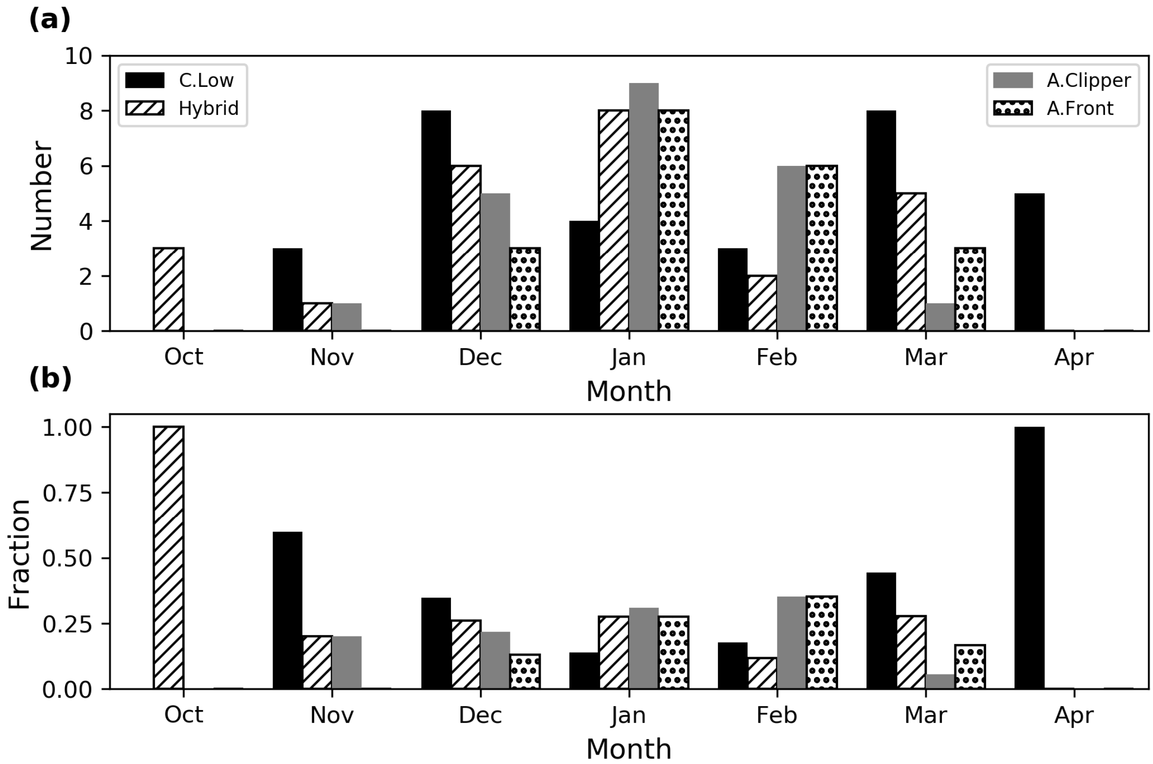

Figure 8. (a) Number and (b) fraction of monthly blizzards for the winter seasons of 1979-1980 to 2017-2018 separated by type.

3.3. Objective classification of patterns using a SOM

Surface and 500 hPa analyses for the midpoint of blizzard events in the 8-class SOM are shown in Figs. 9-10. The SOM shows a progression of patterns that shift from cold fronts associated with CAA (nodes 1/5) to deeper surface lows (nodes 3/4/7/8). These patterns have 500 hPa analyses similar to those seen in earlier composites. For example, nodes 1/5 resemble Arctic Front patterns with strong northwesterly flow aloft, while the rightmost nodes appear as Colorado Lows with either upper-level toughing (nodes 3/4) or a closed low (node 7/8). The progression of systems is also similar to the composites shown earlier (not shown). For example, the rightmost nodes (7/8) progress northeastward like a Colorado Low. Shifting from right-to-left, the mid-latitude cyclones become weaker and have tracks that are displaced northerly, consistent with Hybrid/Alberta Clipper type systems. While the SOM has many positive traits when compared to the composites, it by no means is a perfect reproduction of the subjectively classified classes. For example, Arctic Fronts have pressures that are too low 12 – hrs prior to the midpoint of events resulting in weak cyclones vs. the open trough seen in Fig. 4. This is undoubtedly a result of the neighborhood function within the SOM smoothing this category with other mid-latitude cyclone nodes. Increasing the SOM to a 5x3 map mitigates this issue, but at the expense of decreasing the number of blizzards that occur per class (not shown).

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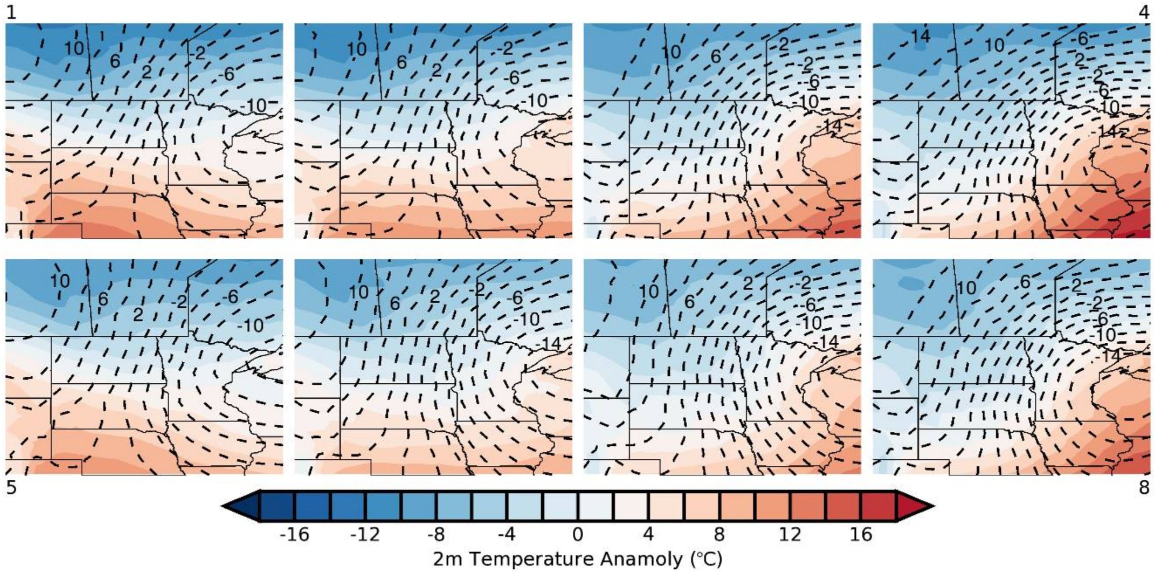

Figure 9. MSLP (mb, dashed lines) and surface temperature (°C, filled contours) anomalies during the midpoint of blizzards for the 8-class (2x4) SOM. Nodes are identified by the external numbers randing from 1-4 (5-8) for the top (bottom) rows.

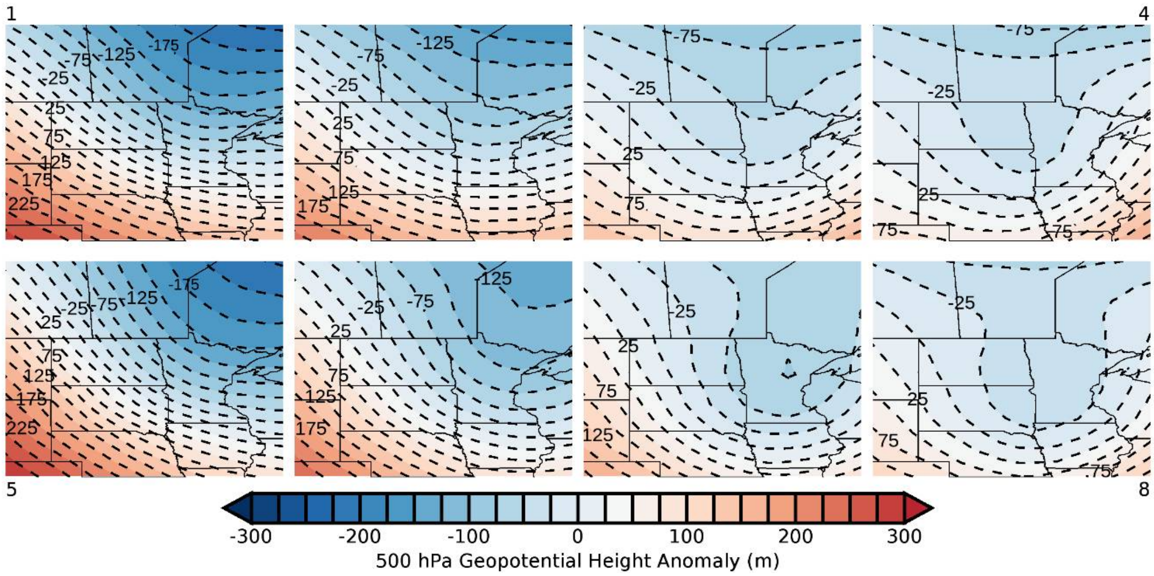

Figure 9. As in Fig. 8 except for 500 hPa height anomalies (shaded and dashed contours).

As a final test of the SOM's ability to segregate patterns, the subjectively classified events were categorized to the 8-class SOM (Fig. 11). As expected by the meteorological interpretation of the nodes, patterns have distinct areas of occurrence. Colorado Lows (Fig. 11a) only occur on the right-hand-side of the SOM, with the majority of the cases occurring within Node 4. Alberta Clippers occur within the left-most 6 nodes, with most occurring within Nodes 1,2,6, and 7. Hybrids, which are subjectively defined as patterns with features of multiple patterns are the only category to occur within every node. That said, the majority of these cases occur within Nodes 3 and 7, in-between Colorado Lows and Alberta Clippers. Finally, Arctic Fronts are primarily on the left-hand-side of the SOM with the majority of the cases occurring in Node 5. From a probability stand-point, categories within the SOM can be arranged in a column fashion, with probability of occurrence shifting from Arctic Fronts (Nodes 1/5), to Alberta Clippers (Nodes 2/6), to Hybrids (Nodes 3/7), to Colorado Lows

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(Nodes 4/8). By doing this, the time period of occurrence for these categories gives results similar to the results shown in Fig. 8 with seasonal occurrence of SOM nodes varying by column (Table 2).

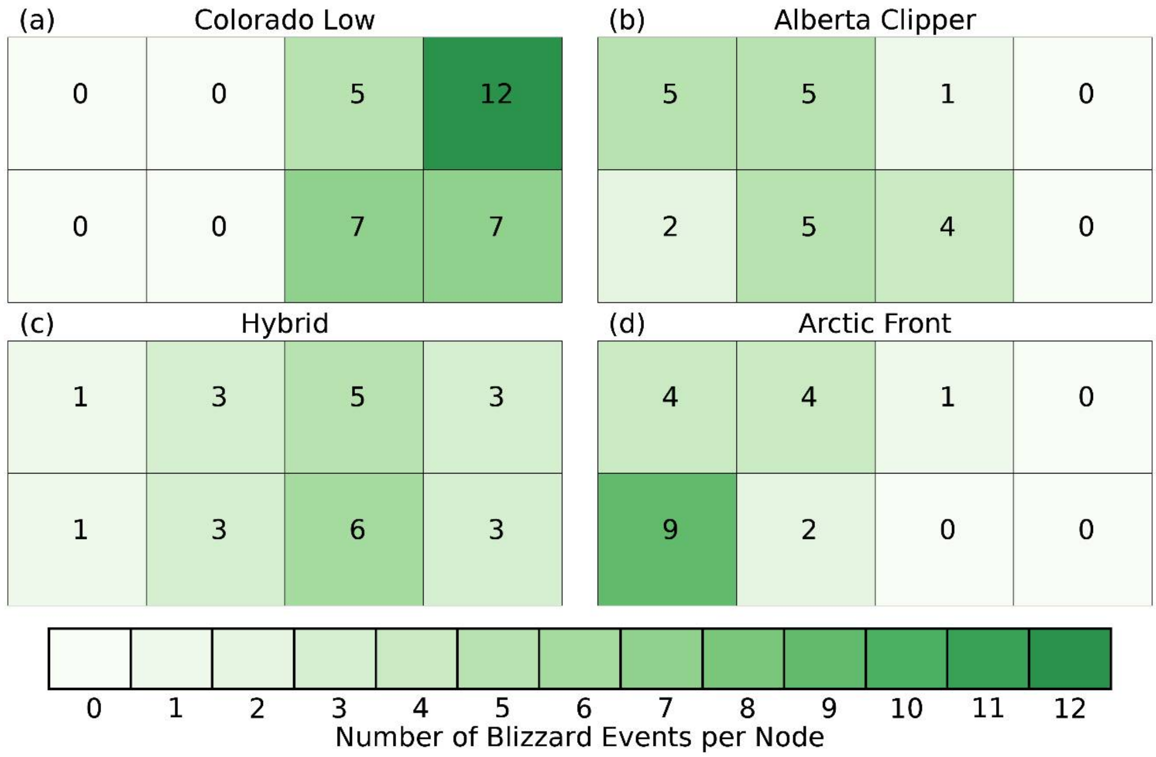

Figure 10. Number of (a) Colorado Low, (b) Alberta Clipper, (c) Hybrid, and (d) Arctic Front blizzards identified within each of the eight SOM nodes.

Table 2. Number of blizzards segregated by month and SOM nodes.

	Nodes 1/5 (Arctic Front)	**Nodes 2/6 (Alberta Clipper)**	**Nodes 3/7 (Hybrid)**	**Nodes 4/8 (Colorado Low)**
October	0	0	2	1
November	0	0	2	3
December	2	7	9	5
January	12	5	8	4
February	6	6	3	2
March	4	4	4	6
April	0	0	1	4

3.4. Discussion and Future Work

The good agreement between subjectively and objectively identified blizzard patterns provides evidence that the characteristics of these events including types of patterns and time periods of occurrence are well understood. The use of a relatively small SOM and inclusion of only several variables to obtain this finding is a positive result that suggests SOMs can be used to investigate a number of outstanding questions regarding blizzards. Some of these activities are now discussed.

Within the realm of weather prediction, a constant struggle is determining whether visibility criteria will be met to justify and verify products such as NWS blizzard warnings. Although blowing snow parametrizations exist [41-42], they are not currently included in operational Numerical NWP models within the US. Instead, local forecasters must use empirical models that determine a probability of blowing snow given conditions such as wind speed, air temperature, and snowpack

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conditions [43]. The context of how these events fit within the scope of forcing mechanism (type of event) is currently only considered subjectively (e.g. Arctic Fronts are harder to forecast vs. Colorado Lows). A possible solution is to include real-time identification and classification of forecast atmospheric patterns from deterministic or even ensemble NWP systems. Prior to the implementation of such a system, the SOM methodology must be applied to null cases to understand the nuances between patterns that do and do not produce blizzard conditions. This retrospective analysis of patterns could also provide insight into events that may have been missed by the observation system or were too limited in scope to fit within the traditional zone/county verification process at the NWS. Pattern recognition could be also be extended farther back in time using datasets such as the 20th Century Reanalysis [44] to yield a long-term climatology of blizzards.

How the frequency and intensity of RRV blizzards may change in a warming climate is also unknown. Previous studies have focused on how precipitation or cyclone frequency may change independently. From the Clausius-Clapeyron relationship, a warmer climate will dictate higher amounts of column water vapor and thus precipitation [45]. During the winter, however, there will be a balance between warmer temperatures, column water vapor, and precipitation phase. Overall, a general decline in snow cover has been found for the northern hemisphere and much of this is due to a significant shortening of the snowy season [46-47]. Despite this trend, the RRV region has seen an increase in snowfall, especially for higher end events with 2+ inches [48-49].

Regarding forcing mechanisms for RRV blizzards, mixed results have been found for extratropical cyclones. While some studies suggest a decrease in NH wintertime cyclone frequency [50-51], other work suggests the strongest cyclones have intensified or could further intensify in future climate projections [52-54]. Regarding specific patterns identified within the present study, [55] identified there will be a projected decrease (increase) in Alberta Clippers (Colorado Lows) over North America. It is unknown how Hybrid lows or Arctic Fronts may change, and this is an avenue of work that SOMs can provide insight to as they can provide information on type and frequency of occurrence of patterns.

4. Summary

A climatology of documented blizzard events within *Storm Data* for the Grand Forks NWSFO CWA for the winter seasons of 1979-1980 to 2017-2018 was presented. The NARR was used to composite and objectively classify patterns. These results are now summarized.

- Over the past 39 years, 100 documented blizzards were reported in *Storm Data*, resulting in an average of 2.6 blizzards per year. This dataset strongly correlates with an unofficial record of societally impactful events named by the Grand Forks Herald, a local newspaper.

- RRV blizzards occur between October and April and have a distinct bimodal distribution of occurrence, with 58% of the events occurring from Dec. 15th to Feb 15th. After a lull in late February, a separate (weaker) maxima occurs in March.

- The Grand Forks NWSFO has subjectively classified blizzard patterns into four classes: Alberta Clippers, Arctic Fronts, Colorado Lows, and Hybrids. Composite patterns resemble the expected meteorological patterns with variations in the intensity, position, and progressiveness of the mid-latitude cyclone and upper-level trough. Hybrids appear as lows that have tracks in-between the Alberta Clipper and Colorado Low systems.

- Patterns have seasonal variability, with most early/late season blizzards caused by Colorado and Hybrid Lows. Alberta Clippers and Arctic Fronts are more common in the middle of the winter with peak occurrence of these latter patterns in Jan.-Feb.

- A relatively simple 8-class (4×2) SOM can reproduce the general characteristics of the composite patterns. A transition in patterns is seen from Colorado Lows → Hybrids → Alberta Clippers →

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Arctic Fronts. This results in reasonable separation of subjectively identified events and good agreement in the seasonality of these patterns. This adds confidence to the subjective classification of patterns.

While these results are most relevant to the local populace, the last point has important ramifications for the broader weather and climate communities. Impactful weather events such as blizzards are challenging to forecast/detect over both short and long time-scales due to properties (e.g. visibility) that are not explicitly simulated by weather and climate models. The success of the SOM technique to objectively classify patterns suggest that pattern recognition can be used to address problems such as the predictability of hazardous weather events in NWP ensembles, or trends in these events in climate simulations. These subjects are the topics of forthcoming work.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Storm Data Blizzards in the Grand Forks NWSFO CWA 1979-1980 – 2017-2018.

Year	Month	Day	Midpoint Hour in NARR	Type
2018	1	11	0	Front
2017	12	4	21	Colorado
2017	3	7	6	Hybrid
2017	1	12	18	Front
2016	12	26	15	Colorado
2016	12	7	12	Hybrid
2016	11	18	12	Colorado
2016	2	8	9	Clipper
2015	1	8	21	Clipper
2015	1	3	12	Clipper
2014	3	31	21	Colorado
2014	3	21	15	Front
2014	3	6	0	Ground
2014	2	26	21	Front
2014	2	13	12	Clipper
2014	1	26	18	Clipper
2014	1	22	12	Front

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2014	1	16	12	Front
2014	1	4	6	Clipper
2013	12	28	21	Front
2013	3	18	9	Hybrid
2013	2	18	21	Hybrid
2013	2	11	3	Colorado
2013	1	19	18	Front
2013	1	12	3	Colorado
2011	3	12	6	Clipper
2011	1	1	9	Colorado
2010	12	30	21	Colorado
2010	10	27	9	Hybrid
2010	1	25	18	Clipper
2009	12	26	3	Colorado
2009	3	10	21	Colorado
2009	1	12	15	Clipper
2008	12	14	15	Colorado
2008	2	9	18	Front
2007	3	3	0	Hybrid
2006	1	24	15	Front
2005	11	16	3	Clipper
2005	10	6	3	Hybrid
2005	1	22	6	Clipper
2004	2	11	18	Clipper
2003	2	11	18	Front
2001	12	23	0	Colorado
2001	10	25	0	Hybrid
2001	2	25	12	Colorado
2000	12	21	3	Clipper
2000	12	16	15	Hybrid
2000	3	9	3	Colorado
1999	12	19	18	Clipper
1999	4	1	18	Colorado
1999	3	17	18	Hybrid
1999	2	12	12	Front
1998	12	18	21	Clipper
1998	11	10	21	Colorado
1998	3	13	18	Front
1997	4	6	12	Colorado
1997	3	4	9	Colorado
1997	1	22	12	Hybrid
1997	1	15	21	Front
1997	1	10	9	Clipper

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1997	1	5	9	Colorado
1996	12	31	21	Valley
1996	12	21	12	Front
1996	12	18	0	Clipper
1996	11	17	9	Colorado
1996	3	25	0	Colorado
1996	2	27	21	Hybrid
1996	2	10	21	Clipper
1996	1	18	12	Hybrid
1995	12	9	0	Hybrid
1995	2	10	6	Clipper
1994	4	26	15	Colorado
1993	12	22	0	Clipper
1992	12	25	6	Front
1991	12	14	3	Hybrid
1990	1	11	12	Clipper
1989	2	1	6	Front
1989	1	7	21	Hybrid
1988	3	12	3	Colorado
1988	2	14	15	Clipper
1988	1	24	21	Hybrid
1988	1	12	15	Hybrid
1987	12	31	3	Colorado
1986	4	15	3	Colorado
1985	11	19	3	Hybrid
1985	3	4	6	Colorado
1985	1	25	0	Front
1984	12	16	18	Colorado
1984	3	10	15	Front
1984	2	5	6	Front
1983	12	25	0	Hybrid
1983	12	15	9	Hybrid
1983	3	8	21	Colorado
1982	4	3	12	Colorado
1982	3	8	15	Hybrid
1982	1	23	15	Colorado
1982	1	10	18	Hybrid
1981	2	1	12	Colorado
1980	1	11	15	Hybrid
1980	1	7	3	Hybrid

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