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Blizzards In The Upper Midwest, 1980-2013

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BLIZZARDS IN THE UPPER MIDWEST, 1980-2013

by

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This thesis, submitted by Lawrence Burkett 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 the work has been done and is hereby approved.

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

Wayne Swisher
Dean of the School of Graduate Studies

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Lawrence Burkett
July 22, 2015

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ABSTRACT

Blizzards are severe snowstorms characterized by high winds and enough snow in the air to significantly reduce visibility near the surface. In the conterminous United States, published scientific literature indicates blizzards as common in the Dakotas and Minnesota. In this study, blizzard frequency by year, month, and county was recorded from 1980-2013 in eastern North Dakota and northern Minnesota. Additionally, blizzard duration and area impacted were estimated including trends in blizzard frequency. Ninety-three blizzards impacted the Upper Midwest in 34 years studied with an average of 2-3 blizzards per year, with a linear increase in blizzards with respect to time. However, variation exists in the number of blizzards each year. All blizzards occurred from October-April with greatest frequency from December through February. Typical blizzard durations were several hours, while areas impacted averaged 50,000 km^2. Differences in blizzard frequency in the Upper Midwest are strongly related to differences in forest cover.

DEFINITIONS

Blizzard (Schwartz 2005): a severe snowstorm with 1) sustained or frequent wind gusts of 15.6 m s^{-1} (35 mi h^{-1}) or greater; and, 2) enough snow in the air to reduce visibility to less than 402.3 m (0.25 mi) for three or more hours.

Macroscale (Markowski and Richardson 2011, 5-7): meteorological phenomenon with 1) (lateral) length scales greater than 2,000 km; and, 2) time scales on the order of several days or more.

Mesoscale (Markowski and Richardson 2011, 5-7): meteorological phenomenon with 1) (lateral) length scales ranging from 2-2,000 km; and, 2) time scales on the order of several hours.

Microscale (Markowski and Richardson 2011, 5-7): meteorological phenomenon with 1) (lateral) length scales less than 2 km; and, 2) time scales on the order of an hour or less.

CHAPTER I

INTRODUCTION

A blizzard is a severe snowstorm that is characterized by high winds and enough snow in the air to significantly reduce visibility near the surface. Sometimes blizzards are referred to as a type of winter storm; even though blizzards have occurred in other seasons (Wagner 1985; Kocin, Gartner and Graf 1998; Schwartz and Schmidlin 2002). Blizzards can close airports, businesses, churches, government offices, rail lines, roadways, and schools. Blizzards may also do damage to structures, sever utilities, and result in injury and loss of life (Schwartz 2004). For example, from 1959-2000 blizzards in the conterminous United States directly resulted in 679 deaths, 2,011 injuries, $22,600,000,000 worth of property damage, and $1,080,000,000 worth of crop damage adjusted to 2001 dollars Schwartz (2001).

Historically, numerous blizzards have impacted locations in the United States. According to Schwartz and Schmidlin (2002), blizzards occur and impact parts of the Dakotas and Minnesota more so than any other areas of the conterminous United States in a region referred to as the “blizzard zone” in their study of blizzards from 1959-2000. Prior to Schwartz and Schmidlin (2002), factual accounts of blizzards in parts of the Dakotas and Minnesota can be found in American literature dating back to the late 19^{th} and early 20^{th} Century with stories of pioneers, urbanites, sailors, and Native Americans battling the worst winter conditions.

In my thesis, *Storm Data* publications were used to study blizzard frequency in the Upper Midwest, a 45 county area covering 180,335 km^2 in parts of Minnesota and North Dakota, as shown in Figure 1 using provincial, state, and county boundaries provided by the Environmental

Systems Research Institute (ESRI).

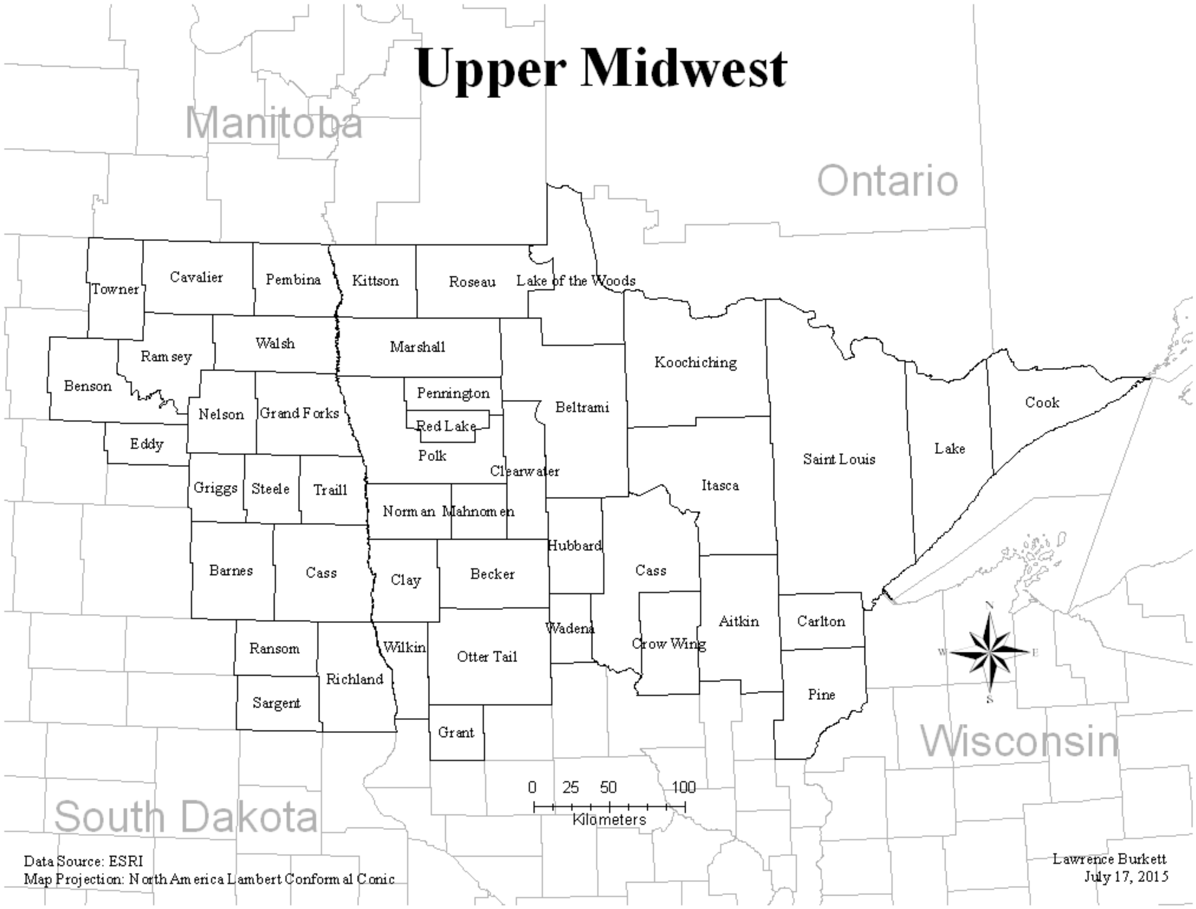

Figure 1. County boundaries of the Upper Midwest are shown with thick black lines. Source: ESRI.

According to Branick (1997), *Storm Data* publications are more likely to contain reports of blizzards than other sources since the occurrence and duration of blizzards would probably require collocating simultaneous observations of snow, visibility, and wind speed as well as the type of any obstructions nearby at the surface. My thesis is a contribution to Branick (1997, 193) who addressed the need to develop a greater understanding of the mesoscale aspects of "winter-type" storms including blizzards. In addition, my thesis is also a refinement to Schwartz and Schmidlin (2002) who studied blizzards in the conterminous U.S. using *Storm Data*.

The landscape in the Upper Midwest is rural in comparison to other parts of the United States, and is primarily covered by a mixture of coniferous and deciduous forest in the east and open areas of croplands and prairie in the west. Differences in elevation in the Upper Midwest are on the order of a few hundred meters with hills dominating in the east and flat to gently rolling orography in the west. Substantial areas of human population in the Upper Midwest include the Duluth, Fargo and Grand Forks metropolitans, several Native American reservations, and a collection of other numerous smaller urban areas ranging from primarily farming and ranching towns in the west to forestry, mining, and lake resort communities in the east.

CHAPTER II

LITERATURE

Early Blizzards

As briefly mentioned in the introduction, a few years after the first official blizzard impacted Iowa and Wisconsin in December 1876 (Wild 1997), a sequence of blizzards impacted parts of what was then the Dakota Territory from the fall of 1880 through the spring of 1881 as described by Laura Ingalls Wilder in her novel *The Long Winter* (Wilder 1940). In Wilder (1940), the lack of warnings caught many off guard leaving those outdoors at the peril of nature's fury in blinding snow, snow drifts, and bitterly cold air. In the late 19th century in Dakota Territory, rail transportation was the primary means by which food and supplies were delivered to towns. In Laura's case, the lack of snow removal equipment to clear a vital rail line between her town and larger towns and cities back east resulted in the seizure of rail transportation for months that would have otherwise delivered necessary items such as food, fuel, medical supplies, and materials needed to make warm clothing (Wilder 1940). In addition, Wilder (1940) indicated that most homes from that era and perhaps most buildings in general, were not built to withstand the wind and snow from blizzards. The dire result was snow being blown into her home from outside while cracks on the rooftop, presumably from a combination of wind-blown debris and snow loading, led to dripping water inside her home.

On January 12th, 1888, the Children's Blizzard impacted part of the Dakotas and Minnesota following a snowstorm on January 7-8th that deposited a dusting of powdery snow over the region. The January 7-8th snowstorm was followed by a bitterly cold airmass before a rapid return to much warmer weather. At the onset of the blizzard, the air was warm enough to support outdoor activities. However, despite the warm airmass that had been in place early on January 12th, 1888, a cold front was reported to have "raced down the undefended grassland like a crack unstoppable army" through the morning and afternoon hours of January 12th, catching many off guard including numerous children (Laskin 2009, 1).

According to Laskin (2009), the severity of the blizzard on January 12th, 1888 in terms of loss of life and injuries was exacerbated by the lack of blizzard preparedness and warning in the 1880s. Blizzards were not very common in heavily populated places such as northeastern United States, Germany, and Norway, where many of the early pioneers had immigrated from to farm the prairies (Wild 1997). Also, during the 1880s, there had not yet been fences or trees planted to help retard wind and snow, and what warnings residents of the interior of United States might have had by agencies such as the United States Army's Signal Service were limited, and in some cases taboo. Certain terms (e.g. tornado) may have caused panic if mentioned in warnings (Bradford 2001; Laskin 2009).

The White Hurricane of November 1913 produced blizzard conditions west to Minnesota even though it is regarded as primarily a Great Lakes event (Brown 2004). The impending blizzard was first noted in Minnesota on November 6th by weather observers employed by the United States Department of Agriculture's Weather Bureau (Brown 2004). By November 7th, blizzard conditions were reported across much of eastern Minnesota, and by November 8th winds were commonly in excess of 22.4 m s^{-1} (50 mi h^{-1}) at Duluth with periods of heavy snowfall. By the time the blizzard had moved east of Minnesota on November 9th, damages occurred from Minnesota east through the Great Lakes including the sinking of numerous large sea-fairing vessels (Brown 2004).

The 1920 blizzard was one of the worst on record for North Dakota in particular. From March 15-18th, 1920, Henke (1998) reported that at least one rail corridor and most telephone services were severed, and that at least 34 people perished during the blizzard. Among those dead were several children who had ventured home from school (Henke 1998).

The Armistice Day Blizzard of November 11-12th, 1940 impacted portions of Minnesota and the Dakotas. In Minnesota, the Armistice's Day Blizzard is regarded as one of the worst on record. According to Seeley (2006), the Armistice's Day Blizzard occurred at a time when the Weather Bureau had been transferred from the United States Department of Agriculture to the United States Department of Commerce. The Department of Commerce was responsible for large areas within interests in aviation versus agriculture. Nevertheless, weather forecasters at the large, U.S. Weather Bureau office in Chicago issued a moderate cold wave warning for Minnesota early on November 11th in advance of a northeasterly-moving cyclone centered in west Texas – and a southeasterly-moving anticyclone located in western Canada (Seeley 2006). By the afternoon hours on November 11th, the drizzle and rain that had started on November 10th had turned to sleet and snow across Minnesota as the low tracked from west Texas to Duluth and sustained winds increased to around 11.2 m s^{-1} (25 mi h^{-1}) with gusts in excess of 26.8 m s^{-1} (60 mi h^{-1}) (Seeley 2006). By late November 11th, blizzard conditions covered much of Minnesota and parts of the Dakotas with snowfall rates close to four inches per hour (Seely 2006). During the blizzard, numerous utility lines snapped and most rail lines and roads became impassable.

When the blizzard was over the following day, thousands of game birds and livestock died, and at least 49 people from Minnesota perished Seeley (2006). The Armistice Blizzard and another blizzard the following March resulted in the Governor of Minnesota and Congress to call for better warnings from the U.S. Weather Bureau. This push led to the first United States Weather Bureau office being opened in Minnesota a short time later (Seeley 2006).

In early March 1966, a blizzard impacted parts of the Dakotas and Minnesota. According to *Storm Data*, extensive blowing and drifting snow paralyzed the region for several days, even though temperatures did not drop sharply during the blizzard. In total, at least 12 people died, numerous injuries resulted, and over $1,500,000 in property damage in 1966 dollars were done during the blizzard despite warnings. In eastern North Dakota, at least 27,300 livestock perished while farther east losses were less because forest cover in parts of Minnesota tended to limit drifting snow during the blizzard.

Blizzard Definitions

According to Black (1971), the first use of the word blizzard in reference to a snowstorm is somewhat obscure. However, it is known that mariner Henry Ellis used the word to describe a storm they endured on Hudson Bay in 1746 (Greely 1888). According to Wild (1997), the first reliably known use of the word blizzard as a storm in the U.S. can be traced back to a severe snowstorm that impacted Iowa and Wisconsin on December 8th, 1876 that was documented in the U.S. Signal Service's *Monthly Weather Review* journal in December 1876.

From the 1870s through the 1970s, blizzards in the U.S. were defined by a variety of different criteria and thresholds; hence, a blizzard that occurred decades ago is not necessarily comparable to a blizzard today (e.g. United States Air Force 1978; Wild 1997; Schwartz 2005). However, according to Schwartz (2005), the National Weather Service abandoned prior definitions of blizzards sometime in the 1970s in favor of using the following standard definition of a blizzard for counties in the United States by the following weather conditions lasting three or more hours: 1) sustained or frequent wind gusts of 15.6 m s^{-1} (35 mi h^{-1}) or greater; and, 2) enough snow in the air to reduce visibility to less than 402.3 m (0.25 mi).

In English-speaking countries outside the United States where blizzards are known to occur, blizzards are defined by a variety of different criteria. For example, in Canada, whether or not a blizzard warning is issued for a location depends on whether the location is north or south of the semi-permanent tree-line (Environment Canada 2015). For locations south of the semi-permanent tree-line, a blizzard warning is issued when winds of 11.1 m s^{-1} (40 km hr^{-1}) or greater occur and cause widespread reductions in visibility to 400 m or less, due to blowing snow, or blowing snow in combination with falling snow, for at least four hours. North of the semi-permanent tree-line in Canada, a blizzard warning using the same criteria as south of the semi-permanent tree-line with a six-hour threshold required during which blizzard conditions occur (Environment Canada 2015). In the United Kingdom, a blizzard is defined for a location when moderate or heavy snowfall with winds of at least force 7 or 12.8 m s^{-1} (46 km h^{-1}) causes drifting snow and reduced visibility to less than 200 m (Wild 1997). However, Wild (1997) indicates that blizzards are not mentioned in official advisory products issued by the Meteorological Office in the United Kingdom.

Photo Evidence of Blizzards

Photos in Figures 6-15 in the Appendix were obtained in-situ, during or immediately following blizzards in Grand Forks County, North Dakota, while earning my Master's degree at The University of North Dakota. It is important to note that all photos in the Appendix were taken while cautiously to avoid injury or death.

Meteorology of Blizzards

Despite having endured numerous historical blizzards from the late 1870s through the early 1940s, it was not until about the mid-1940s that scientific research in the United States on the topic of blizzards began. Haurwitz and Austin (1944) represent what is perhaps the earliest scientific research on blizzards stating that blizzards tend to occur in Köppen (1931) Type D continental climates that are characterized by winter snow cover and definite seasonal temperature cycles.

From the late 1940s through the mid-1970s, much of the scientific research done on the topic of blizzards was embedded in literature that addressed macroscale features of cyclones such as fronts, jets, and upper-air troughs that were thought to be responsible for driving cyclone origin, depth, intensity, and track (Teweles and Norton 1950; McQueen and Loopstra 1957; Hughes 1958; Black 1971; United States Air Force 1978). The macroscale treatment of blizzards as exceptionally deep or deepening snow-producing cyclones in scientific literature during this era Black (1971), was concurrent with developments in the ability to obtain routine, simultaneous, or synoptic, upper-air measurements from around the world following World War II. The availability of synoptic upper-air measurements eventually helped Bjerknes and Holmboe (1944), Sutcliffe (1947), Sutcliffe and Forsdyke (1950), and Petterssen (1956) theoretically confirm the mechanisms controlling cyclone origin, depth, intensity, and track in the extra-tropics in what became known as quasi-geostrophic theory which stemmed from research pioneered by Bjerknes and Solberg several decades before in their "Norwegian frontal cyclone model" (Bjerknes 1919; Bjerknes and Solberg 1921; Bjerknes and Solberg 1922).

Focusing on the research done by Black (1971), a sample of snow-producing cyclones that impacted the north-central conterminous United States from 1957-1967 were subject to quasi-geostrophic theory to determine the characteristics of cyclones that had resulted in blizzard conditions. Black (1971) discovered blizzards were generally a severe wind phenomenon resulting from the passage of deep or deepening cyclones in the presence of snow, whether blowing or falling. To improve weather forecasts of blizzards, Black (1971) applied quasi-geostrophic theory to observations from across North America and used those observations in determining the controls of several snow-producing cyclones, including several that resulted in a blizzard, as they tracked across the north-central United States from two favored regions: 1) the lee of the Rockies in Colorado and, 2) the lee of the Rockies in Alberta. In total, Black (1971) identified 53 cyclones that resulted in blizzard conditions in the north-central conterminous U.S. with 25 originating in Colorado as "Colorado Lows", 20 in Alberta as "Alberta Lows", and the remaining 8 classified as "Other" (Black 1971, 5-6).

According to Black (1971), Colorado low-type cyclones are one of the major year round weather producers in the United States and typically formed in one of the most favored areas of cyclogenesis in the United States and then migrate onto the nearby plains. Black (1971) found that on the average 39 Colorado lows form from November to March, and that two to three blizzards will generate from such lows. Alberta lows in comparison occur most frequently compared to all lows over western North America; on average, forty-two Alberta lows occur during between November and March. Alberta lows cause storminess on both sides of the Canadian-United States boarder, but the storms most frequently occur across the prairie provinces of Canada. Approximately two blizzards per year result from Alberta lows. The month of March had the greatest number of blizzards during the 10 years studied with 10 of the blizzards having been Colorado low-type cyclones. The greatest number of Alberta low blizzards occurred from December to February, the months when the Canadian storm track is farthest south. In November, as in March, there were more blizzards from Colorado low-cyclones than from Alberta low-cyclones (Black 1971).

From the late 1970s through the early 1990s, scientific research on the topic of blizzards relied more upon recent advances in computing as well as newer weather instruments such as radar and satellite. For a thorough review of numerical weather prediction up through the late 1970s, the reader is encouraged to refer to Shuman (1978). Focusing on blizzards, in Salmon and Smith (1980), a thorough analysis of a cyclone that resulted in a blizzard for a large part of the United States in January 1978 was performed using a numerical model that solved for cyclone origin, depth, intensity, and track using quasi-geostrophic theory. By comparing model solutions with observations, Salmon and Smith (1980) were able to determine that the cyclone that resulted in epic snowfall and snow drifts across a large part of the central United States was different than typical snow-producing cyclones in terms of the phasing of two anomalously vigorous upper-air troughs in the westerlies that resulted in the unusual depth and intensity of the surface low. In Zapotocny, Johnson and Reames (1993), a blizzard that impacted the Chicagoland area in January 1979 was studied from an isentropic perspective by comparing solutions from a numerical model that used entropy as the vertical coordinate in comparison to another more traditional model that used scaled-pressure, or sigma, as the vertical coordinate. As early as the 1980s, Kocin (1988) demonstrated that it is possible to reconstruct prior blizzards that predate the use of upper-air observations in a re-analysis in their study of a supposed blizzard that impacted the Northeast United States in 1888. Although not exclusive to blizzards, Zishka and Smith (1980) contributed to research on the topic of blizzards by identifying cyclone tracks during the month of January, 1950-1977. Relevant findings from Zishka and Smith (1980) were: 1) cyclones in January most often formed in lee of the Rockies of Alberta and

Colorado and tracked downstream onto the plains; and, 2) the number of cyclones appeared to perhaps be decreasing with respect to time.

As the science of meteorology matured from the about the mid-1990s onward, research on the topic of blizzards began to incorporate a variety of other both new and old sub-disciplines of meteorology such as mesoscale meteorology and clouds physics to study the finer scale structure of snow-producing cyclones resulting in blizzards (e.g. Kocin 1992; Marwitz and Toth 1993; Heffernan and Marwitz 1996; Wei and Marwitz 1996; Zupanski et. al 2002). For example, Brock et al. (1995) indicated the development of a state-wide mesonet in Oklahoma, while Benjamin, Brundage and Morone (1994) summarized their development of a terrain-following numerical weather prediction model aimed at forecasting finer scale phenomenon. In addition, Halpert and Smith (1994), showed that exceptional snow-producing cyclones resulting in blizzards could occasionally be found in literature related to topics of climatology and climate teleconnections as indicators of signals, or anomalous shifts, in longer-term patterns. Dery and Yau (2001) addressed a blizzard in the Arctic using numerical modeling as a turbulent microscale interaction between blowing snow and the mesoscale structure of the atmospheric boundary layer near the surface. In Coutts and Grace (1995), several seminal studies were presented on the topic of wind flow and its interaction with trees. In particular, Finnigan and Brunet (1995) show different types of turbulent wind flows in and around forests in flat versus hilly terrain to better understand wind flow origins and impacts. When coupled with the Black (1971) generalization of blizzards as a severe wind phenomenon along with the observations made by Bavendick (1920), who reported that blizzards were influenced by microscale obstacles such as buildings, fences, and tree stands, Finnigran and Brunet (1995) were undoubtedly unraveling the acute behavior of blizzards on scales comparable to Upper Midwest.

Blizzard Frequency

Several authors have written about blizzard frequency either directly, or indirectly, as part of studies focused on snowstorms. The most extensive study of blizzard frequency to date for the conterminous United States was done by Schwartz and Schmidlin (2002) in their study of blizzard frequency using *Storm Data* publications from 1959-2000. By identifying 1) the average area impacted by blizzards; and, 2) a decreasing trend towards smaller areas impacted with respect to time from 1959-2000, Schwartz and Schmidlin (2002) provided evidence in support of Branick (1997) who regarded blizzards as phenomenon with mesoscale aspects. Schwartz and Schmidlin (2002) also identified parts of the Dakotas and Minnesota as having the highest blizzard frequency in the conterminous United States with an average of one or two blizzards per year per county, and identified January as the most favorable month of the year for blizzards in the Dakotas and Minnesota. Additional findings from Schwartz and Schmidlin (2002) relevant to my study were: 1) annual probabilities of blizzard frequency of 50 to 76% in parts of the Dakotas and Minnesota; and, 2) the finding that the number of blizzards in the conterminous United States increased linearly with respect to time from 1959-2000. One of the shortcomings of Schwartz and Schmidlin (2002) was that all reports of blizzards in *Storm Data* were pooled together from 1959-2000 regardless of the definition used. The definition used different thresholds for visibility and wind speed as well as a temperature criterion prior to the 1980s (Schwartz 2005); hence, Schwartz and Schmidlin (2002) contains a problem of definition in that a blizzard from the 1960s, for example, might not be comparable with a blizzard from the 1990s as listed in *Storm Data*.

In addition to Schwartz and Schmidlin (2002), Branick (1997) studied the frequency of blizzards by county, 1982-1994, in the conterminous United States using *Storm Data* and included other types of significant winter-type weather events such as heavy snow, freezing rain and sleet events. Since Branick (1997) considered blizzards from 1982-1994 (no temperature criterion for blizzards), only reports of blizzards in *Storm Data* that share the same, modern definition were included. An important finding from Branick (1997) was the prevalence of significant winter-type weather events on mesoscales.

For those given the task of forecasting the weather, it is generally accepted that blizzards occur most often during the passage of cyclones. Prior to Schwartz and Schmidlin (2002) and Branick (1997), Black (1971) studied blizzards in the north-central conterminous U.S. from 1957-1967. While exhaustive for its time in that Black (1971) was able to identify macroscale features that would potentially drive high winds near the surface by tracing the origins and tracks of several cyclones that generated blizzards, Black (1971) did not address the influence that surface features might have had on the otherwise fast moving air circulating throughout the interior of cyclones. This is primarily because application of quasi-geostrophic theory at that time traditionally invoked equations representative of smooth, frictionless flow. In addition, the definition of a blizzard in Black (1971) is different from the definition of a blizzard used today. Nevertheless, Black (1971) represents one of the first scientific contributions on the topic of blizzard frequency.

Prior to Black (1971), Bavendick (1920) also wrote about the frequency of blizzards in more or less detail. In *Blizzards and Chinooks of the North Dakota Plains*, Bavendick (1920, 1) likened the most favorable time for a blizzard as "after a snowstorm, when the temperature is low and the snow has not packed" following his years of experience as a weather observer in North Dakota. Bavendick (1920) addressed the influence that microscale features such as buildings, fences and trees might have on the wind flow during blizzards. In Fox (1952), meteorological conditions which were thought to lead to the development of blizzards were presented in a magazine article titled *Blizzards in the Northern Plains* which appeared in one of the early editions of *Weatherwise*.

Focusing on authors who have written about snowstorms without regard for blizzards include Zielinski (2002) who researched several snowstorms that impacted the eastern and central United States in order to develop a classification and rating scheme for such storms on the basis of several parameters. However none of the parameters Zielinski (2002) used to classify and rate such storms were relatable to the definition of a blizzard. Similarly, Kocin and Uccellini (2004) developed a scale to rate snowstorms in the heavily populated Northeast United States using a sample of snowstorms on the basis of snowfall amount and where the snowfall occurred in terms of human population density. Kocin and Uccellini (2004) argued that higher snowfall amounts from snowstorms in highly urbanized areas are more disruptive than lighter snowfall amounts from snowstorms in rural areas. Kocin and Uccellini (2004) applied their scale to numerous additional storms east of the Rocky Mountains. Changnon, Changnon and Karl (2006) developed a climatology of snowstorms in the conterminous United States using snowfall amounts obtained from numerous surface weather stations from 1901-2001. To define a snowstorm, Changnon, Changnon and Karl (2006) used a threshold snowfall amount over a period of time. To illustrate their findings, Changnon, Changnon and Karl (2006) used a variety of useful figures showing the spatial and temporal frequency of snowstorms. In addition, Changnon, Changnon and Karl (2006) also indicated decadal periods with more or less snowstorms in the conterminous U.S. as related to cyclone frequency.

Outside of the United States, substantial research pertaining to blizzards included Lawson (2003) who studied blizzards in Canada using a standard definition applied to data obtained by select surface weather stations from 1953-1997. In Lawson (2003), an important finding was that no change was detected in terms of the number of blizzards reported just across the border in Canada even though the definition of a blizzard in Canada is different from the definition used in the United States. In the British Isles, Wild, O'Hare and Wilby (1997) performed a historical review of severe snowstorms, including blizzards, that impacted the United Kingdom from 1880-1989. In Wild (1996), careful effort was taken in defining a blizzard in the United Kingdom.

CHAPTER III

METHODOLOGY

Mining Storm Data Publications

To determine blizzard frequency in the Upper Midwest, I used reports of blizzards in monthly *Storm Data* publications that are compiled by the United States National Weather Service using information from a variety of sources which include: 1) weather reporting stations; 2) county, state and federal emergency management officials; 3) local law enforcement officials; 4) storm spotters; 5) official damage surveys; 6) newspapers; 7) the insurance industry; and, 8) the general public. In each monthly *Storm Data* publication, I searched for the keyword "blizzard" in the "Character of Storm" column and recorded the date of the storm, and the counties reported to have had blizzard conditions; identical to Schwartz and Schmidlin (2002).

Using "Character of Storm" in *Storm Data*, I identified and assigned a 1 for blizzard occurrence or a 0 for non-occurrence by counties impacted using an Excel 2010 spreadsheet according to date. In cases where specific counties were not listed, a consistent logical method was used to assign counties to area impacted. In my spreadsheet, blizzards spanning several days were regarded as one continuous blizzard event, while two or more blizzard reports separated by more than three hours were regarded as multiple blizzard events by assigning a two or greater for those dates, however rare. Using the time column in *Storm Data*, the start and end times of blizzards were recorded in my spreadsheet to the nearest hour. In cases where specific hourly start and end times were not listed, times were estimated from text provided in the description of the event.

Annual Blizzard Frequency and Trends

To determine annual blizzard frequency, I organized blizzards in terms of the year they occurred using years that begin on August 1st and end on July 31st such that the midpoint of each year occurs during the winter in the Earth's northern hemisphere; hence, the period from August 1st, 1980-July 31st, 1981 would be regarded simply as 1980, for example. An important note to consider is that all blizzard reports included multiple counties, and as such, a 'blizzard' in this case refers to all counties impacted by that particular blizzard.

To describe blizzard frequency, I created a table that included calculations of the total number of blizzards in the Upper Midwest as well as several measures of central tendency such as the mean, standard deviation, median, and mode, and extremes. To determine long-term trends in blizzard frequency, I created a histogram from data organized in my spreadsheet and performed an ordinary least square linear regression to determine whether there was a linear increase or decrease in blizzard frequency. By regarding sum of squares (R^2) values greater than 0.50 as meaningful, I determined whether blizzard frequency was very reliably changing; that is, to the extent that the ordinary least square linear regression is a reasonably good fit to the data.

Monthly Blizzard Frequency and Trends

Similar to how I organized annual blizzard frequency, I organized blizzards in terms of the month they occurred. Again, an important note to consider is that all blizzard reports included multiple counties, and as such, a "blizzard" in this case refers to all counties impacted by that particular blizzard.

To analyze annual blizzard frequency, I created a histogram in my spreadsheet and performed a regression by fitting the monthly blizzard frequency data to a second-order polynomial to determine trends in frequency since my data roughly exhibited the shape of a higher order polynomial with extreme values. By regarding R^2 values greater than 0.50 as meaningful, I was able to determine whether or not blizzard frequency exhibited a pattern.

Blizzard Duration and Area Impacted

To crudely determine blizzard duration, I calculated the difference between the start and end times for each blizzard in my spreadsheet. In cases when blizzards on the same date had different hourly start and end times, I calculated the average start and end times for that date. To summarize my results, I created a table that included extremes and several measures of central tendency to allow for differences in reporting efficacy in *Storm Data*.

To obtain the area impacted by each blizzard in the Upper Midwest, a GIS shapefile of county boundaries that I obtained via ESRI was used to replace the one list in my spreadsheet with county area. Area impacted by blizzards was summarized with a table in my spreadsheet that includes extremes, and several measures of central tendency.

County Blizzard Frequency

To determine county blizzard frequency in the Upper Midwest area, I summed all reports of blizzards by county in my spreadsheet and loaded the sums into ArcMap 10.2. Using a GIS shapefile of county boundaries that I obtained via ESRI, I projected my map layer as a North America Lambert Conformal Conic and classified blizzard frequency using a six-class Jenks scheme.

CHAPTER IV

RESULTS

Annual Blizzard Frequency

Table 1 summaries extremes and central tendencies calculated. In total, ninety-three blizzards impacted the Upper Midwest from 1980-2013. On average, 2-3 blizzards impacted my study each year. However, as indicated by Figure 2 there is a considerable spread in terms of the number of blizzards annually. For example, in 1980, 1982, 1989, and 1990, no blizzards occurred while in 1996 and 2013, nine blizzards occurred. Between 1980 and 2013 there were nine years with one blizzard, and twelve years with four or more blizzards. As a result and due to high variability in blizzard frequency, annual probabilities were not constructed.

Table 1. Total, measures of central tendency, and other relevant values pertaining to blizzard frequency in the Upper Midwest from 1980-2013 are indicated. Source: *Storm Data*, 1980-2013.

Number of Blizzards	93
Mean	2.7
Standard deviation	2.3
Median	2.0
Mode	1
Years with no Blizzard	4
Years with 2-3 Blizzards	9
Years with >3 Blizzards	12

The long-term trend in annual blizzard frequency in the Upper Midwest forms a positive slope as indicated in Figure 2. However, the low sum of squares value from the ordinary least squares regression performed offers little evidence for a long-term increasing or decreasing trend in blizzard frequency from 1980-2013 (i.e. $R^2 = 0.09$).

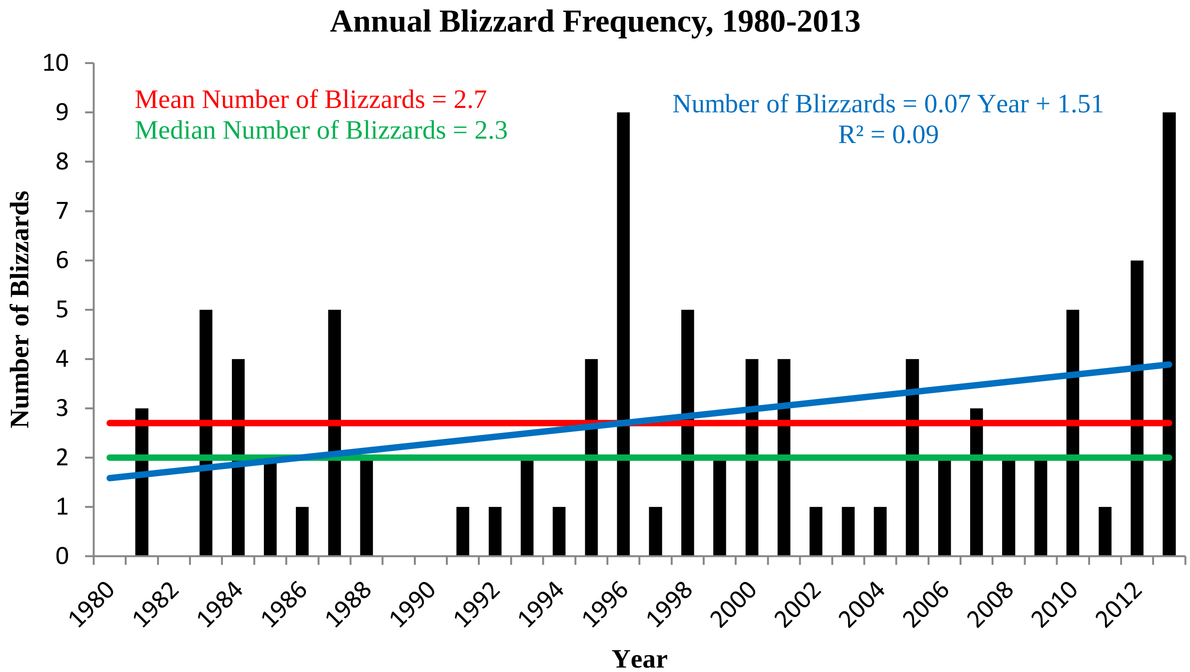

Figure 2. Annual blizzard frequency in the Upper Midwest from 1980-2013 is shown with black bars. Annual blizzard frequency averages 2-3, and ranges from no blizzards in 1980, 1982, 1989 and 1990 to nine blizzards in 1996 and 2013. The mean number of blizzards is shown in red, and the median number of blizzards is shown in green. The annual trend line, and ordinary least squares linear regression equation and sum of squares are shown in blue. Source: *Storm Data*, 1980-2013.

Monthly Blizzard Frequency and Trends

Figure 3 indicates monthly blizzard frequency in the Upper Midwest. Unlike annual blizzard frequency which varied considerably from year to year and exhibited no clear long-term trend, when blizzards occur, it does appear they tend to happen at certain times of the year. In particular, from Figure 3 notice how all blizzards from 1980-2013 occurred during the months of

October through April with a peak in occurrence in January. To make predictions about the time of year blizzards are most common, the second-order polynomial is quite reliable (i.e. $R^2 = 0.83$), although the polynomial does not capture the subtle changes in slope from month to month.

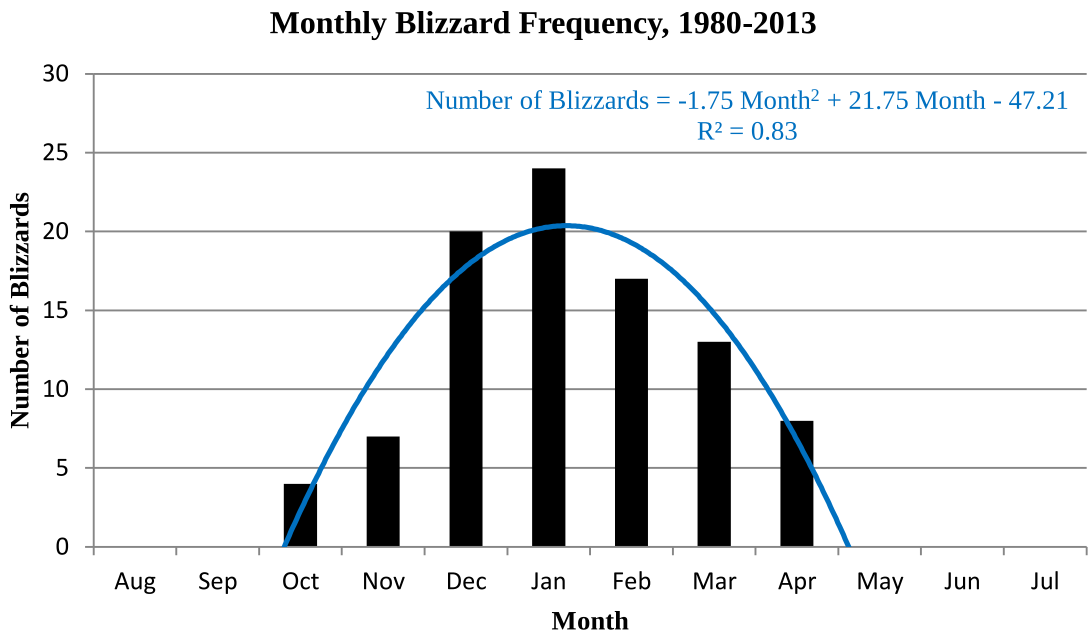

Figure 3. Monthly blizzard frequency in the Upper Midwest from 1980-2013 are shown with black bars. The second-order polynomial curve, equation and sum of squares for monthly blizzard frequency are shown in blue. Source: *Storm Data*, 1980-2013.

Blizzard Duration and Area Impacted

Table 2 shows extremes and several measures of central tendency for blizzard duration in the Upper Midwest. Blizzard duration in the Upper Midwest ranged from three hours to as long as two days. On average however, most blizzards typically range in duration from approximately 6 to 18 hours.

Table 2. Extremes and several measures of central tendency for blizzard duration in the Upper Midwest from 1980-2013 are shown. Source: *Storm Data*, 1980 2013.

Shortest Blizzard Duration	3 h
Longest Blizzard Duration	48 h
Mean Blizzard Duration deviation	17.3 h
Median Blizzard Duration	14.0 h
Mode	12 h

Table 3 shows extremes, and two measures of central tendency for area impacted by blizzards in the Upper Midwest. The area impacted by blizzards ranged from one county to the entirety the Upper Midwest; however cases of blizzards having impacted all of the Upper Midwest or one or two counties were quite rare. The average area impacted by a blizzard was on the order of roughly 50,000 km^2.

Table 3. Extremes and several measures of central tendency for area impacted by blizzards in the Upper Midwest from 1980-2013 are shown. Source: *Storm Data*, 1980-2013.

Largest Area Impacted by a Blizzard	180,333 km^2
Smallest Area Impacted by a Blizzard	1,489 km^2
Mean Area Impacted by Blizzards	60,145 km^2
Standard Deviation in Area Impacted by Blizzards	37,544 km^2
Median Area Impacted by Blizzards	52,018 km^2

County Blizzard Frequency and Trends

Figure 3 shows county blizzard frequency from 1980-2013. Blizzard frequency ranged from 46 or more blizzards along and west of line from Kittson County south through Wilkin County to fewer than 10 blizzards along and east of a line from Koochiching County south through Cass County in Minnesota – a difference of about 100 to 200 km from line to line. Walsh County in North Dakota had the highest frequency with 67 blizzards, while Aitkin, Cass, Crow Wing, and Pine counties in Minnesota had the lowest frequency with four blizzards.

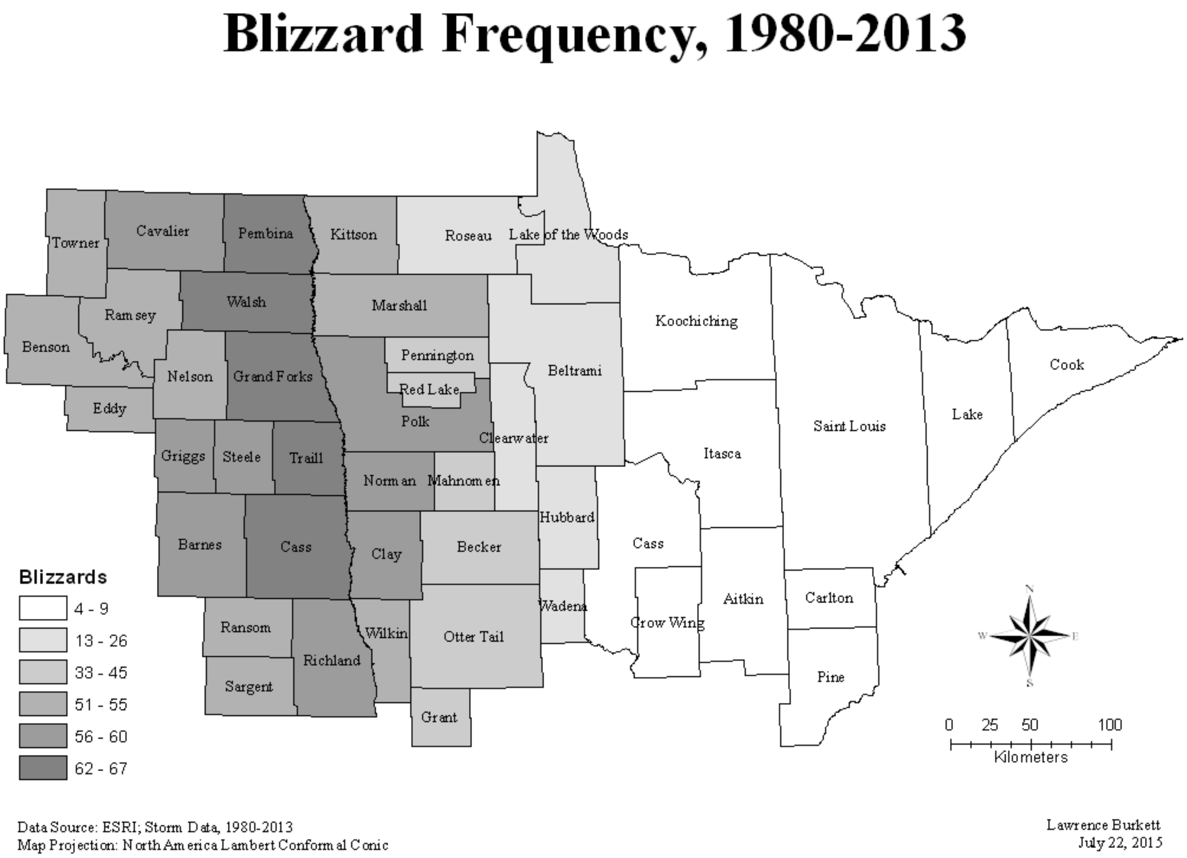

Figure 4. County blizzard frequency in the Upper Midwest from 1980-2013 is shown using a six-class Jenks natural breaks classification algorithm. Sources: ESRI; *Storm Data*, 1980-2013.

CHAPTER V

DISCUSSION

Annual Blizzard Frequency and Trends

Annual blizzard frequency in the Upper Midwest: 1) varied considerably from year to year from 1980-2013; and, 2) exhibited no meaningful long-term trend from 1980-2013 as indicated in Table 1 and Figure 2. Considering that annual blizzard frequency in the Upper Midwest varied considerably from year to year suggests that using annual averages or probabilities to describe blizzard frequency as was done by prior authors is perhaps rather inappropriate since averages and probabilities in this case give little clue as to what should be expected from year to year (Black 1971; Schwartz and Schmidlin 2002). Nevertheless, it is clear that no years endured 10 or more blizzards. Annual blizzard frequency exhibited no meaningful trend from 1980-2013, which disagrees with Schwartz and Schmidlin (2002) in particular who identified a linear increase in blizzard frequency, albeit for the entire conterminous United States from 1959-2000.

Monthly Blizzard Frequency and Trends

Monthly blizzard frequency showed a favorable result in terms of blizzard frequency with respect to time as indicated in Figure 3. Similar to Schwartz and Schmidlin (2002), it is clear that certain months of the year are more or less favorable for blizzards. Recalling that most snow-producing cyclones that generated blizzards from December-February in the north-central conterminous United States where Alberta lows (Black 1971), suggest that most blizzards in the

Upper Midwest probably resulted from circulations embedded in intense cyclones that originated in Alberta and tracked southeast through the Upper Midwest. Intense Colorado lows (Black 1971) were probably more often associated with blizzards in the Upper Midwest in other months as they tracked northeast through the Upper Midwest. The polynomial fit to the monthly blizzard frequency histogram in Figure 3 does offer reliable guidance about the time of year blizzards occur although it fails to capture the subtle differences in frequency from month to month.

Blizzard Duration and Area Impacted

Blizzards ranged in duration from three to 48 hours. On average, most blizzards generally last between roughly 6 and 18 hours. Due to differences in reporting efficacy in *Storm Data* however in terms of start and end times, longer-term trends in blizzard duration where not constructed. When blizzards occurred, most were typically on the order of about 50,000 km^2 in size, or roughly between one-quarter to one-half of the Upper Midwest. The largest area impacted by a blizzard covered the entirety of the Upper Midwest while the smallest covered a single county. Combining typical durations on the order of several hours, and areas impacted on the order of several tens of thousands of kilometers, supports the discovery that blizzards do indeed have mesoscale aspects as suggest by Branick (1997).

County Blizzard Frequencies

Considering the order of magnitude difference in blizzard frequency in the Upper Midwest from west to east, as indicated in Figure 4, irrespective of snow, my premise is that the presence of forest cover or lack thereof might lend insight into explaining differences in county blizzard frequencies. Further, if blizzards can be generalized as a severe wind phenomenon resulting from the passage of intense, snow-producing cyclones as they were in Black (1971), and markedly mesoscale as indicated in Branick (1997), then the efforts of Coutts and Grace (1995) who authored a book titled *Wind and Trees* which reviews much of the seminal research done on the interaction between wind and trees might lend new insight into explaining blizzard frequency on such scales.

Exploring Forest Cover Premise

To explore my premise that forest cover might be able to explain the differences in blizzard frequency observed across the Upper Midwest from west to east, I obtained percent forest canopy cover data from the United States Department of Agriculture's United States Forest Service, in *Forest Resources of the United States, 2007*. The forest cover data in *Forest Resources of the United States, 2007* was made available as a choropleth map with each county in the conterminous Unites States classified as integers ranging from 1 to 7 depending on the percent forest canopy cover normalized by county area. The purpose of normalizing forest cover data is that individual trees which make up forests are considerably smaller in scale in terms of length versus counties. As an extension of my methods, I chose to modify the forest cover data classes by combining the two lowest classes so the first class includes county forest cover of less than 10%. Following the same method I used to generate Figure 4, Figure 5 shows a map created using ArcMap 10.2 to indicate county forest cover.

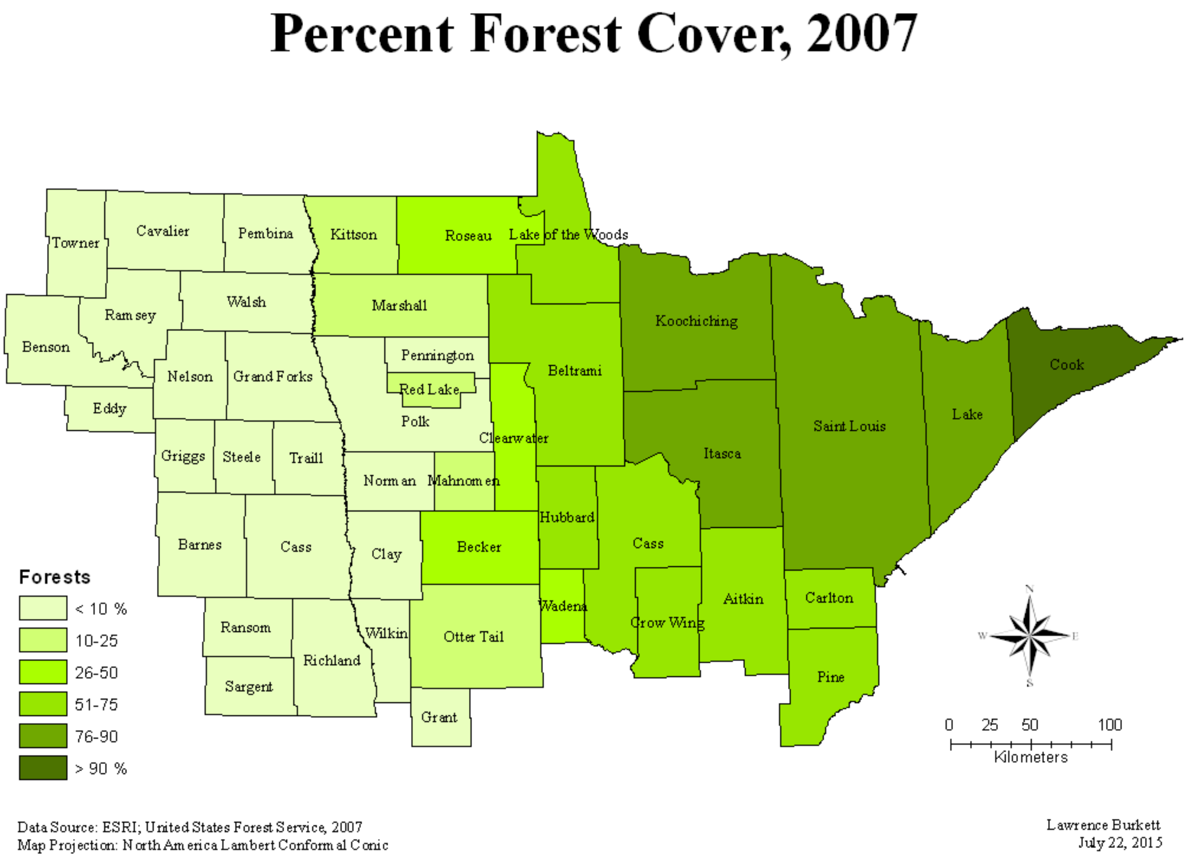

Figure 5. Percent forest covers from 2007 for counties in the Upper Midwest are shown using a percent classification scheme inherited from the United States Forest Service. Sources: ESRI; United States Forest Service, 2007.

Examining Forest Cover Premise

By comparing Figures 4 and 5 under the assumption that forest cover has not changed appreciably from 2007, it appears that blizzard frequency is indeed related to percent forest cover. Counties with high blizzard frequencies tend to overlap with counties with low percent forest cover. To determine the strength of the relationship between blizzard frequency and percent forest cover, I regarded blizzard frequency and percent forest cover as statistical parameters and calculated a Pearson product-moment correlation coefficient relating the two. Statistically speaking, I regarded correlation values between -0.75 and +0.75 as weak, and correlations less than -0.75 or greater than +0.75 as strong. In my analysis, I obtained a correlation of -0.91 relating blizzard frequency to percent forest cover. A Pearson correlation of -0.91 indicates that counties with little forest cover – like Pembina, Walsh, Grand Forks, Traill, and Cass counties – show the greatest number of blizzards. Hence, blizzard frequency is strongly related to percent forest cover as indicated in Table 4.

Table 4. Pearson correlations: blizzard frequency, forest cover, and winter storm frequency. Sources: Storm Data, 1980-2013; United States Forest Service, 2007.

Parameter 1	**Parameter 2**	**Correlation**	**Regard**
Blizzards, 1980-2013	Percent Forest Cover	- 0.91	Strong
Winter Storm, 2000-2009	Percent Forest Cover	- 0.49	Weak
Blizzards, 2000-2009	Percent Forest Cover	- 0.90	Strong
Winter Storm, 2000-2009	Blizzards, 2000-2009	+0.46	Weak

To exclude the possibility that the strong relationship obtained between blizzard frequency and percent forest cover is: 1) shared among other similar, comparable types of winter weather hazards such as winter storms (Branick 1997); and, 2) whether there is a spatial reporting bias in *Storm Data*, I identified the frequency of winter storms in *Storm Data* from August 1, 2000 through July 31, 2010 (winter seasons from 2000 to 2009), in “Character of Storm” by assigning a 1 for occurrence or a 0 for non-occurrence for counties impacted in my spreadsheet. Identical to how I treated blizzard reports in *Storm Data*, winter storms spanning several days were regarded as one continuous winter storm while days with two or more winter storms separated by more than three hours were regarded as separate winter storms by assigning a two or greater for those dates. By restricting my sample of blizzards to align with my new winter storm data set in my spreadsheet, I obtained a new, temporally smaller sample period that represents approximately one-third of the original data in terms of time (i.e. 1980-2013), and calculated three more Pearson product-moment correlation coefficients relating: 1) winter storm frequency from 2000-2009 to percent forest cover; 2) winter storm frequency from 2000-2009 to blizzard frequency from 2000-2009; and, 3) blizzard frequency from 2000 – 2009 to percent forest cover to ensure that blizzard frequency maintained a strong correlation with percent forest cover over the temporally smaller sample period chosen from 2000-2009.

To test the strength of the three new relationships, I once again regarded correlations between -0.75 and +0.75 as weak, and correlations less than -0.75 or greater than +0.75 as strong. In my review, I obtained: 1) a weak correlation of -0.49 relating winter storm frequency from 2000-2009 to percentage forest cover; 2) a weak correlation of +0.46 relating winter storm frequency from 2000-2009 to blizzard frequency from 2000-2009; and, 3) a strong correlation of -0.90 relating blizzard frequency from 2000-2009 to percent forest cover as summarized in Table 4.

CHAPTER VI

CONCLUSION

In total, ninety-three blizzards impacted the Upper Midwest from 1980-2013. On the average, 2-3 blizzards were reported each year in the Upper Midwest. However, blizzard frequency from year to year varied considerably with 2-3 blizzards having occurred in only 26% or about one-quarter of the years studied, while 35% of years studied had four or more blizzards. Moreover, in four out of 34 years in my study, there were no blizzards, and in two years there were as many as nine blizzards; hence, notations of average or annual probabilities seems rather inappropriate. In addition, no linear trend was evident in blizzard frequency from 1980-2013. However, when blizzards did occur, it appears they tended to occur most often from December-February when 66% of blizzards occurred, in a blizzard season lasting from October-April.

Typical blizzard durations in the Upper Midwest ranged from about 6 to 18 hours. However, some blizzards last as long as 48 hours while others were as short in duration as three hours; the minimum threshold for a blizzard in terms of time. Due to differences in reporting efficacy however, identifying specific hourly start and end times for all blizzards was not possible. Nevertheless, it is clear that most blizzards generally last on the order of several hours. The average area impacted by blizzards in the Upper Midwest was on the order of several tens of thousands of kilometers which is roughly one-quarter to one-half the size of the Upper Midwest. The largest area impacted by a specific blizzard covered the entire Upper Midwest study region while the smallest blizzard only covered one county in that part of the United States.

Differences in blizzard frequency from county to county in the Upper Midwest can primarily be explained by forest cover as evidenced in Table 4. Provided that blizzards in Upper Midwest occur most often during the passage of what Black (1971) referred to as Alberta lows during the blizzard favorable months of December-February, and to a lesser extent Colorado lows in other months, suggests that forests slowed the flow of air circulating through the interior of intense cyclones with falling or blowing snow as they tracked through the Upper Midwest, which agrees with Finnigan and Brunet (1995) in *Wind and Trees* in that forests absorb momentum from air flow, lowering wind speed. Supposing there had been a spatial reporting bias in *Storm Data*, it would be expected that winter storms would have correlated more strongly with percent forest cover, which was not the case. Also, it appears that the frequencies of winter storms are not related to the frequencies of blizzards; meaning that high or low winter storm frequency is not an indicator of blizzard frequency despite their regard as severe snowstorms. This is probably because blizzards, unlike winter storms, are defined on the basis of a wind speed near the surface which is more sensitive to obstacles such as forest cover which tend to slow air that would have otherwise been circulating rapidly through the interior of cyclones; hence, blizzards are much more frequent a hazard to flat or gently rolling landscapes such as cropland and prairie than in areas with substantial forest cover during the passage of intense cyclones associated with falling or blowing snow.

Whether or not blizzard frequency is sensitive in part to other obstacles on the mesoscale such as hills, for example, might explain why I was unable to more strongly correlate blizzard frequency to forest cover since part of the Upper Midwest is located within a broad, flat river basin while other parts are located in hills. And indeed, on even finer scales, it is reasonable to consider the possibility that blizzards may be locally altered in terms of their severity by buildings, and other wind-reducing features such as shelter belts, fences, overpasses, and utility poles, for example, unless winds are high enough to damage such obstacles.

In summary, my findings stress the need for further refinement to blizzard climatology in the United States, and perhaps other parts of the world where blizzard or blizzard-like storms are known to occur. Aside from offering improvements to our understanding of blizzard frequencies annually and monthly, and providing new rough estimates of duration and area impacted, my study was successful in establishing a strong relationship between blizzards and forest cover; hence, my methods could be applied to other parts of the United States in particular wherever intense cyclones that are associated with falling or blowing snow occur in order to develop a blizzard susceptibility index.

APPENDIX

Appendix 1

Photo Evidence of Blizzards

The following photos were taken in-situ during blizzards in Grand Forks County, North Dakota. Caution statement: All photos in the Appendix were taken cautiously to avoid injury or death.

Figure 6. What it looked like behind the dashboard of a vehicle during a blizzard in Grand Forks County, North Dakota on December 28th, 2013.

Figure 7. The wind swept landscape following a blizzard in Grand Forks County, North Dakota on January 22nd, 2014.

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Figure 8. Blizzard in Grand Forks County, North Dakota on January 26th, 2014.

Figure 9. Blizzard in Grand Forks County, North Dakota on February 13th, 2014.

Figure 10. Blizzard in Grand Forks County, North Dakota on February 26th, 2014.

Figure 11. Plumes of wind-blown snow cover following a blizzard that impacted Grand Forks County, North Dakota on March 21st, 2014.

Figure 12. Blizzard in Grand Forks County, North Dakota on March 31st, 2014.

Figure 13. The aftermath of a blizzard that impacted Grand Forks County, North Dakota on March 31st, 2014 as evidenced with this snow-drifted vehicle.

Figure 14. Blizzard in Grand Forks County, North Dakota on January 3rd, 2015.

Figure 15. Blizzard in Grand Forks County, North Dakota on January 8th, 2015.

BIBLIOGRAPHY

Bavendick, F. J. 1920. "Blizzards and Chinooks of the North Dakota Plains." *Monthly Weather Review* 48(2): 82-83.

Bjerknes, J., and Jt Holmboe. 1944. "On the Theory of Cyclones." *Journal of Meteorology* 1(1): 1-22.

Benjamin, Stanley G., Kevin J. Brundage, and Lauren L. Morone. 1994. "Implementation of the Rapid Update Cycle." Part I: Analysis/Model Description. *NOAA/NWS Tech. Procedures Bull* 416: 16.

Black, Robert E. 1971. *A Synoptic Climatology of Blizzards on the North-Central Plains of the United States*. US Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Central Region.

Environment Canada. "Blizzard." Accessed June 1, 2015. http://www.ec.gc.ca/meteo-weather/default.asp?lang=En&n=d9553ab5-1#blizzard.

Bradford, Marlene. 2001. *Scanning the Skies: A History of Tornado Forecasting*. Norman, OK: University of Oklahoma Press.

Branick, Michael L. 1997. "A Climatology of Significant Winter-Type Weather Events in the Contiguous United States, 1982–94." *Weather and Forecasting* 12(2): 193–207.

Brock, Fred V., Kenneth C. Crawford, Ronald L. Elliott, Gerrit W. Cuperus, Steven J. Stadler, Howard L. Johnson, and Michael D. Eilts. 1995. "The Oklahoma Mesonet: A Technical Overview." *Journal of Atmospheric and Oceanic Technology* 12(1): 5-19.

Brown, David G. 2004. *White Hurricane*. New York, NY: Mc-Graw Hill.

Changnon, Stanley A., David Changnon, and Thomas R. Karl. 2006. "Temporal and Spatial Characteristics of Snowstorms in the Conterminous United States." *Journal of Applied Meteorology and Climatology* 45(8): 1141–1155.

Coutts, M. P., and John Grace, eds. 1995. *Wind and Trees*. Cambridge University Press.

Finnigan, J. J., and Y. Brunet. 1995. "Turbulent Airflow in Forests on Flat and Hilly Terrain." in *Wind and Trees,* Coutts, M. P. and John. Grace, eds. New York, NY: Cambridge University Press.

Greeley, Adolphus W. 1888. *American Weather*. n.p.

Halpert, Michael S., and Thomas M. Smith. 1994. "The Global Climate for March-May 1993: Mature ENSO Conditions Persist and a Blizzard Blankets the Eastern United States." *Journal of Climate* 7(11): 1772-1793.

Haurwitz, B., and J. M. Austin. 1944. "Climatic Types of the Earth (after Koppén)" in *Climatology*. New York, NY: McGraw-Hill.

Heffernan, Ellin, and John Marwitz. 1996. "The Front Range Blizzard of 1990. Part II: Melting Effects in a Convective Band." *Monthly Weather Review* 124(11): 2469-2482.

Henke, Warren A. 1998. *The Legacy of North Dakota's Country Schools*. Bismarck, N.D.: North Dakota Humanities Council.

Hughes, Lawrence A. 1958. "Comments on "Cyclogenesis and Precipitation in the Blizzard of March 21-26, 1957"." *Monthly Weather Review* 86(7): 265-267.

Kocin, Paul J. 1988. "Meteorological Analyses of the March 1888 "Blizzard of '88"." *Eos, Transactions American Geophysical Union* 69(10): 137-147.

Kocin, Paul J. 1992. *Snowstorms and Blizzards*" in *Natural and Technological Disasters: Causes, Effects, and Preventive Measures*, S. K. Majumdar, G. S. Forbes, E. W. Miller, and R. F. Schmalz, eds. Camp Springs, MD: NOAA.

Kocin, Paul J., William E. Gartner, and Daniel H. Graf. 1998. "The 1996–97 Snow Season." *Weatherwise* 51(2): 47-54.

Kocin, Paul J., and Louis W. Uccellini. 2004. "A Snowfall Impact Scale Derived from Northeast Storm Snowfall Distributions." *Bulletin of the American Meteorological Society* 85(2): 177–194.

Köppen, Wladimir Peter. 1931. "*Grundriss der klimakunde*." n.p.

Laskin, David. 2009. "*The Children's Blizzard*." New York, NY: Harper Collins.

Lawson, Bevan D. 2003. "Trends in Blizzards at Selected Locations on the Canadian Prairies." *Natural Hazards* 29(2): 123-138.

Markowski, Paul, and Yvette Richardson. 2011. *Mesoscale Meteorology in Midlatitudes*. Vol. 2. Advances in Weather and Climate, P. Inness and W. Beasley, eds. New York, NY: John Wiley and Sons.

Marwitz, John, and James Toth. 1993. "The Front Range Blizzard of 1990. Part I: Synoptic and Mesoscale Structure." *Monthly Weather Review* 121(2): 402-415.

McQueen, Henry R., and John F. Loopstra. 1957. "Cyclogenesis and Precipitation in the Blizzard of March 21-26, 1957." *Monthly Weather Review* 85(3): 99-111.

Petterssen, Sverre. 1956. *Weather Analysis and Forecasting*. Vol. 1. New York, NY: McGraw-Hill.

Salmon, Ellen M., and Phillip J. Smith. 1980. "Focus on Forecasting: A Synoptic Analysis of the 25-26 January 1978 Blizzard Cyclone in the Central United States." *Bulletin of the American Meteorological Society* 61(5): 453-453.

Schwartz, Robert M. 2001. "*Geography of Blizzards in the Conterminous United States, 1959-2000*." PhD diss., Kent State University.

Schwartz, Robert M., and Thomas W. Schmidlin. 2002. "Climatology of Blizzards in the Conterminous United States, 1959–2000." *Journal of Climate* 15(13): 1765–1772.

Schwartz, Robert M. 2005. "Blizzard Climatology." in *Encyclopedia of World Climatology*, 165-167. New York, NY: Springer.

Seeley, Mark W. 2006. *Minnesota Weather Almanac*. St. Paul, MN: Minnesota Historical Society.

Shuman, Frederick G. 1978. "Numerical Weather Prediction." *Bulletin of the American Meteorological Society* 59(1): 5-17.

Sutcliffe, R. C. 1947. "A Contribution to the Problem of Development." *Quarterly Journal of the Royal Meteorological Society* 73(317-318): 370-383.

Sutcliffe, R. C., and A. G. Forsdyke. 1950. "The Theory and Use of Upper Air Thickness Patterns in Forecasting." *Quarterly Journal of the Royal Meteorological Society* 76(328): 189-217.

Talman, C. F. 1914. "Origin of the Word 'Blizzard'." *Monthly Weather Review and Annual Summary* 42: 692.

Teweles, Jr., Sidney, and Lewis C. Norton. 1950. "The Intense Midwest Storm of March 25-27, 1950." *Monthly Weather Review* 78(3): 52-57.

Wagner, A. James. 1985. "The Climate of Spring 1984-An Unusually Cold and Stormy Season Over Much of the United States." *Monthly Weather Review* 113(1): 149-169.

Wei, Yulan, and John Marwitz. 1996. "The Front Range Blizzard of 1990. Part III: Numerical Simulations of Melting Effects." *Monthly Weather Review* 124(11): 2483-2496.

Wild, Richard, Greg O'Hare, and Robert Wilby. 1996. "A Historical Record of Blizzards/Major Snow Events in the British Isles, 1880–1989." *Weather* 51(3): 82-91.

Wild, Richard. 1997. "A Historical Review on the Origin and Definition of the Word 'Blizzard'." *Journal of Meteorology* 54: 331-339.

Wilder, Laura Ingalls. 1968. *The Long Winter*. New York, NY: Scholastic Book Services.

Zapotocny, Tom H., Donald R. Johnson, and Fred M. Reames. 1993. "A Comparison of Regional Isentropic-Sigma and Sigma Model Simulations of the January 1979 Chicago Blizzard." *Monthly Weather Review* 121(7): 2115-2136.

Zielinski, Gregory A. 2002. “A Classification Scheme for Winter Storms in the Eastern and Central United States with an Emphasis on Nor’easters.” *Bulletin of the American Meteorological Society* 83(1): 37–51.

Zishka, Kennan M., and Phillip J. Smith. 1980. "The Climatology of Cyclones and Anticyclones Over North America and Surrounding Ocean Environs for January and July, 1950-77." *Monthly Weather Review* 108(4): 387-401.

Zupanski, Milija, Dusanka Zupanski, David F. Parrish, Eric Rogers, and Geoffrey DiMego. 2002. "Four-Dimensional Variational Data Assimilation for the Blizzard of 2000." *Monthly Weather Review* 130(8): 1967-1988.