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DEVELOPMENT AND ANALYSIS OF RADAR BASED THUNDERSTORM CLIMATOLOGY FOR NORTH DAKOTA

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DEVELOPMENT AND ANALYSIS OF RADAR BASED THUNDERSTORM CLIMATOLOGY FOR NORTH DAKOTA

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ABSTRACT

The usage of radar data in the development of thunderstorm climatologies was investigated. Thunderstorm data for three WSR-88D radar and eight surface stations in North Dakota in the USA for 2002-2006 were analyzed in order to develop a reliable database for the thunderstorm cells in the state. The analysis results obtained from radar data matched with that obtained from the surface data and also with the results obtained by previous researchers. It was found that June and July are the peak months and late-afternoon to early-morning is the peak time for thunderstorms. Each year, there are 19 to 35 thunderstorm-days at a particular place in North Dakota and 9 to 14 thunderstorm-days with peak wind reports with an overall average peak wind speed of 59.4 km/hr all over the state. The presence of the Missouri river and Lake Sakakawea leads to the presence of a high thunderstorm-initiation-frequency belt in the mid-western part of the state. The life cycle analysis for individual thunderstorm cells in North Dakota was also done and it was found that the average lifetime of thunderstorm cells is 23.6 minutes, the average track-length is 21.8 km and the average forward speed is 59.0 km/hr and the average heading varies with month from north-west to north, north-east and east directions. The distribution patterns and the life cycle characteristics of thunderstorm cells obtained in this research can further be used to develop a parametric risk model for North Dakota and southern Manitoba.

Keywords:
Thunderstorm, climatology, WSR-88D radar data, ASOS data, North Dakota, Manitoba, maximum reflectivity, wind speed, ArcGIS, Meteorology.

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INTRODUCTION AND MOTIVATION

1.1 GENERAL

For the last few years natural disasters like thunderstorms, floods, tsunami, hurricanes and tropical cyclones have been increasing all over the world leading to billions of dollars of financial losses and deaths of lots of people. Thunderstorms are one of the most devastating natural disasters in the world. According to National Climatic Data Center in United States and different news in media, every year all over the world, thunderstorms kill a lot of people and animals, destroy forests and damage crops worth of millions of dollars and damage lots of properties and destroy different types of structures like houses and electricity transmission lines etc. Each year financial losses due to natural disasters like thunderstorms are increasing. For this reason, understanding the climatological behaviour of thunderstorms is a vital issue now-a-days for saving lives and properties all over the world.

1.2 GENERAL BACKGROUND AND MOTIVATION

Thunderstorms are one of the most severe natural disasters. The economic damages due to thunderstorms in terms of the amount of insured property losses are increasing every year (Fig. 1.1). Due to thunderstorms, human lives and lots of livestock (both domestic and wild life animals) perish, crops and forests are damaged and aviation operations are at risk. Thunderstorms also damage properties, houses and structures causing billions of dollars of economic losses each year. With its major four damaging forces – high wind speeds, large hail, lightning and flash flooding due to heavy rainfall, thunderstorms cause all of these damages. According to Munich Reinsurance America Inc. (2006), thunderstorm perils caused 85% of all the natural disaster-related costs in the United States of America (USA) in 2006 and the three most severe thunderstorm events in 2006

in USA alone have caused a financial loss of more than $1 billion US dollars. Again, the insurance companies in USA have paid $5.5 billion US dollars per year due to thunderstorm related damages for the years 2002-2006 while this amount is $1 billion higher than that for the years 1992-1996 and more than three times than that for 1982-1986. So it can be clearly understood that the amount of financial losses due to the devastating effects of thunderstorms are increasing each year.

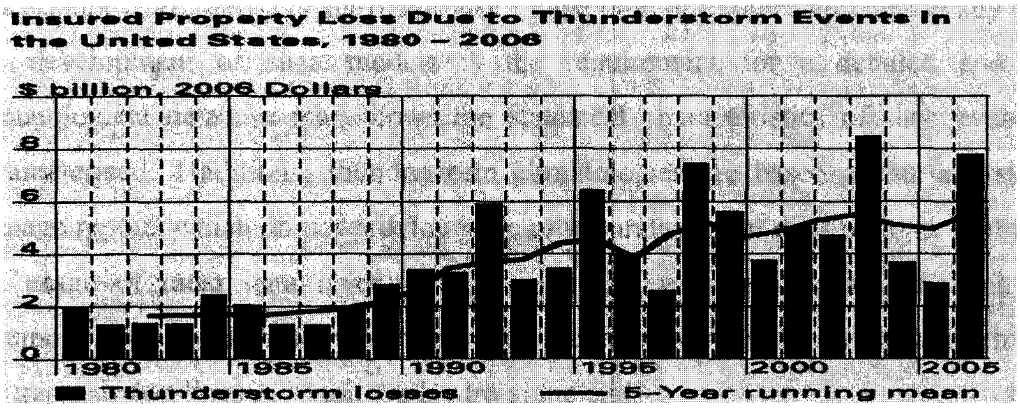


Figure 1.1: The increasing trend of economic losses due to thunderstorms in USA between 1980 and 2006 (Munich Reinsurance America Inc., 2006)

In addition to damage to human lives and insured properties like buildings, structures and crops, thunderstorms can cause significant damage to infrastructure such as electricity transmission lines etc. According to Environment Canada (1996) and Manitoba Hydro (1999), a severe thunderstorm with an average wind speed of 100 km/hr hit the province of Manitoba, Canada, especially in the place between the Poplar Point and the Stony Mountain region of the province on September 5, 1996 and that thunderstorm with wind speed peak of 150–180 km/hr brought down couple of the Manitoba Hydro electricity transmission line towers. Then the combined force of the wind speeds of the thunderstorm and the extended tension of the failed towers on both sides caused a cascading failure of several other towers of in that region. This lead to an interruption of the electricity supply from the electricity generation plants in northern Manitoba to the USA for the next couple of weeks which caused a big financial loss to the company (in terms of failure of the transmission line and towers and also due to the sudden break in the electricity sale to USA) and also caused a great suffering to the people. This incident has lead Manitoba

Hydro to fund a research project for the modelling and prediction of the failure of transmission lines due to High Intensity Winds (HIW), the current research forming a part of that project.

Risk assessment for the transmission lines of Manitoba Hydro is one of the major goals of that project. In order to assess the risk on transmission lines due to thunderstorms, it is useful to have some form of parametric risk model, similar to those used to assess tornado risk (Banik et al., 2007) or hurricane risk (Vickery et al., 2000). One of the key issues in the development of such models is the requirement for a detailed and reliable climatological database that allows the statistical characteristics of such events to be parameterised. Traditional thunderstorm climatologies are based on surface station or damage reports which do not provide wide or accurate spatial distributions. In this thesis, the usage of radar data is explored to obtain a reliable database containing these parameters which will finally be used in the development of a parametric risk model for the transmission lines of Manitoba Hydro at the end.

1.3 OBJECTIVES AND SCOPES

North Dakota is a state in the United States of America (USA) which is situated on the southern side of the province of Manitoba in Canada. North Dakota is a thunderstorm-prone state in USA. It is one of the fifteen most thunderstorm affected states in USA in the sense of financial losses of more than US$250 million per thunderstorm events (Munich Reinsurance America Inc., 2006). The damages due to different activities of thunderstorms in North Dakota during the time period of 1993-2007 are given in Table 1.1 according to the National Climatic Data Center (NCDC) storm events database. This database is available at http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~storms for North Dakota and at http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~storms for all USA thunderstorm events. According to this database considering the total damage, it was also found that thunderstorms with its four major devastating effects: wind, hail, lightning and flash flood, are one of the worst catastrophic natural events among all types of natural disasters which include thunderstorms, flood, drought, snowing etc. in the state.

Table 1.1 Damages by different activities of severe thunderstorms in North Dakota for 1993 to 2007 (Source: NCDC storm events database)

Thunderstorm activity	No of deaths	No of injuries	Property damage ($ in million)	Crop damage ($ in million)
Wind	2	44	198.826	168.068
Hail	0	21	457.588	150.585
Lightning	1	8	1.799	0.01

The reasons which lead to the decision to use North Dakota thunderstorm data for this Manitoba Hydro funded research work are as follows:

1. Any reliable thunderstorm radar data for Canada are not available in a usable format.
2. North Dakota is situated on the USA side of the USA–Canada border, to the immediate southern side of Manitoba. Since North Dakota and Manitoba are situated side by side, it was assumed that the climatological behaviour of thunderstorms in these two states would be similar.
3. Traditionally surface reports of thunderstorms or the storm events database maintained by the NCDC have been used to develop thunderstorm climatologies in USA. However these databases are biased towards population centres or the presence of surface station locations (Kelly et al., 1985). And all the previous researchers recommended for investigating the use of radar data in the development of thunderstorm climatology. So we were interested in using radar data because it was assumed that radars might provide an unbiased spatial coverage within the radar range and radar data for thunderstorms is available for North Dakota.

4. The radar data for North Dakota are free and are in a readily usable format provided by the NCDC website.

The objectives of this research are as follows:

1. To construct a reliable database for the climatological characteristics of the thunderstorms in North Dakota from the maximum available radar data.
2. To verify the accuracy, completeness and usability of the new database.
3. To investigate the distribution and characteristics of the thunderstorm climatology of North Dakota on monthly and diurnal cycles and spatial distributions using both radar and surface data.
4. To investigate the characteristics of thunderstorm cells like the intensity, duration, travelled distance, forward speed, heading etc.

1.4 PREVIEW OF THE THESIS

Chapter Two provides a literature review of all of the previous works in the field of climatology of thunderstorms in USA over the last one hundred years. This chapter also discusses about the definitions of severe thunderstorms, the evolution and various phases of the formation process of a typical thunderstorm and also the classifications of thunderstorms. The scanning principles of radars, the algorithms used to process these data, types of radar data and the components of the level-III radar data are also described in this chapter. Chapter Three discusses the sources and types of data used, the methodologies used for the construction of the database, the challenges faced during the construction process of the database and also the verification process and verification results of the new database. In chapter Four, different climatological characteristics of thunderstorms in North Dakota are discussed. Climatological characteristics of thunderstorm tracks like the number of thunderstorm days per year, monthly, diurnal and spatial distribution of thunderstorms in North Dakota and also about the duration, forward speed, direction of storms and intensity of the thunderstorms are also discussed in this chapter. Chapter Five is the concluding chapter. It discusses the concluding remarks and recommendations about the thunderstorm climatology of North Dakota.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Thunderstorms are natural atmospheric phenomena. In this chapter, different thunderstorm related terms are defined and described. The factors behind the development of a thunderstorm, the phases of a thunderstorm evolution process and the classification of thunderstorms are also discussed here. Different previous research works regarding the thunderstorm climatology are also discussed in this chapter. Besides these, the working principles, data types, algorithms and components of radar data are also discussed in this chapter.

2.2 THUNDERSTORMS

Thunderstorms are atmospheric weather events caused by convection, the circulation of air mass and the transfer of heat from one layer to another layer in the atmosphere. Thunderstorms cause thunder and lightning and are also usually accompanied by high wind speeds, large amounts of rainfall (or a possible large snowfall in winter), large diameter hails and sometimes tornadoes. A thunderstorm is capable of causing a significant damage to human life, animal life – domestic and wild, property, structures, trees and crops and it is a significant threat to aviation.

2.3 SEVERE THUNDERSTORMS

According to the USA National Weather Service, a severe thunderstorm is a thunderstorm which causes one or more of the following:

- Gust wind speed of at least 93 km/hr (58 miles/hr, 25.8 m/sec or 50 knots).
- Hail of at least 19 mm diameter (3/4 inch)
- Producing tornadoes
- Combination of the above three criteria.

According to the Canadian Meteorological Service, a severe thunderstorm is a thunderstorm which causes one or more of the following:

- Wind gusts of greater than 90 km/hr (55.9 miles/hr, 25 m/sec or 48.6 knots)
- Hail of greater than 20 mm in diameter.
- Rainfall of greater than 50 mm in an hour or greater than 75 mm in three hours
- Producing tornadoes.
- Combination of the above four criteria.

Although most of the criteria (wind gust speed, size of hail and production of tornado) in the American and Canadian definitions of severe thunderstorms are very near to each other, the basic difference between the two is the presence of an amount of rainfall parameter in the Canadian Meteorological Service definition.

2.4 FACTORS FOR THE FORMATION OF THUNDERSTORMS

Convection is the primary cause of the formation of thunderstorms. Convection causes instability in the atmosphere causing the warm air to move upward and the cool air to move downward and thus a thunderstorm is developed. Convection and thus thunderstorms can be initiated by any one or more of the following factors:

- Availability of warm and moist air, preferably provided by any gulf, sea or big lake. Thunderstorms in coastal areas or near to the Gulf of Mexico in USA or in the surrounding area of the Great Lakes in Canada and USA are caused by this factor.

- Extreme solar heating or differential heating of the ground and the lower atmosphere causes updrafts and thus thunderstorm at the end. The thunderstorms in the summer are caused by this factor.

- Topographic condition of the area and presence of mountains or hills in any location. The leeward side of the mountains or hills face direct solar radiation and the air needs to move upward since there is a barrier to its flow and thus a strong updraft is created causing a thunderstorm at the end. The presence of the Rocky Mountains in USA causes thunderstorms on the eastern side of this mountain range in this way.

- Fronts and dry lines may cause development of thunderstorms. Fronts are the boundary between two air masses with different temperatures and dry lines are the boundary between two air masses of different moisture content. These situations also lead to the development of thunderstorms.

- Maritime polar air or outflow boundaries can also create thunderstorms. The few thunderstorms on the west coast of Canada and USA or the thunderstorms in the winter are caused by this factor.

2.5 PHASES IN THE EVOLUTION OF A THUNDERSTORM

The evolution of thunderstorms has three phases in their life cycle. The phases are: Cumulus phase, Mature phase and Dissipation phase. The phases are shown in Fig. 2.4.

2.5.1 CUMULUS PHASE:

The cumulus phase is the initial phase in the formation process of a thunderstorm. According to Byers (1948), when the Earth's surface in a place is heated up, winds from different directions converge and the air there moves upward and the air also carries the moisture upward along with it. The lifting of air with moisture results in condensation and the release of the latent heat within it. Thus, at an increased elevation, the air becomes cool and the water vapour becomes liquid and a cloud is formed, this cloud is called a cumulus cloud (Fig. 2.1). When the water vapour turns into liquid, the latent heat inside the water vapour is released again and it heats the air again and the air and moisture becomes warm and moves upward and thus a low pressure zone is created in the lower atmosphere which leads to the formation of a thunderstorm. In this stage, the cumulus cloud may develop vertically to a maximum height of 6 km (20,000 ft) from the ground (Fig. 2.4-a).

Figure 2.1: Development of thunderstorm cloud at the cumulus stage. (Source: UCAR Digital Image Library)

2.5.2 MATURE PHASE:

The mature phase is the most significant phase during the lifetime of a thunderstorm. In this phase, thunderstorms gain strength. During this stage, air and moisture continue to move upward until it reaches the tropopause layer of the atmosphere, typically 12-18 km (40,000-60,000 ft) at the top (Fig. 2.4-b). After reaching that height, the air starts to spread out laterally and the thundercloud turns into an anvil and cauliflower shape. When a cumulus cloud become dense enough to produce thunder and lightning, then that cumulus cloud is called as cumulonimbus or thunderstorm cloud. In Fig. 2.2, the presence of the cauliflower shape on the left and a well developed anvil shape on the right indicate that the cloud has reached its mature phase. (Byers, 1948)

Figure 2.2: Cauliflower and anvil shaped mature thunderstorm cloud (Source: UCAR Digital Image Library)

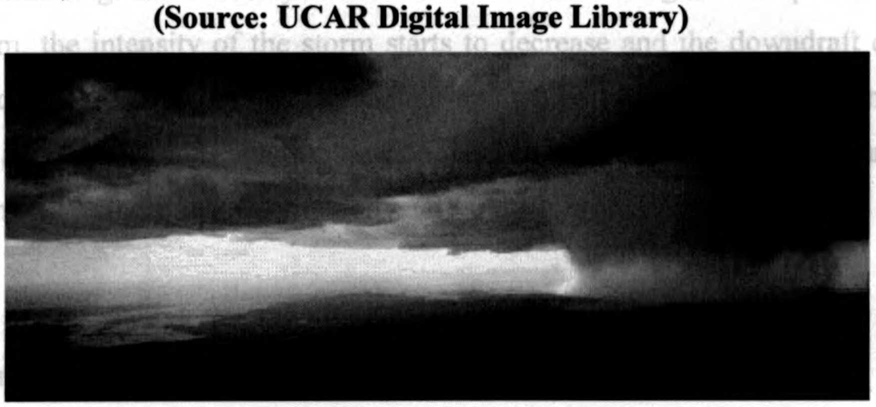


Figure 2.3: Downdrafts and rainfall from the cloud to the ground surface in a mature thunderstorm. (Source: UCAR Digital Image Library)

According to Ackerman and Knox (2003), during the mature stage, the cloud water-drops merge with one another and ice particles are formed and the strong upper stratospheric layer wind spreads the ice particles on the top of the cloud. When the ice particles become heavier, they start to fall. The ice particles melt when they fall and a downdraft is created (Fig. 2.3). Thus in a mature stage, both updrafts and downdrafts are present. The updrafts contain warm air and the downdrafts contain cold air. Since both updrafts and downdrafts are present in this stage, an internal turbulence is created which may cause strong wind speeds, heavy rainfall with large diameter hail and even tornadoes. Again, a larger size hail is created by strong updrafts. A large hail is caused by the repetitive presence of solid ice made hard layers and frozen moisture and air bubble made soft layers in the alternate layers in the cumulonimbus cloud. On the other hand, smaller size hail is created by the presence of a thunderstorm cloud with a soft centre and a single outer coat of ice. Again, if there are variations in wind speeds in different layers of the atmosphere, it may cause the separation of updraft and the downdraft and supercells can be created. In this stage the diameter of the thunderstorm can be several kilometres at the base of the storm cell.

2.5.3 DISSIPATION PHASE:

This is the final stage in the life cycle of a thunderstorm. During the dissipation stage of a thunderstorm, the intensity of the storm starts to decrease and the downdraft dominates over the updraft (Fig. 2.4-c). Thus the cool air and the hail moves downward and reaches the ground and spreads out, thus the air and the moisture come out of the thunderstorm and the thunderstorm diminishes gradually. (Byers, 1948)

Usually, it takes around 20-30 minutes to complete the three phases of a typical thunderstorm cell (Ackerman and Knox, 2006).

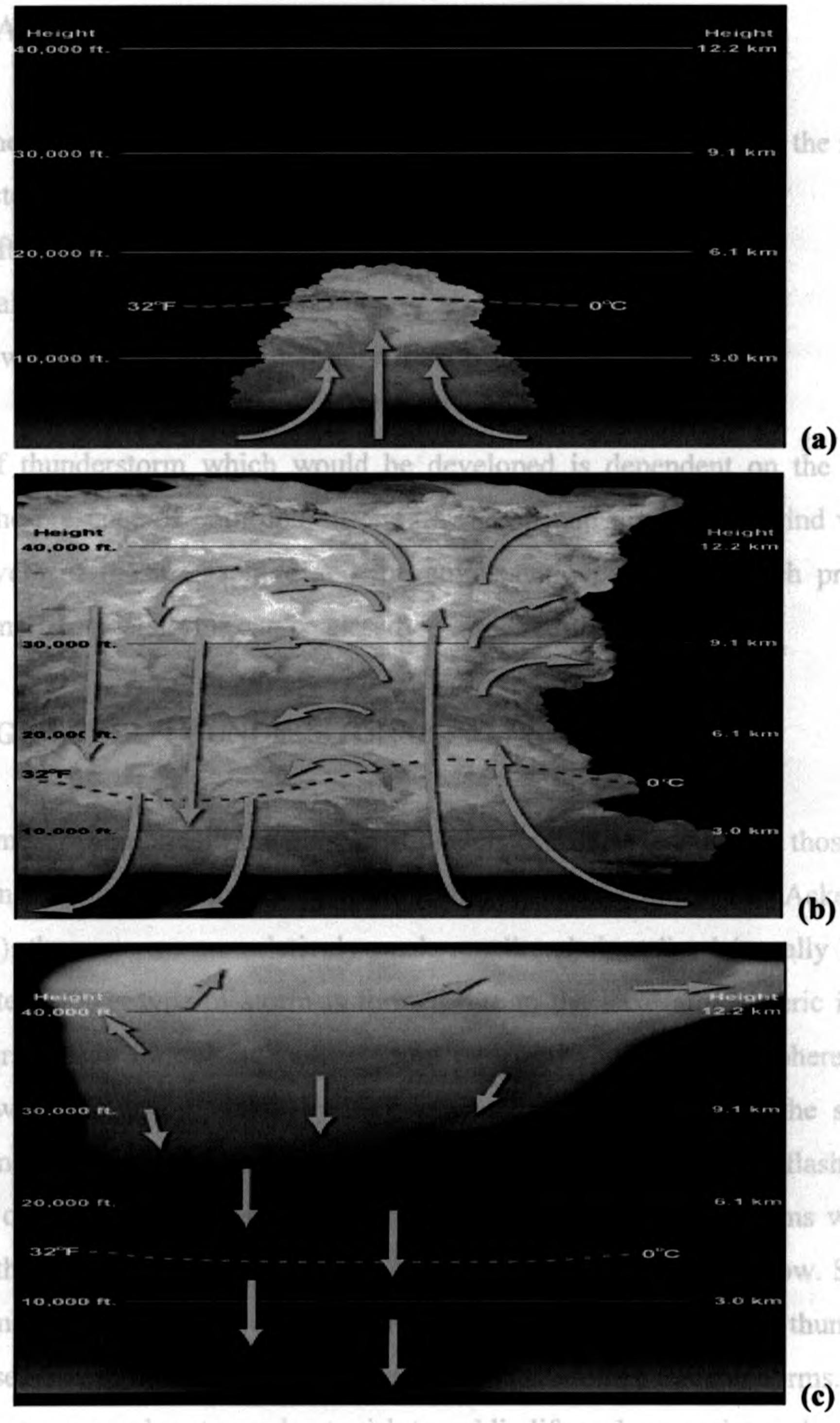


Figure 2.4: Different phases of thunderstorms (a) Cumulus stage (b) Mature stage and (c) Dissipating stage.

(Source: National Weather Service photo library)

2.6 CLASSIFICATIONS OF THUNDERSTORMS

The components in a thunderstorm structure which determine the type and the severity of the thunderstorm are as follows:

1. Updraft and downdraft
2. Vertical wind shear
3. Outflow phenomenon like microburst, gust front etc.

The type of thunderstorm which would be developed is dependent on the instability caused by the presence of both updraft and downdraft and the relative wind velocity at different layers of the atmosphere and the atmospheric processes which produce the thunderstorms. Thunderstorms can be classified into the following types:

2.6.1 SINGLE CELL THUNDERSTORMS:

This is the most common and the simplest thunderstorm. Single cells are those types of thunderstorms which are formed separately as single cells. According to Ackerman and Knox (2003), these storms are relatively weak, small and short lived (usually lasting for 20-30 minutes). This type of storm is formed due to the local atmospheric instability. This thunderstorm is formed in quite random patterns within an atmosphere which is moist and which is accompanied by high pressure systems. Most of the single cell thunderstorms move, but if they don't move, they may cause catastrophic flash flooding. The degree of predictability for predicting which single cell thunderstorms would turn into severe thunderstorms at the end and which would not, is extremely low. Single cell thunderstorms are also known as pulse thunderstorms. Typical summer thunderstorms and typical sea breeze thunderstorms are examples of single cell thunderstorms. This type of thunderstorms cause low to moderate risk to public life and properties and moderate to high risk to aviation.

2.6.2 MULTICELL CLUSTER

When several thunderstorm cells form a cluster and move as a cluster of cells, but each cell has its own life cycle of different phases, then they are called multicell cluster thunderstorms (Ackerman and Knox, 2003). In this type of thunderstorm, the mature stage cells moves along the centre of the multicell cluster, the new cells move at the front edge of the cluster along the upwind edge and the dissipating cells move along the downwind edge of the cluster. Figure 2.5 shows a typical multicell cluster thunderstorm.

Thunderstorms near mountain ranges are examples of this type of thunderstorm. These types of thunderstorms are accompanied by convective updrafts and strong cold fronts. Usually, multicell clusters are stronger thunderstorms than the single cells but weaker than super cells. Multicell cluster thunderstorms quite often cause flash floods.

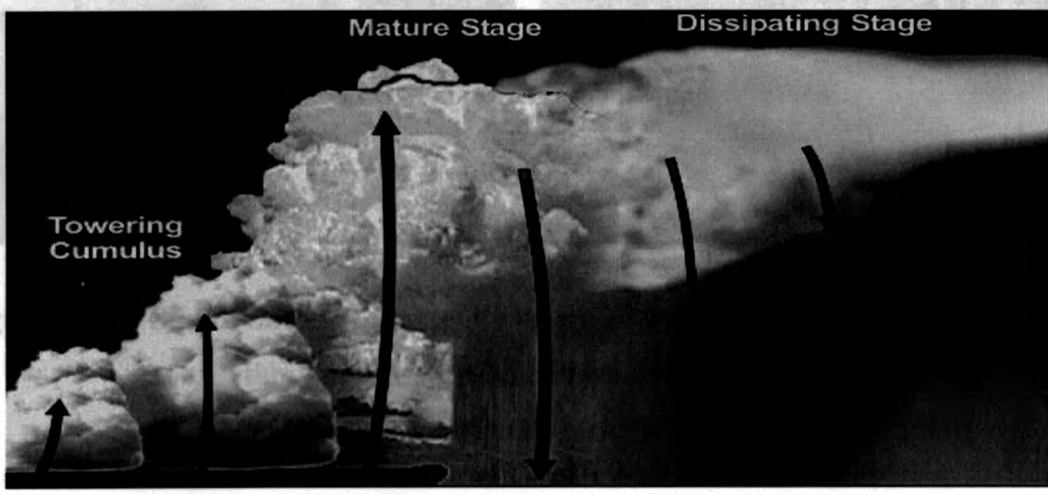


Figure 2.5: Multicell cluster thunderstorms (Source: National Weather Service photo library)

2.6.3 SQUALL LINE AND DERECHO

The squall line is one of the most severe type of thunderstorms. Squall lines can be hundreds of miles long. According to Bluestein et al. (1985) and Klimowski et al. (2003), when several thunderstorm cells are formed into a chain or line instead of clusters, then they are called squall lines or multicell lines. A great number of closely spaced updrafts and downdrafts develop in this complex storm structure which is quite different from the storm structure of multicell clusters. Usually squall lines are accompanied by well developed gust fronts at the leading edge, heavy rain and hail, very strong wind and sometimes tornadoes. A squall line can consist of some other bow echoes and supercells. Figure 2.6 shows a typical squall line, longer than the state length, in the satellite image.

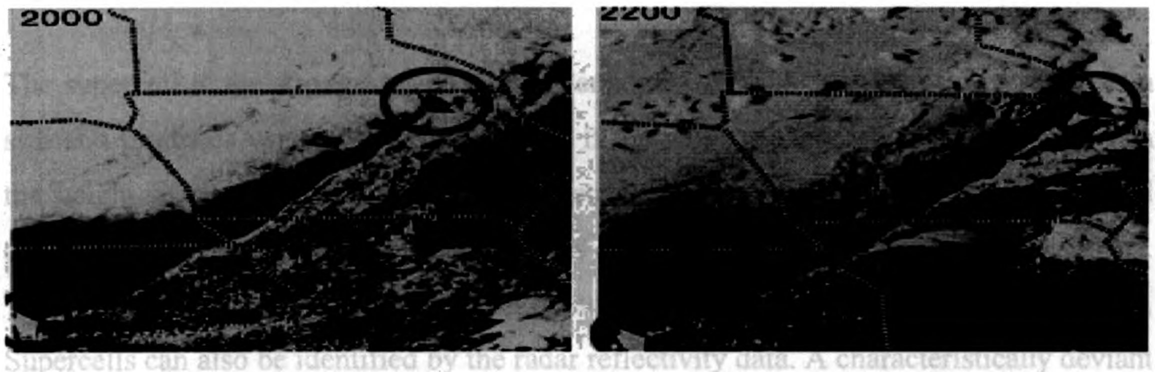


Figure 2.6: Squall lines in the satellite image on 24th September, 1984. The line convection and the start and end points of the squall line are indicated by arrows within circles. (from Dorian et al., 1988)

Squall lines can be identified by a number of factors. A squall line is a thunderstorm system which has a radar reflectivity length to width ratio of 5:1 and which has convective thunderstorms cells in a line of at least 50 kilometres in length and which sustains for at least 30 minutes. (Klimowski et al., 2003 and Bluestein et al., 1985)

With its leading edge high speed wind and larger size hail, squall lines usually cause severe weather. For this reason, a thunderstorm warning is issued as soon as a squall line phenomenon is detected and pilots should be cautious and avoid the squall line area,

especially the gust front of the squall line. But since a squall line is very long and the storm cells are distributed over a large area, it usually does not bring the threat of a flash flood. (Klimowski et al., 2003 and Bluestein et al., 1985)

When squall lines are very long lasting and travel for several hundreds of miles and generate a series of strong downburst winds (often more than 100 mile/hour), they are called Derechoes. Usually the thunderstorms which are more than 386 km (240 miles) long are termed as Derechoes. This type of thunderstorm usually causes damage in a very wide range of area. (Coniglio et al., 2004)

2.6.4 SUPERCELL

The supercell is the strongest type of thunderstorm. If the thunderstorm is very large in size and produces very strong wind speeds, if the wind velocity and direction vary with the height of the storm, if the updraft is strong and rotating and if the updrafts and downdrafts are separate, that thunderstorm is called a supercell (Klimowski et al., 2003). The most important characteristic of a supercell is its deep and rotating updraft. Supercells can also be identified by the radar reflectivity data. A characteristically deviant motion in the reflectivity feature indicates a supercell. The height of supercells can be several kilometres and the width of it can be as large as 24 km and it can produce large size hail (diameter of hail can be as high as 0.1 m), high wind speeds (as high as 130 km/hr) and it can produce strong tornadoes and occasionally flash floods. Many of the strongest tornadoes originate from this type of thunderstorms. Figure 2.7 shows a typical supercell thunderstorm cloud.

Figure 2.7: Supercell thunderstorm (Source: UCAR Digital Image Library)

2.6.5 BOW ECHO:

The bow echo is the last type of thunderstorm. According to Fujita (1978), John (1993) and Klimowski et al. (2003), bow echoes are special type of thunderstorms usually formed from weakly organized squall lines or supercells. If the multicell clusters or the squall line cells are organized in a bow or crescent shape while moving rapidly, that type of thunderstorm system is called as a bow echo. Bow echo cells propagate in a convex shape along its direction. This type of thunderstorm is usually accompanied by strong straight line winds in the lower 2 to 3 km of the atmosphere at the centre of the bow echo. Bow echoes can range in size between 20 km to 200 km and can have a life time between 3 to 6 hours. Bow echoes form an environment suitable for the formation of tornadoes.

2.7 THUNDERSTORM CLIMATOLOGY IN NORTH DAKOTA

Almost all the available journal papers related to the climatology of thunderstorms in USA covering thunderstorms from as early as 1906 until the present all over USA were reviewed to understand the possible climatology of thunderstorms in the research area of North Dakota from the previous relevant research works.

2.7.1 EARLIER WORK

Most of the early research works related to climatology of thunderstorms over the last 100 years were based either on damage report based thunderstorm databases or on databases available from the surface stations located only in three or four locations in North Dakota. Also most of the databases were prepared on a broader view taking into consideration the whole USA at a time, so there was not much scope to give emphasis on any specific state with less population like North Dakota in a detailed way. In a big state like North Dakota, data from only three or four surface stations are not sufficient enough since those stations cover only the thunderstorms that move through those specific station locations, not all over the state. Again, a damage based severe thunderstorm report was counted only when damage worth of $5000 occurred or damage that was caused by a wind speed of 50 knots (25.8 m/sec) or more (Kelly et al., 1985). According to Kelly et al. (1985) and Klimowski et al. (2003), some of the major drawbacks in the damage report based thunderstorm reports are their complete dependence on the presence and density of population, demographic factors like education level of the population (like knowledge about severe thunderstorms and the awareness about the necessity to report a thunderstorm event) and degree of urbanization like highway distribution and distance of a possible storm location to the nearest surface station and the presence of forest in any region to locate a thunderstorm from the damage of the woods. So the places where there were no population dwellings, no surface weather stations or no forests nearby were completely absent from those previous thunderstorm databases and the places with higher population have had more thunderstorm reports concentrated in those locations (places like the

south-eastern region in North Dakota where Fargo and Grand Forks, two of the biggest cities of North Dakota are situated). So most of the previous researchers have urged about the necessity of using a more consistent, more equally spatially distributed and more intense thunderstorm records in any location preferably data obtained from satellite or from well distributed radar systems.

2.7.2 NUMBER OF THUNDERSTORM DAYS PER YEAR

The number of thunderstorm days was studied from all the previous works. From all of the previous work done by Alexander (1935), Court and Griffiths (1981) and Changnon (1988b), it was found that there were on average 20 to 30 thunder days at any place in North Dakota in a year. From the analysis of around 75,000 severe thunderstorm damage reports between 1955 and 1983 all over USA, Kelly et al. (1985) have found that an average of 2608 severe thunderstorms are reported all over USA each year and of these severe thunderstorms, 61% are caused by extreme wind speeds and 39% are caused by hail. Again from the analysis of thunderstorm reports of thirty years between 1904 and 1933, Alexander (1935) found that there were 884 and 843 thunderstorm days in the northern and the middle and southern regions of North Dakota respectively over that thirty year time period. From that information it can be found that there are around 28 to 29 thunderstorm days at any specific place in North Dakota over a year. From an analysis of first order station data from 1951 to 1975, Court and Griffiths (1981) have also found out that each year 20-30 thunderstorm days on average were observed in most of the regions in North Dakota and only in the southern border of the state average 30-50 thunderstorm days were present. Again from the thirty year (1948-1977) first order station data, Changnon (1988b) found that an average of 40 thunder events were observed at any place in North Dakota (Fig. 2.8) and the ratio of thunder event frequency to thunderstorm day frequency in a year was 1.4 in North Dakota (Fig. 2.9), which means that for each 10 thunderstorm days at a place in a year, there are 14 thunder events. This indicates that more than one thunder event occurs on a given thunderstorm day. This also

indicates that on average of 29 thunderstorm days were observed at a place in North Dakota per year between 1948 and 1977 (Changnon, 1988b).

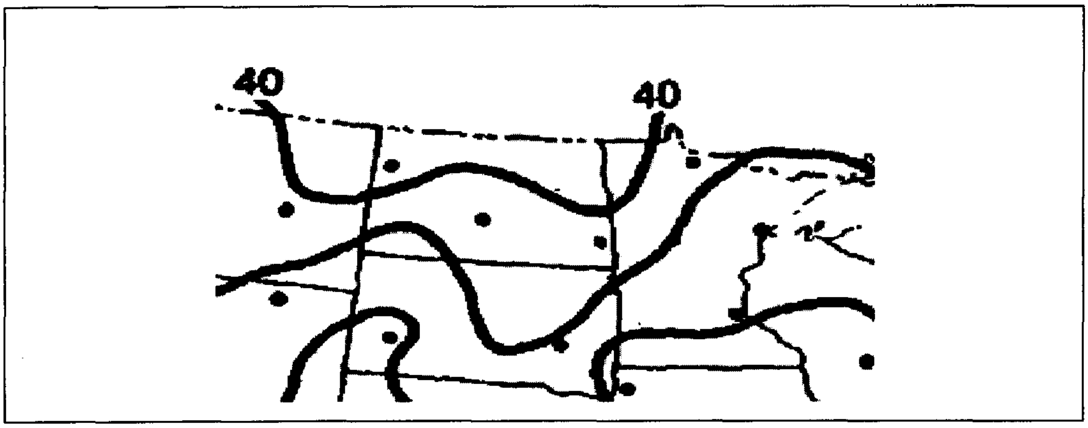


Figure 2.8: Annual average number of thunder events in North Dakota. (from Changnon, 1988b)

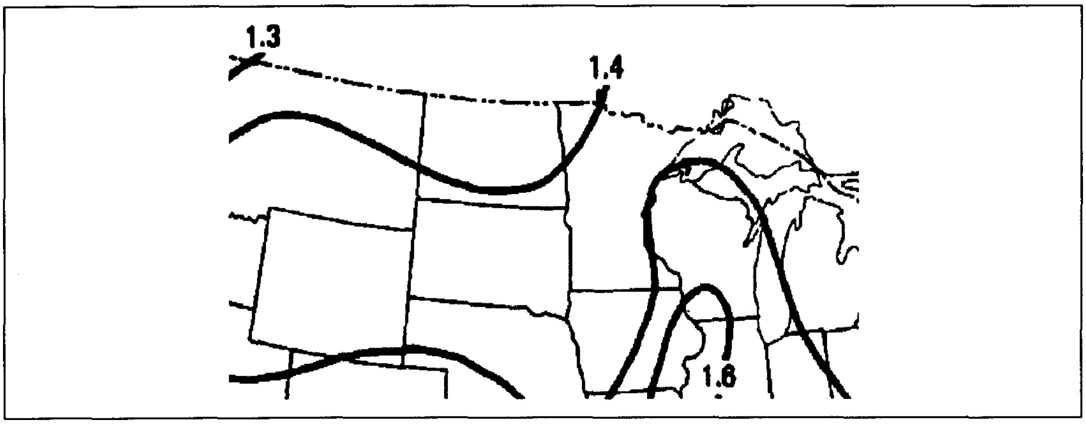


Figure 2.9: Ratio pattern of annual average frequency of thunder events to annual average frequency of thunderstorm days in North Dakota. (from Changnon, 1988b)

2.7.3 MONTHLY DISTRIBUTION

The monthly distributions of thunderstorms in North Dakota in all previous works have been studied. According to Alexander (1935), Kelly et al. (1985), Easterling and Robinson (1985), Changnon (1988a) and Klimowski et al. (2003), July is the most frequent and October to February are the least frequent months for thunderstorms all over the USA especially for the regions on the eastern side of the Rocky Mountains range. From the damage oriented thunderstorm data for 1955-1983, Kelly et al. (1985) found that June and July are the peak months for high wind speed related severe thunderstorms and that May and June are the peak months for hail related severe thunderstorms all over USA and only 2% of all the thunderstorms occur during the winter months of November, December, January and February. Klimowski et al. (2003) have analyzed WSR-88D radar data for the Northern states in USA for 1996-1999 and also found that June and July are the peak months for the thunderstorms (Fig. 2.10) and 86% of all the thunderstorms occur in the three summer months of June, July and August. From the thunderstorm data of 1904-1933, Alexander (1935) also found that July is the most thunderstorm prone month in the North Dakota region and in the eastern region to the Rocky Mountain, the frequency of thunderstorms starts to diminish from the month of September and rises again in March. Easterling and Robinson (1985) and Changnon (1988a) have also said that the summer months are the most frequent months for thunderstorms in North Dakota region and during the winter, there are hardly any thunderstorms there.

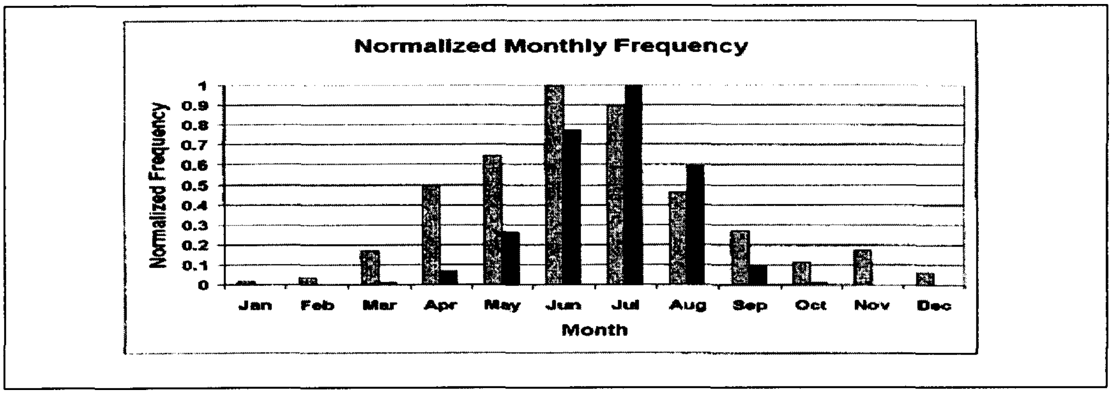


Figure 2.10 : Histogram of monthly distribution of severe thunderstorm wind for 1996-1999 (from Klimowski et al., 2003). Here, the dark black bars indicate histograms for North Dakota.

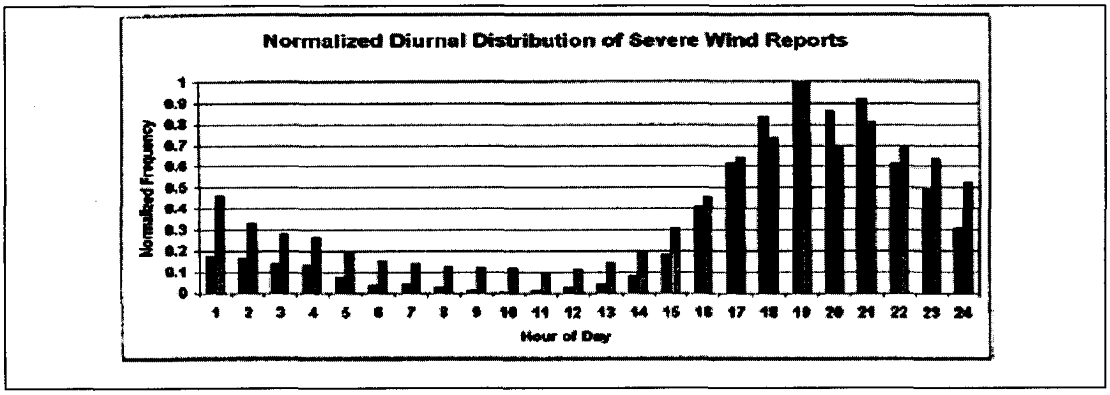


Figure 2.11 : Histogram of hourly distribution of severe thunderstorm wind for 1996-1999 (from Klimowski et al., 2003). Here the dark black bars indicate histograms for North Dakota.

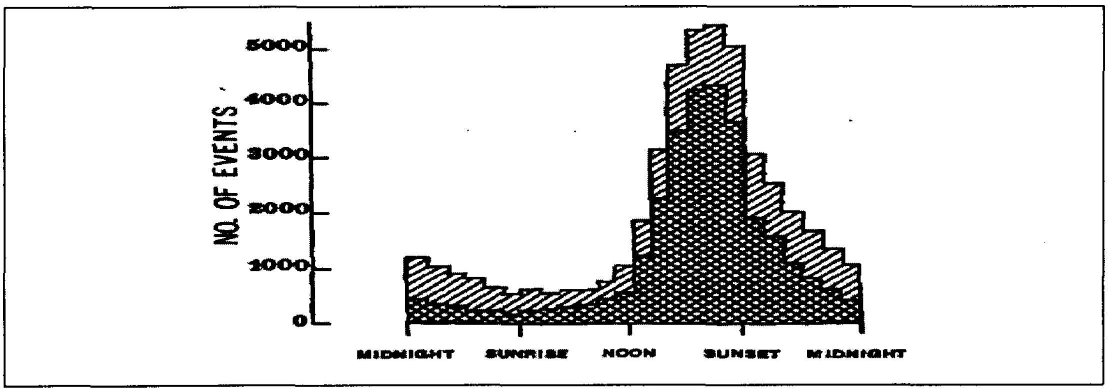


Figure 2.12: Hourly distribution of severe thunderstorms (a) due to extreme wind speed (upper right to lower left hatching) and (b) due to large hails (cross hatching) for 1955-1983 for the whole USA. (from Kelly et al., 1985)

2.7.4 DIURNAL DISTRIBUTION

From all the available literature, it was found that the late afternoon to midnight is the most frequent and the late morning to noon is the least frequent time for thunderstorms in the region of USA where North Dakota is situated. Using the radar data for 1996-1999 in the Northern states, Klimowski et al. (2003) found that 18:00 – 21:00 hour local time is the most frequent and 8:00 – 11:00 hour local time is the least frequent time for thunderstorms to occur on a given day in that region (Fig. 2.11). From the damage based reports for 1955 to 1983 for all over USA, Kelly et al. (1985) also found that mid-afternoon to sunset time are the peak time for both types of severe thunderstorm (wind storms and hail storms) and sunrise to noon time is the least thunderstorm prone time of a day, while a high percentage of thunderstorms also occur between sunset to midnight (Fig. 2.12). They also have found that windstorms are more frequent than the hailstorms all over the day in whole USA (Fig. 2.13). Dai (2001b) has also found out that 14:00 – 21:00 hour local time is the most frequent time range for rainfall based thunderstorms all over the USA while 17:30 hour has the most frequency for those thunderstorms. From thirty years (1948 to 1977) of data from the surface station thunderstorm reports, Easterling and Robinson (1985) have found different definite peak times for thunderstorms all over the North Dakota in different seasons. According to them, during the spring months, 18:00 hour and 20:00 hour local time are the most frequent time for thunderstorm activities in the western and rest of the state area respectively (Fig. 2.13-a) and 20:00 to 22:00 hour local time is the peak time for thunderstorm events during the summer in the western, south-eastern and most of the middle, northern and southern regions in North Dakota respectively (Fig. 2.13-b). Again, 21:00 to 23:00 hour local time is the most frequent time for thunderstorms during the fall season in the western, south-eastern and most of the middle, northern and southern region respectively (Fig. 2.13-c) (Easterling and Robinson, 1985).

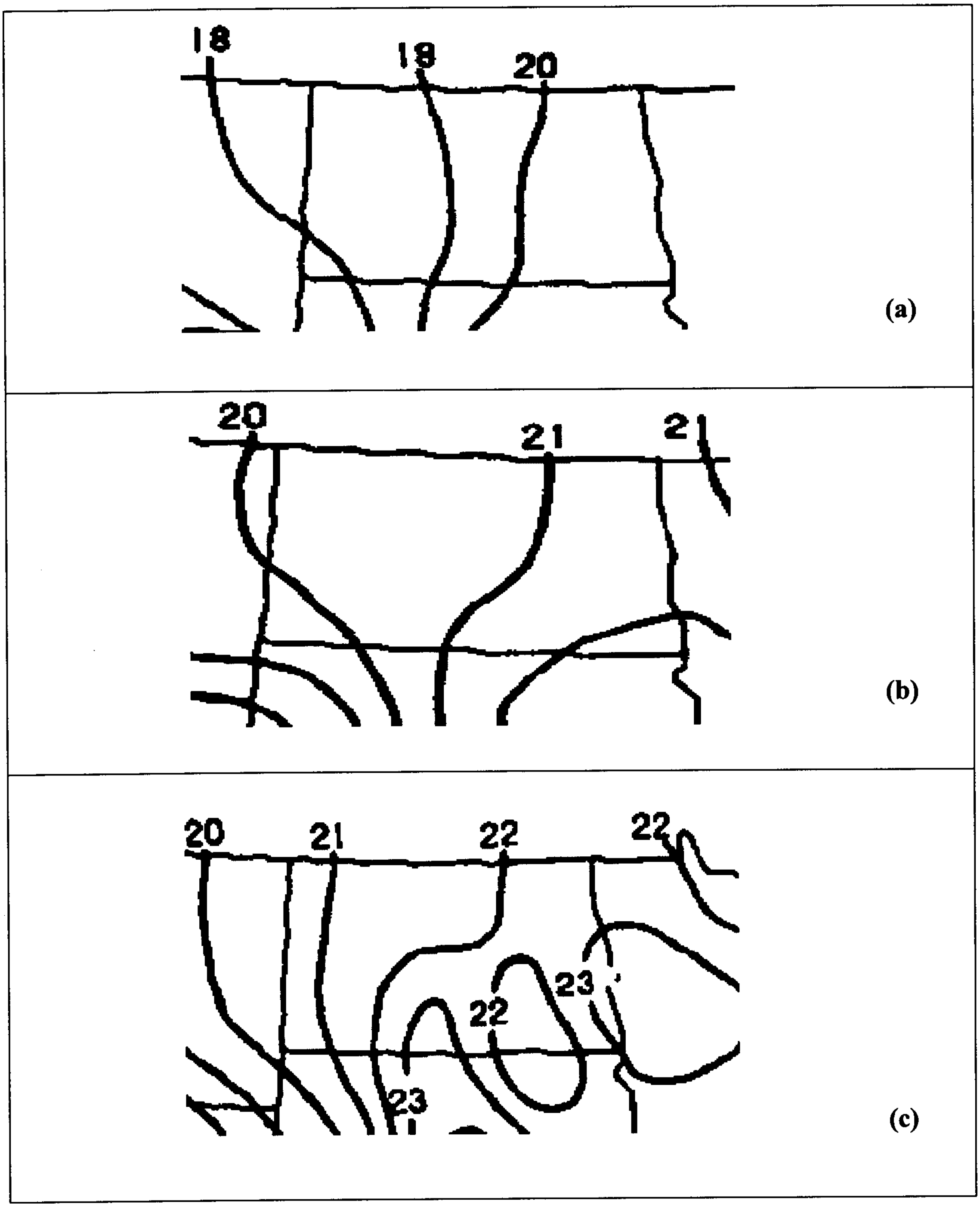


Figure 2.13: **Peak time of thunderstorm activities in North Dakota for (a) Spring, (b) Summer and (c) Fall. (from Easterling and Robinson, 1985)**

2.7.5 SPATIAL DISTRIBUTION

According to Klimowski et al. (2003), there are two thunderstorm prone zones in North Dakota: one region in the western part in North Dakota on the eastern side of Rocky Mountains and the other in the mid-eastern part near to Fargo city (Fig. 2.14). The found an average of 150 thunderstorm reports per 10,000 km^2 in these two regions between 1955 and 1995. From the analysis of data for 1955 to 1983, Kelly et al. (1985) have also found out that the severe windstorms with wind speed greater than 33.5 m/sec are the most frequent in the mid-western and the mid-eastern region of North Dakota. From Fig. 2.15(d) it can also be understood that the mid-western region of North Dakota is the most frequent zone in the state for thunderstorms to originate. But both Kelly et al. (1985) and Klimowski et al. (2003) have also mentioned that their findings of the spatial distribution were based on surface wind reports and the damage reports and these spatial distribution were biased towards the presence of population, number of trees, degree of urbanization and the location of the surface stations. So they recommended for using satellite or radar based thunderstorm data to obtain a non-biased and more accurate spatial distribution of the thunderstorms.

Figure 2.14: Spatial distribution of damage-based severe thunderstorm wind reports for North Dakota for years between 1955 and 1995. The numbers in the figure shows the number of thunderstorm events per 10,000 km^2 per year (from Klimowski et al., 2003)

2.7.6 LIFETIME OF THUNDERSTORMS

From the thunderstorm recording rules of the first order surface stations of the National Weather Service (NWS), many of the previous authors assumed that the minimum duration of a thunderstorm is fifteen (15) minutes considering the fact that in the first order stations, the start time of a thunderstorm was recorded as soon as thunder was heard but the end time of thunderstorm was recorded as the time fifteen minutes later than the last thunder heard. Following this rule and analyzing the first order station data for thirty years from 1948 to 1977, Changnon (1988a) found that the average duration of a thunderstorm event in North Dakota was 90 minutes and the average total minutes of all thunderstorm events at a place in North Dakota as 4000 minutes per year. He also found that thunderstorms at night had an average duration of 100 minutes, which is longer than day time thunderstorm events which were on average of 90 minutes duration. He also found out that thunderstorm event durations vary with the month of the year. According to Changnon (1988a), the average duration of thunderstorm events in North Dakota are 80 minutes, 100 minutes and 60 minutes during the months of May, July and October respectively. He also found a very negligible number of thunderstorms in February to get any average duration in that month for North Dakota. On the other hand, Robinson and Easterling (1988) found that only 6% and less than 1% thunderstorm events were of more than 180 minutes and 360 minutes durations respectively. But at the same time, they have observed that spatial and temporal pattern of these long duration thunderstorm events are significantly different than the shorter duration events all over USA. From the analysis of radar data for Northern High Plains of the United States which includes North Dakota for 1996-1999, Klimowski et al. (2003) also have found that the average life span of severe thunderstorms is 3.8 hours for squall lines, 3.4 hours for bow echoes and 3.9 hours for supercells and between 3 to 4 hours for all types of severe thunderstorms in that region.

2.7.7 TYPES OF THUNDERSTORMS

Klimowski et al. (2003) have analyzed the WSR-88D radar data for 1996-1999 for the Northern High Plains of the United States which includes North Dakota. According to them, of all the severe thunderstorms in that region in that time period, 29% are bow echoes, 20% are squall lines, 9% are supercells and 7% are other convective thunderstorm systems and 29% are single cells. They found that 51% of all of squall lines, 86% of all bow echoes and 40% of all supercells are caused by severe wind speeds. From Fig. 2.15, it can be seen that most of the severe thunderstorms within North Dakota are squall lines and there are some bow echoes also and almost all the supercells in the Northern High Plains are outside of North Dakota.

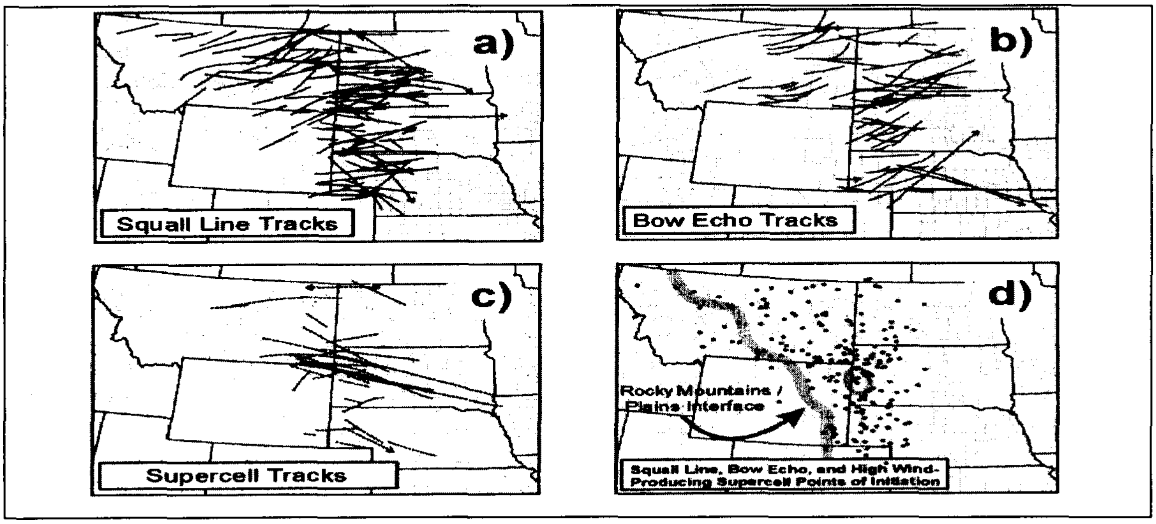


Figure 2.15: Tracks of severe wind producing thunderstorms for (a) squall lines, (b) bow echoes, (c) supercells and (d) the initiation points of all the severe thunderstorms for North Dakota for 1996 and 1999. (from Klimowski et al., 2003)

2.7.8 INITIATION LOCATION AND HEADING OF THE THUNDERSTORMS

From Fig. 2.15(d) produced by Klimowski et al. (2003), it can be found that most of the initiation points of the severe thunderstorms in that region are in the western border of North Dakota, the initiation points mostly were situated just towards the eastern side of the Rocky Mountain region. The presence of the Rocky Mountain range has created a thunderstorm creation zone in the western part of the state.

From the Fig. 2.15(a) and Fig. 2.15(b) it can also be understood that the heading of most of the severe thunderstorms (especially the squall lines and the bow echoes which are dominant in the state) in that region are towards the north-east direction.

2.8 WSR-88D RADAR DATA

The NCDC is a climate research centre under the Department of Commerce in the USA. NEXRAD (**Nex**t-Generation Weather **Rad**ar) is a network of a total of 158 WSR-88D radars all over the USA, operated by the National Weather Service, an agency of the National Oceanic and Atmospheric Administration (NOAA). WSR-88D stands for **W**eather **S**urveillance **R**adar – **D**oppler radars, first installed in 1988 at Norman in Oklahoma in USA. The radars are strategically located in a way that all the radars' ranges overlap with adjacent radars' ranges so that all the weather events can be detected even if one radar may not able to detect any event in case. And many of the radar stations were co-located with the National Weather Service's weather forecast offices (i.e. KBIS in North Dakota) to permit access to maintenance technicians and also to have surface data at the same location as the radar data. (Klazura and Imy, 1993)

WSR-88D radars have several advantages over other radars. According to Polger et al. (1994), the advantages of the WSR-88D radar over other conventional radars are its improved sensitivity, improved resolution, automatic volume scanning and enhanced capabilities. Due to its improved sensitivity, it can able to detect different types of

thunderstorms, especially thunderstorms due to cold fronts, dry-lines, gust fronts etc. An increased resolution helps this radar to obtain information about the storm structure which was not available in other conventional radar data. Due to the automatic volume scanning and enhanced capabilities, this radar can obtain the three dimensional storm structure information in every few minutes depending on the mode of the weather – clear, precipitation or convection.

2.8.1 WORKING PRINCIPLE AND SCANNING STRATEGIES OF WSR-88D RADAR

WSR-88D radars follow some scanning strategies. According to Klazura and Imy (1993) and OFCM (2006), there are three major components of the WSR-88D radar system. They are: Radar Data Acquisition (RDA), Radar Product Generation (RPG) and Principal User Processor (PUP). A radar emits a short pulse of energy in all directions and if the pulse strikes anything on its way– anything including objects in the atmosphere like clouds, rain drops, snow flakes or flying objects like birds and aircraft or even solid objects like buildings or hills, the radar waves get scattered from its way and a portion of the wave (depending on the type of the object) is reflected and again gets caught by the radar receiver (RDA). Then computers in the radar station (RPG) analyze the reflected wave considering the frequency of the reflected wave, the time required for the wave to return, the strength of the wave and especially the Doppler Effect. An algorithm was also applied during the analysis to remove the waves reflected by the solid ground objects like buildings or hills and also to separate the waves reflected by birds and aircraft. The radar's computers then calculate the latitude and longitude of the object, the frequency of the reflected wave and convert it into the velocity of the object and also the direction of the wind – towards the radar or away from the radar and also the values of range, azimuth, reflectivity, VIL etc. Thus a WSR-88D radar collects the weather information.

The WSR-88D radar is an automated system which continually refreshes its scan patterns depending on the weather. These radars have a dish antenna of 28 feet diameter and this antenna is used to transmit and receive the radio signals. It has several Volume Coverage

Patterns (VCP) which have different rotation speeds, elevation angles and transmission-receiving mode. A VCP is a series of 360 degree sweeps of the antenna up to 19.5 degrees of elevations to cover a wide range of atmosphere within those angle limits. There are two modes: "clear air mode" and "precipitation mode". Depending on the mode, the radar automatically assigns itself to a specific VCP. Each VCP has pre-programmed set of azimuth scans, elevation scan angles and a fixed scan time to complete a complete cycle. The radar collects the weather data by rotating the antenna through 360 degrees at the lowest elevation. When one scan is completed, it will go to the immediately higher elevation and sweeps the 360 degree scanning and once when it is completed, it goes to the next higher elevation scan. Thus the radar completes one cycle of scanning the atmosphere in the fixed scanning time depending on that specific VCP. Of all VCPs, VCP 31 and VCP 32 are the clear air mode VCPs for long and short distances respectively. These two VCPs scan only five low elevation angles: 0.5, 1.5, 2.5, 3.5 and 4.5 degrees and complete one cycle of scanning in ten minutes. VCP 21 is active during the precipitation mode and VCP 121 is active during the tropical systems or rotating storms. VCP 11 and VCP 12 are the VCPs during severe weather events, i.e. thunderstorms at short and long distances from the radar station respectively. They have a wide range of elevation angles from 0.5 to 19.5 degrees. Both of them have 14 different azimuth angles and they complete one cycle of scanning in 5 and 4.5 minutes respectively. Besides these, there are three special VCPs: 211, 212 and 221 which work only for low elevation angles (usually below 1.5 degrees) and use a different algorithm – the Sachidananda-Zrnic Algorithm (SZ-2). Table 2.1 describes the different VCPs of WSR-88D radars and the specifications of WSR-88D radars are shown in Table 2.2

Table 2.1: WSR-88D radar Volume Cover Patterns

VCP Name	Scan time (Minute)	Elevation angle range	Elevation scans	Azimuth scans	Usage
11	5	0.5° – 19.5°	14	16	Convection close to radar
12	4.5	0.5° – 19.5°	14	17	Convection at long distance
121	5	0.5° – 19.5°	9	20	Rotating storms or tropical systems
21	6	0.5° – 19.5°	9	11	Precipitation
31	10	0.5° – 4.5°	5	7	Clean Air, long pulse
32	10	0.5° – 4.5°	5	7	Clean Air, short pulse

Table 2.2: WSR-88D radar specifications

Variable	Value
Wavelength	10.0 – 11.1 cm
Frequency	2.8 – 3.0 GHz
Rotation Rate	36° per second
Peak power	750 KW
Antenna Diameter	28 ft

2.8.2 RANGE OF THE RADARS

According to Crum and Alberty (1993), the ranges of NEXRAD WSR-88D radars are as follows:

- The maximum range of a NEXRAD WSR-88D radar is 460 km (263 miles).
- The radars can detect all types of precipitation, hail and thunderstorm cells within 144 km (90 miles) of the radars.
- The radars can detect intense rain and snow within around 230 km (155 miles) range of the radars.
- Individual storms and their locations are identified and tracked within a range of 345 km from the radar.
- Reflectivity products are available at distance of 345 to 460 km from the radar, but no algorithms are active in that range.

2.8.3 TYPE OF RADAR DATA

There are four levels of data are produced by the WSR-88D radars. These are: level-I, level-II, level-III and level-IV data. Of these, level-I data are the data received by the radar receiver in analog format. It is produced by the RDA system. Level-IV Data are developed by the PUP system. These are the base radar products. The two publicly available and more user friendly data types are the level II and level-III data. Level-III data are the data that were used in the current research work.

LEVEL-II DATA

NEXRAD WSR-88D radar level II data are available through the NCDC website. Level-II data are the digital output from the signal processor – the RDA system. Level-II data consists of three parameters: base reflectivity, mean radial velocity and spectral width. The data are available at five, six or ten minute intervals depending on the type of VCP of the radar. This data also includes the information of synchronization, calibration, date, time, antenna position and the operational mode (VCP).

LEVEL-III DATA

NEXRAD WSR-88D radar level-III data are also available through the NCDC website. Level-III data are the output from the algorithm of the RPG system of the radar station. Some algorithms are applied to the level-II data to convert it into a more user friendly form to obtain the level-III data. The advantage of using level-III data over level-II data is that no base data processing is required to use this data for analyzing the climatology of weather events (Crum et al., 1993). There are a total of 41 level-III products available through the NCDC. The products include: (1) general products, i.e. base reflectivity (NOR); (2) precipitation products, i.e. one hour precipitation (N1P) etc.; (3) overlay products, i.e. storm structure products (NSS), hail index products (NHI), meso-cyclone (NME), storm tracking information (NST) etc. and (4) radar message products. Of those products, storm structure (NSS) product, an overlay product, provides information about the storm cell characteristics which include storm position, storm tilting angle, maximum reflectivity, storm area base and top, the mass weighted storm volume, etc. For this current research, the NSS products of the WSR-88D radar level-III were used.

2.8.4 STORM CELL IDENTIFICATION AND TRACKING ALGORITHM

According to OFCM (2006), the Storm Cell Identification and Tracking (SCIT) is the algorithm that is used by radar operators to identify individual thunderstorm cells from the WSR-88D level II radar data. This algorithm is used to identify, characterize, track and forecast the three dimensional storm cells. The SCIT algorithm was developed based on the centroid identification and tracking techniques. Using this technique, SCIT is able to identify individual storm cells in close proximity which earlier algorithms could not identify. Due to the usage of this technique in this algorithm, individual storm cells and their properties are tracked instead of a big thunderstorm system, so those storm cell characteristics like maximum reflectivity, VIL and other properties can be used for this research work for the characterization of thunderstorm activity in an area over a day and over the year and also to predict future thunderstorm activities in an area. This algorithm

uses seven reflectivity thresholds: 30, 35, 40, 45, 50, 55 and 60 dBZ compared to the earlier methods' single threshold of 30 dBZ. It can be noted that no wind velocity data are processed by this algorithm (Johnson et al., 1998). Johnson et al. (1998) analyzed 6561 storm cells for the performance evaluation of SCIT algorithm and found out that the SCIT algorithm is able to track 96% and 68% of all storm cells that have a maximum reflectivity of 50 dBZ or greater and 40 dBZ or greater compared to the earlier algorithm, WSR-88D storm series algorithm's 41% and 24%. They evaluated the accuracy of the SCIT algorithm on the basis of: (1) cell identification, (2) cell tracking (tracking the volume scan to volume scan life cycle of all the identified cells, the accuracy of the time associated with the cell and calculating the percentage of cells accurately tracked by the algorithm etc.) and (3) position of the cell (positional accuracy and spatial proximity etc.) and came to the conclusion that the SCIT algorithm also can able to detect more than 90% of all storm cells accurately (Johnson et al., 1998 and OFCM, 2006).

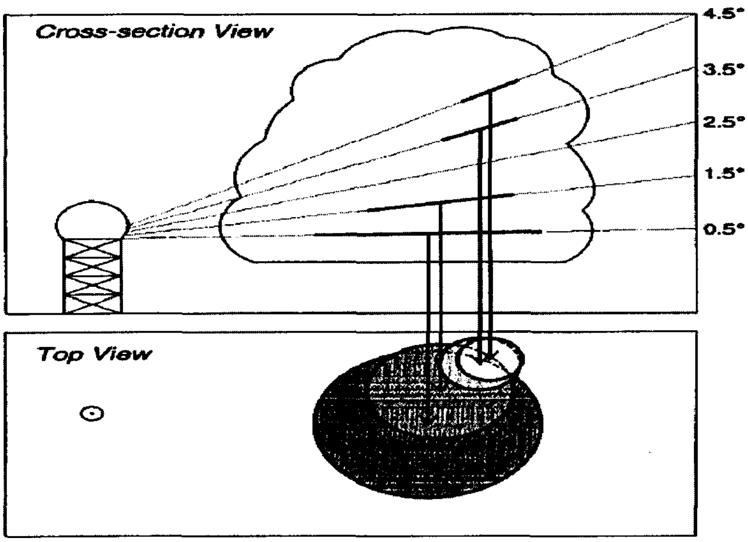


Figure 2.16: Two storm cells identified at the same location with a vertical gap by the WSR-88D radar using the SCIT algorithm. (Johnson et al., 1998)

According to Johnson et al. (1998), the SCIT algorithm identifies the segments of reflectivity in the 1-D plane and categorizes them in the seven reflectivity thresholds (i.e. 50-54 dBZ segments fall into the 50 dBZ threshold) and then merges same reflectivity segments into 2-D storm segments by matching the azimuth and range values before

stacking them into 3-D storm cells combining the elevation scan outcomes and thus the final outputs are 3-D storm cells. Since the highest reflectivity threshold components are used to define the final 3-D cells, the maximum reflectivity values are associated with the final data for each storm cell. Figure 2.16 shows the storm detection process by the SCIT algorithm by line segments into plane (circle) and then into a 3-D cell (cylinder or cone). With the radar's wide range of scanning angles, this algorithm is also able to identify more than one storm cell at the same location separated by a vertical gap (Fig. 2.16).

In this algorithm system, an ID is assigned is assigned to each individual storm cells and this ID consists of a letter-number combination like A0, B0, C0,...Z0, A1, B1, C1,...Z1, A2, B2,.....Z9. This assignment of IDs to all storm cells can able to identify the storm cells having longer life times. But this list of IDs is reset automatically to start with A0 when the RPG is restarted or when a threshold time interval has lapsed without any storm cells within it.

The SCIT algorithm has a few limitations. According to OFCM (2006), the limitations are as follows:

1. Storm tops higher than the highest elevation angles cannot be identified.
2. At longer distances, a radar may not able to detect storm cells due to the presence of only the lowest elevation volume scan. For example, at a distance of 120 nautical miles, the bottom radar beam at 0.5° angle reaches 18000 feet in height – the lowest height of the radar beam at that distance and there is no top beam available at that location. Since at least two consecutive elevations scan are required to detect a storm cell and since two elevation scan are not present at that distance, storm cells cannot be detected at a greater distance using this algorithm system in the WSR-88D radar.
3. When there are several storm cells at a very close distance, errors may take place in detecting them or in calculating the respective cell properties.
4. Due to the Cone Effect, a radar cannot send any beam at more than 19.5 degrees and cannot detect any storm above that beam and large errors may occur for the storm cells very near or at the top of radar.

2.8.5 DIFFERENT COMPONENTS OF WSR-88D RADAR LEVEL III STORM STRUCTURE (NSS) DATA

WSR-88D radar level-III NSS data include the following information:

1. Latitude and longitude of storm cells.
2. Top height, base height of a storm cell and the height of maximum reflectivity.
3. Range and azimuth of a storm cell.
4. Maximum reflectivity (MAXREF) and Vertical Integrated Liquid (VIL).

FID	Shape*	WSRID	DATETIME	LAT	LON	ID	RANGE	AZIM	BASEHGT	TOPHGT	VIL	MAXREF	HEIGHT
0	Point	KBIS	19970313080913	46.63446	-100.51561	R0	13	129	3.2	4.1	0	35	4.1
1	Point	KBIS	19970313080913	46.43155	-100.4535	U0	24	148	4.2	6.9	0	35	4.2
2	Point	KBIS	19970313080913	46.83937	-100.51235	L0	11	68	2.1	3.7	0	36	2.1
3	Point	KBIS	19970313080913	46.76169	-100.85604	G0	4	262	1.2	2.1	0	37	1.3
4	Point	KBIS	19970313080913	47.04032	-100.56769	V0	18	26	<1.2	2.8	0	35	1.2
5	Point	KBIS	19970313080913	46.72956	-100.71935	W0	3	146	1.9	3.5	0	35	1.9
6	Point	KBIS	19970313080913	46.81242	-100.71929	O0	3	34	1.5	2.5	0	36	1.5
7	Point	KBIS	19970313080913	46.69904	-100.48868	X0	12	111	2.3	2.9	0	32	2.9

Figure 2.17: Sample level III NSS radar data showing different characteristics of thunderstorm cells at a certain time.

The table in Fig. 2.17 shows the different components of level-III NSS thunderstorm cell characteristics. Here, the exact locations of the thunderstorm cells are indicated by the latitude and longitude of the thunderstorm cell at a particular time. The linear distance of a storm cell from the radar is defined as the range of the storm cell. Azimuth indicates the angle of a storm cell with regard to the radar and relative to the true north. Storm base height indicates the elevation of the thunderstorm cell from the ground level and the top height indicates the elevation of the top point of the thunderstorm cell from the ground level. WSR-88 radar level-III data expresses the base and top heights in units of thousands of feet. Besides these two, the height of the maximum reflectivity of storm cell information is also present in the level-III NSS WSR-88D radar data.

The reflectivity is the echo intensity measured by the Doppler radar in dBZ unit. Since reflectivity covers a very wide range of signals, a decibel (or logarithmic) scale (dBZ) is used for ease in reflectivity calculations and comparisons. The value of reflectivity is

calculated from the amount of power (in Watts) received considering the distance and nature of the object. The level-III WSR-88D radar data contains the composite reflectivity which means the maximum base reflectivity - the highest echo intensity among all the echoes of different azimuth and elevation angle scans. Reflectivity indicates the intensity trends of the thunderstorm; express the storm structure features, hail and precipitation potential and the boundaries of the storms. In the 'clear air' mode, maximum reflectivity values vary from -28 to +28 and in the 'precipitation' mode; those values may vary between 5 dBZ and 90 dBZ. The higher the intensity of rainfall, the higher will be the dBZ value of reflectivity and the larger the hail, the higher will be dBZ value of the reflectivity. Again, storm cells with a maximum reflectivity value of 30-50 dBZ have a 82% probability of having a duration less than 30 minutes while storm cells with a maximum reflectivity greater than 55 dBZ have a probability of 44% of having a duration less than 30 minutes (MacKeen et al., 1999).

Vertical Integrated Liquid (VIL) is the amount of liquid water in a vertical column of the atmosphere for an area of precipitation. WSR-88D level-III radar expresses VIL in a unit of kilograms per square metre surface of atmosphere. VIL determines the condensation and dynamic development of the thunderstorms and detects the hail and identifies the areas of heavy rainfall and thus regions of thunderstorms caused by hail and heavy rainfall. VIL detects an approximate size of hail. Since hail has much higher reflectivity value than water-rainfall, so a high value of VIL indicates hail. So the higher the value of VIL, the higher will be the size of hail. A VIL value of 10-25 kg/m^2 indicates a hail of nickel size and a VIL value of 25-40 kg/m^2 indicates a hail of dime size. A rapid decrease in VIL value usually indicates rapid increase in wind speed value and thus indicates wind storms in that location. In the SCIT algorithm, VIL values are calculated from the reflectivity values. According to Johnson et al. (1998), the VIL values are found using the following equation,

$$\text{VIL} = \sum_{i=1}^{n} 3.44*10^{-6}\left[\frac{(Z_i + Z_{i+1})}{2}\right]^{4/7} \Delta h \ \ (\text{kg/m}^2) \qquad (2.1)$$

Here, Z_i and Z_{i+1} are the reflectivity values at successive elevation scan levels and Δh is the height between those two levels.

CHAPTER 3

DATABASE CONSTRUCTION AND VERIFICATION

3.1 INTRODUCTION

This chapter discusses the data and the methodology used to create the radar based thunderstorm database for North Dakota. This chapter also discusses the challenges faced during the construction of the database and the verification results of the database for accuracy and completeness through the comparison with the surface data, the county damage reports and the NCDC storm events database for North Dakota for the same time period. Furthermore, this chapter also discusses the few limitations present in the new database.

3.2 SOURCES OF DATA

Thunderstorm data from two primary sources were used for this research work. The sources of the data are:

1. Level-III data products for the three WSR-88D radar stations in North Dakota obtained from the NCDC in United States.
2. Surface weather data from the eight Automated Surface Observing Systems (ASOS) stations in North Dakota.

These data were also supplemented by some selected county thunderstorm data that were obtained from the NCDC's damage based thunderstorm events database.

The station call sign and the locations of the three radar stations in North Dakota and the date on which those stations went into operation are described in Table 3.1. This table also shows that the radar station at Bismarck (KBIS) and at Grand Forks (KMVX) cover thunderstorm data for ten years (1997 to 2006) and the radar station at Minot AFB (KMBX) covers it for a five year time period from 2002 to 2006 for this research work. Figure 3.1 shows the maximum ranges (460 km or 263 miles) of individual radar stations in circles around each station. From this figure it can be seen that the whole of North Dakota, most of South Dakota and much of the southern region of Manitoba are covered by these radars. Figure 3.1 also shows that the range of one station is overlapped by another one or two other stations in that region. This overlapping of radar stations was done considering the fact that all the storm cells would be detected by other radars if any of those radars is out of service or fails to detect a weather event.

Similarly, the station call signs and the locations of the eight ASOS surface stations considered in this research are described in Table 3.2. Figure 3.2 shows that the ASOS stations are relatively evenly distributed all over the state. Since the radar data is available for the ten year time period of 1997 to 2006, the surface station data were collected for the same time period to compare these two types of data and thus to increase the confidence about the research results at the end.

Table 3.1 Details of the three radar stations in North Dakota

Radar station call sign	Location in North Dakota	Latitude	Longitude	Elevation above sea level (m)	Date from which data is available	Duration of data used in research
KBIS	Bismarck	46.77	-100.76	505	18/10/1994	1997-2006
KMVX	Grand Forks	47.53	-97.32	300	16/12/1995	1997-2006
KMBX	Minot AFB	48.39	-100.86	455	01/05/2001	2002-2006

Table 3.2 Details of the eight ASOS surface stations in North Dakota

ASOS station call sign	Location	Latitude	Longitude
KBIS	Bismarck Municipal Airport	46.77	-100.75
KJMS	Jamestown Municipal Airport	46.93	-98.68
KDIK	Dickinson Municipal Airport	46.80	-102.80
KFAR	Hector Int'l Airport, Fargo	46.93	-96.81
KGFK	Grand Forks Int'l Airport	47.95	-97.18
KHEI	Hettinger Municipal Airport	46.01	-102.66
KISN	Sloulin Field Int'l airport, Williston	48.20	-103.64
KMOT	Minot Int'l airport	48.26	-101.28

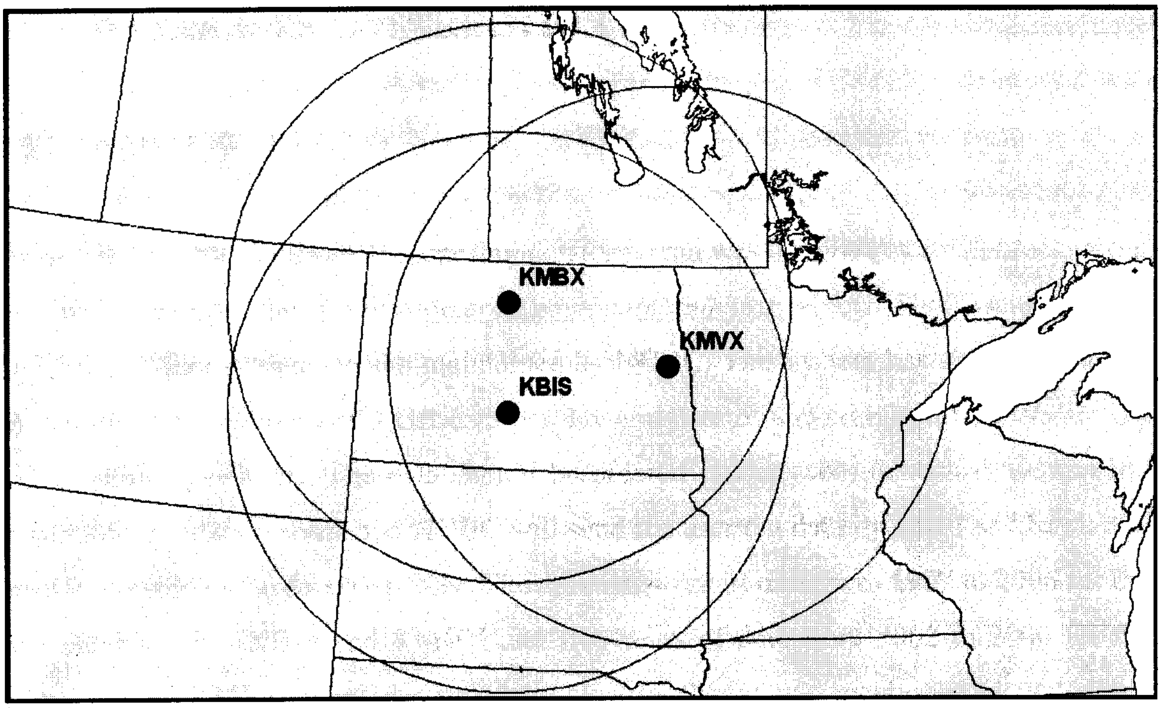


Figure 3.1: Map showing the location of the three WSR-88D radar stations in North Dakota with an indication of their maximum coverage.

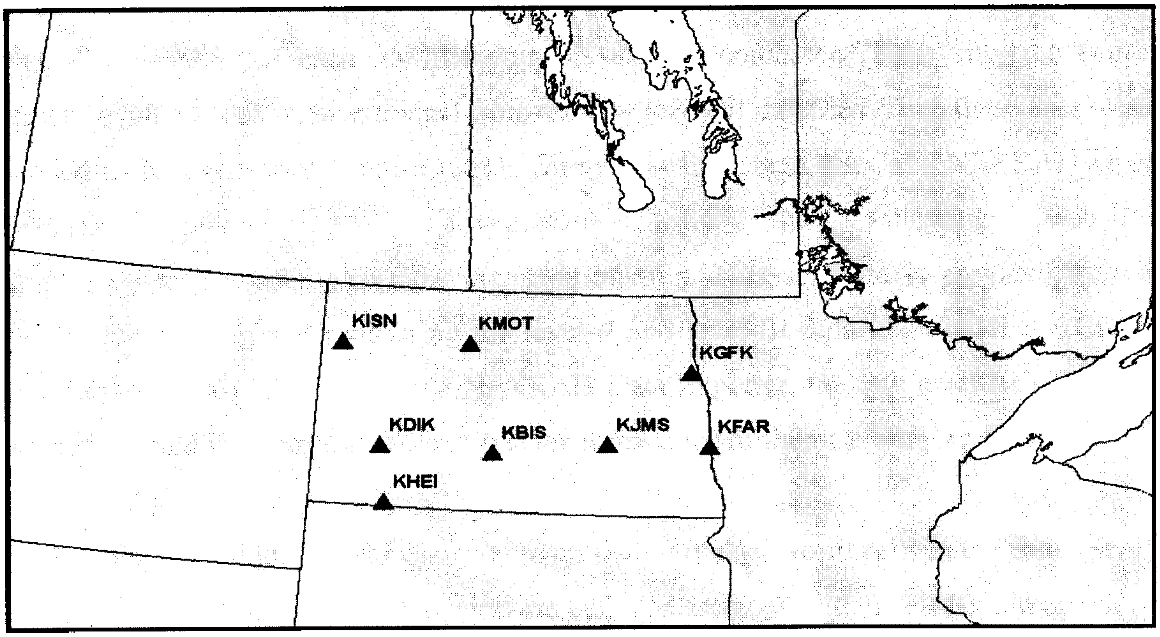


Figure 3.2: Map showing the location of the eight ASOS surface stations in North Dakota.

3.3 DATABASE CONSTRUCTION

3.3.1 RADAR DATA

At first the NEXRAD level III radar thunderstorm data was obtained in small blocks from the website: http://hurricane.ncdc.noaa.gov/pls/plhas/has.dsselect. This website is a hierarchical data storage system maintained by NCDC. This system has a data download limitation of a maximum of 9 GB data per day and data of a maximum of 7 days and 10 radar stations per order. The data should be ordered in that website with those specific limitations for data amount and NCDC will send the user the data by email and he should need to download the data manually. Thus the ten years of data from 1997 to 2006 for the two radar stations KBIS and KMVX and five years of data from 2002 to 2006 for the radar station KMBX were downloaded. Due to the above mentioned downloading restrictions of this system, a considerable amount of time was required to download this data.

Then the downloaded raw level-III data were processed for further use. These data was in *.tar.Z format. Since each .tar file contains a huge amount of data, only the storm structure (NSS) files were extracted from the raw level-III datafiles. Then these data were needed to be transformed into a usable format. At this stage, the Java NEXRAD Data Exporter software was downloaded from the following website: http://www.ncdc.noaa.gov/oa/radar/jnx/jnt-install.php. This software is provided by the NCDC for viewing and processing the level-II and level-III radar data products (Greco and Ansari, 2006). Using the Java NEXRAD Data Exporter, the raw level-III NSS data were converted into shapefile format (vector format) for further use with ArcGIS.

At this stage, a unique ID was assigned to all the individual storm cells in the database. It was found that each different thunderstorm cell was assigned with a cell ID and the date-time information in the raw data. This cell ID is a two digit value which consists of one character and one number. The characters are distributed from "A" to "Z" (total 26 characters) and the numbers between "0" and "9" (total 10 numbers). Thus the maximum

number of available cell IDs is 260 and these cell IDs are redistributed among completely different storm cells at regular intervals (OFCM, 2006). Since cell IDs are recycled, an ArcGIS macro was written to create and assign a unique cell ID to all the different storm cells. This unique cell ID was formed of the cell ID and the date-time stamp for the time when that particular cell ID was first identified. Later, data from all months and years were merged and individual radar databases were prepared for the whole time period. The three radar databases were then merged into a combined database.

At this stage, a bug was discovered in the Java NEXRAD Data Exporter that led to the truncation of longitude, azimuth and range values that were greater than ± 100.00 and the values containing '>' or '<' symbols. This error was corrected by using a Perl script program to extract the variable values from the text version of the level-III NSS files and then using these values to update the original shapefiles in the database. Thus this truncation error from the database was removed.

The lifecycle characteristics of the thunderstorm cells were then analyzed. An ArcGIS macro was written to create path-lines representing the storm cell tracks in the map and also to create a summary table of the characteristics of the storm cells in the database. This macro determined the latitude and longitude where a storm cell first developed, the date and time when it was developed, different characteristics of the storm cell during its lifetime including the duration, travelled length, average speed, average heading, and intensity of the thunderstorm tracks in terms of maximum reflectivity and maximum VIL values. Since there were no data available for 1997-2001 for radar station KMBX and since the average number of thunderstorm cells were doubled after the year 2001 in all radar stations, only five years of data between 2002 and 2006 were considered for this lifecycle analysis.

3.3.2 SURFACE DATA

Surface thunderstorm data were downloaded for the eight ASOS stations in North Dakota from the NCDC and the surface reports from county based thunderstorm reports were

also downloaded from the NCDC storm event database and unzipped. At this stage, according to Lombardo and Main (2006) and Lombardo et al. (2008), using ASOS-WX, a MATLAB based program to extract surface weather parameters from the ASOS data, the thunderstorm beginning and end times and the thunderstorm gust wind reports consisting of wind speed and direction at a specific date and time and also all the peak wind reports for the ten year time period between 1997 and 2006 were extracted for each ASOS station.

Then the radar based databases were compared with the surface data for accuracy and completeness of the radar based database using the database handling package Microsoft ACCESS. The initial comparison was done by comparing the thunderstorm beginning and end times in the surface data with the date and time of the thunderstorm cells in the radar data. For advantage in the comparison, another program was written in MATLAB to find out the beginning and end times of the thunderstorm cells in the radar data. Then the thunderstorm wind reports in surface data were investigated if they fell within the radar and surface thunderstorm time frames by comparing them.

3.4 VERIFICATION OF THE DATABASE

ASOS is the primary surface weather observation system in the USA covering the whole country with its 967 stations. This is a program jointly inaugurated by the Department of Defence, the Federal Aviation Administration and the National Weather Service. ASOS provides surface weather information which is primarily used for forecasting weather and for aviation purposes and the surface data from the ASOS program is also available to researchers for use. ASOS programs collect surface weather data all the year and 24 hours a day (NOAA, 1998).

ASOS stations usually collect the following information about the local surface weather:

- Wind speed, wind direction and time.
- Type of wind (thunderstorm wind or non-thunderstorm wind).
- The start and end time of all the thunderstorms
- Height and size-type of the cloud up to 12,000 feet.

- Visibility in that place.
- Amount of precipitation and the beginning and end times of it.
- Atmosphere pressure, ambient temperature and dew point temperature.

For this research work the following information from the ASOS data were used:

1. Thunderstorm beginning and end time.
2. Peak wind reports with wind speeds above 25 knots (46 km/hr) - thunderstorm wind speed and direction data.

The radar based thunderstorm database was verified for accuracy and completeness by comparing with the surface data. Two ASOS stations were selected for this comparison – the ASOS station at Jamestown (KJMS) and the station at Bismarck (KBIS). Since both radar and surface stations are co-located in Bismarck, surface station KBIS was selected for the comparison with results from radar station KBIS. Again the surface station KJMS was selected due to its location in the middle of the three radar stations KBIS, KMVX and KMBX (Fig. 3.1 and Fig. 3.2). For this reason, KJMS was selected for comparison with data from individual radar stations and also with the combined radar data.

At this stage, two criteria were set for the comparison of the radar and the surface data – (1) the radial distance around the ASOS stations and (2) the time range around the ASOS station's recorded beginning and end time of a thunderstorm. According to the NCDC, a thunderstorm is recorded in an ASOS station from the sound of thunder or from the visibility of lightning or from the peak wind reports. Since thunder is heard and lightning is visible from a reasonably long distance, two radial distances of 10 km and 25 km around the surface station locations were assumed for this comparison. Again in an ASOS station, the beginning time of a thunderstorm is recorded as soon as a thunder is heard or a lightning is seen and the end time of it is recorded as the time 15 minutes after the last thunder is heard or the last lightning is seen. For this reason, two time ranges, ± 0 minute and ± 15 minute time were considered as an additional time range to compare with the ASOS station's recorded beginning and end time of a thunderstorms.

In order to compare the radar and the surface data, at first, buffer zones of 10 km radius were created around the ASOS station locations using ArcGIS. Then the radar data within the 10 km radius around those the two surface stations, KBIS and KJMS, were separated to find out the thunderstorm cells identified by radars in that region. Then the date-times of the radar-detected thunderstorm cells were compared with the surface thunderstorm beginning and end date-times and only the radar detected thunderstorms which fell into the ASOS thunderstorm time ranges were found as the thunderstorms detected by both the radar and the surface stations. A MATLAB based program was used to calculate the thunderstorm beginning and end times in the radar data. Similarly, both the radar and the surface thunderstorm time ranges were then compared with the surface peak wind reports. Then the above procedure was repeated for 25 km buffer zones around the surface stations for all radar stations separately and also for the combined radar data.

From Table 3.3 it can be seen that if the 25 km distance range and 15 minute time range is considered, the maximum number of peak wind reports can be detected by the radars at any specific location. Figure 3.3(a) shows that at a location like Jamestown where the ASOS station KJMS is situated in the middle of three radar stations, most of the thunderstorm days were detected by at least one of the three radars but there are still a few thunderstorm days which are not detected by any of these radars (i.e. 21/5/2005 and 20/7/2005 in Fig. 3.3-a). Figure 3.3(a) shows that 26/06/2005 – this thunderstorm day is detected by the surface station and only one radar, KBIS and 03/07/2005 – this thunderstorm day is detected by the surface station and by an another radar, KMBX. Thus it is found that most of the thunderstorm days are covered by any of the radars at that location. Thus from this figure, it can be clearly understood that one radar is not always sufficient in detecting all the thunderstorms. Again from Fig 3.3 (b), it is found that if we consider the 25 km buffer distance instead of 10 km, all the thunderstorm days are covered by at least one of the radar stations.

From Table 3.4, it can be seen that 119 thunderstorm days in total were detected by the surface station KJMS over the ten year time period. Of all those thunderstorm days in that location, the radar KBIS detected 35% and 72% of all the thunderstorm days if 10 km and

25 km buffer ranges are considered respectively. At the same time, the radar KMVX detected 50% and 84% of the thunderstorm days for 10 km and 25 km buffer ranges respectively. Again, if we consider the combined radar data, it covered 60% of the thunderstorm days for the 10 km buffer. But if we consider the 25 km buffer range, 100% of the thunderstorm days are covered for the whole ten year research period by the combined radar data. Table 3.3 also shows that one radar is able to detect only a small fraction of all the thunderstorm events at a distant place, while the combined radar is able to detect a larger fraction of all the storm events. And using a 25 km buffer radius and a ± 15 minute time range, almost all the thunderstorm events were detected.

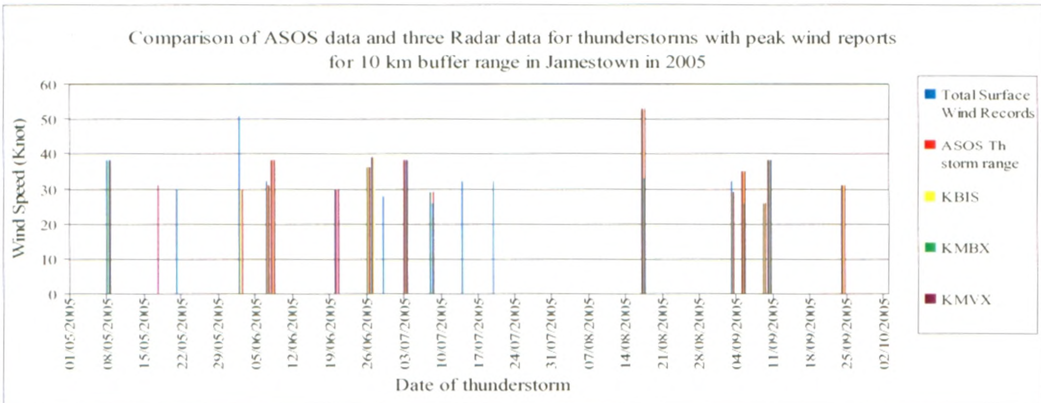
Again if the radar and surface stations are co-located, i.e. in Bismarck, it is also found that the combined radar data with 25 km buffer radius and ± 15 minute time range covered all the thunderstorm events but a 10 km buffer or ± 0 minute time range could not do it (Table 3.5).

But from Table 3.6, we see a different picture. From this table it can be found that the average number of thunderstorm days at a location is almost same for both radar and surface stations (30 and 29 thunderstorm days per year at Bismarck by radar and surface stations respectively). The average number of thunderstorm days due to peak wind speeds also matched for a co-located radar and surface station (14 windstorm days per year).

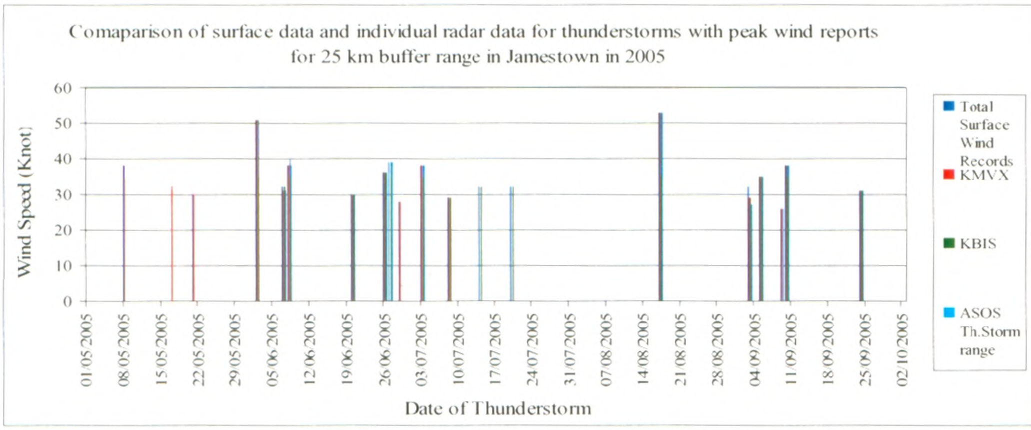
Thus from the above comparison of radar and surface data, it can be concluded that:

1. Individual thunderstorm events are not well correlated but the number of thunderstorm days for the combined data are very good matches. The reason behind this is that the events which might not be covered by the radars were also included in the same thunderstorm system on the same thunderstorm day and that thunderstorm system and thunderstorm days were covered by the radar. This can also be explained by the 'Cone Effect' of the radar. Radars cannot detect any storm very near or at the top of the radar stations - if the storm cell is situated above 19.5° elevation angle, which is the top most elevation angle for all modes in WSR-88 D radar. Thus radars cannot detect storm cells very near to them.

2. At some distance from the radar station, a single radar is not sufficient enough to detect all the thunderstorms, but if more than one radar is considered, all the thunderstorms are covered by the combined radar system.
3. In the case of a 25 km buffer range, a radar can detect a larger number of thunderstorm events than a 10 km buffer range. The matter of this increasing thunderstorm detecting ability of radars at larger distances can be explained by the definition of thunderstorms. A thunderstorm is recorded when lightning is seen or thunder is heard. But lightning can be seen or thunder can be heard from a long distance. So a thunderstorm detected at a surface station does not necessarily occur exactly at that surface station location, it can take place at a larger distance and still can be detected by a surface station. This is the main reason for the variation of radar and surface station based thunderstorm reports.



(a)



(b)

Figure 3.3: Thunderstorm days covered by individual radars and surface data at Jamestown in 2005 at (a) 10 km and (b) 25 km radial distance.

Table 3.3: Number of thunderstorm cells at Jamestown

Distance range around the surface station KJMS	Extended time range	Number of thunderstorm events during March to September in 1997-2006			
		ASOS station KJMS	Radar station KBIS	Radar station KMVX	Combined radar data
10 km	0 minute	517	173	188	247
	15 minute	517	192	216	285
25 km	0 minute	517	289	304	387
	15 minute	517	334	331	421

Table 3.4: Number of thunderstorm days at Jamestown

Range of distance from the surface station KJMS	Number of thunderstorm days with peak wind reports between March and September between 1997 and 2006			
	Surface station KJMS	Radar station KBIS	Radar station KMVX	Combined radar data of all three stations
10 km	119	42	59	72
25 km	119	86	100	128

Table 3.5: Number of thunderstorm cells at Bismarck

Distance range around the surface station KBIS	Extended time range	Number of thunderstorm events during March to September in 1997-2006		
		ASOS station KBIS	Radar station KBIS	Combined radar data
10 km	0 minute	443	179	183
	15 minute	443	218	253
25 km	0 minute	443	299	510
	15 minute	443	315	668

Table 3.6: Number of thunderstorm days at Bismarck

Criteria	Radar station KBIS	ASOS station KBIS
Average number of thunderstorm days per year	30	29
Average number of thunderstorm days with gust wind reports per year	14	14

3.4 LIMITATIONS OF THE DATABASE

The radar based thunderstorm track database has a few limitations. The limitations are as follows:

- Radar data are available for North Dakota from the year 1994 (for KBIS) and 1995 (for KMVX). But the radar data before the year 1997 did not cover a whole radius of its full range; it covered only a fraction of their total range. So all the radar data before the year 1997 were not considered for this database.

- Thunderstorm data for the months between October and February were not included in the radar database. Most of the previous authors like Kelly et al. (1985), Alexander (1935), Easterling and Robinson (1985) and Changnon (1988a), who have previously worked on the climatology of thunderstorms in USA have told that March to September is the prime time for thunderstorms in North Dakota and there are hardly any incidences of thunderstorms during the months between October and February. This is the reason why the data between October and February were not included in the radar based database. Later after comparing the combined radar database with the surface data for the whole year, it was found that this limitation could be significantly reduced only if the data for October would have been included. Around 1.5% data would be missed in this way by excluding the four winter month's data. It was also found that if we had included October, 98.5% of all the thunderstorms over the year would have been included in the radar database.

- Storm structure NSS files were not available in the NCDC database for some of the months over the research time period for different radar stations. No NSS files were found for the radar KMBX in 2004 between the months of April and July and for the radar KMVX, it was the whole year of 2002 and for the radar station KBIS, no NSS files were available for the months between March and June in 2001 and for the months of March and April in 2006. So possible thunderstorm data were missing for those above mentioned months in the final database.

- The initial thunderstorm individual cell database was created for ten year time period (1997-2006). But data from radar station KMBX is available only from 2002. Again for all the radar stations KBIS, the number of thunderstorm cells doubled or tripled after the year 2001 (Table 4.1). For this reason, in order to compare the three radar station data for the same time period and also for getting a more confident results, the analysis for the lifecycle characteristics of the thunderstorm tracks were done for only five years period between 2002 and 2006 ignoring the data between 1997 and 2001.

These above database limitations are in addition to the WSR-88D SCIT algorithm limitations which were discussed in section 2.8.4 in chapter 2.

3.5 SUMMARY

Since the radar stations are not synchronized with one another, radar data from individual radar is not sufficient to detect all the thunderstorm cells at a longer distance. But if we merge two or more radar data together and then compare it with the surface data, it was found that 100% thunderstorm days are covered by the combined radar data. So it can be stated that a combined radar database which is a merged file of more than one radar data is a complete database to detect all the thunderstorms at a location. Again, a thunderstorm is recorded when a lightning is seen or a thunder is heard. But that lightning can be seen from a long distance. So a thunderstorm detected at a surface station can take place at a long distance from the surface station. This is the main reason for the variation of radar and surface station based thunderstorm event reports.

The accuracy of this new database is associated with the matters that (1) the WSR-88D radar scans the atmosphere in each 4.5-6 minutes in precipitation mode and in each 10 minutes in clean air mode of the atmosphere, not being able to detect storm cells in the meantime and (2) the SCIT algorithm is able to track 96% of all storm cells that have a maximum reflectivity of 50 dBZ or greater and more than 90% of all storm cells accurately.

CHAPTER 4

DISTRIBUTION PATTERN AND LIFE CYCLE ANALYSIS OF THUNDERSTORMS IN NORTH DAKOTA

4.1 INTRODUCTION

This chapter discusses the distribution patterns and characteristics of the life cycle of thunderstorms in North Dakota. Both the radar based databases and the surface based databases were analyzed to investigate the characteristics of thunderstorms in this region. This chapter focuses mainly on the results of these analyses and provides a discussion on these results as well as comparing the results with previously published works by other researchers.

4.2 THUNDERSTORM CELLS AND TRACKS

At first, three separate databases of thunderstorm cell data points for the three radar stations KBIS, KMVX and KMBX were produced. Of these three databases, the first two cover the period between 1997 and 2006 while the last one covers the period from 2002 to 2006. The three databases were then merged into a combined database for North Dakota. As shown in Fig. 4.1, these three radars also cover most of South Dakota and a large region in the southern part of the province of Manitoba in Canada. The combined database contains a total of 2.2 million thunderstorm data points in that region for that time period (Fig. 4.1). Of these data points, KBIS and KMVX detected 0.8 million and 0.9 million thunderstorm data points, respectively, over the ten year time period, 1997-2006 while KMBX detected around 0.5 million storm data points over the five year time period, 2002-2006.

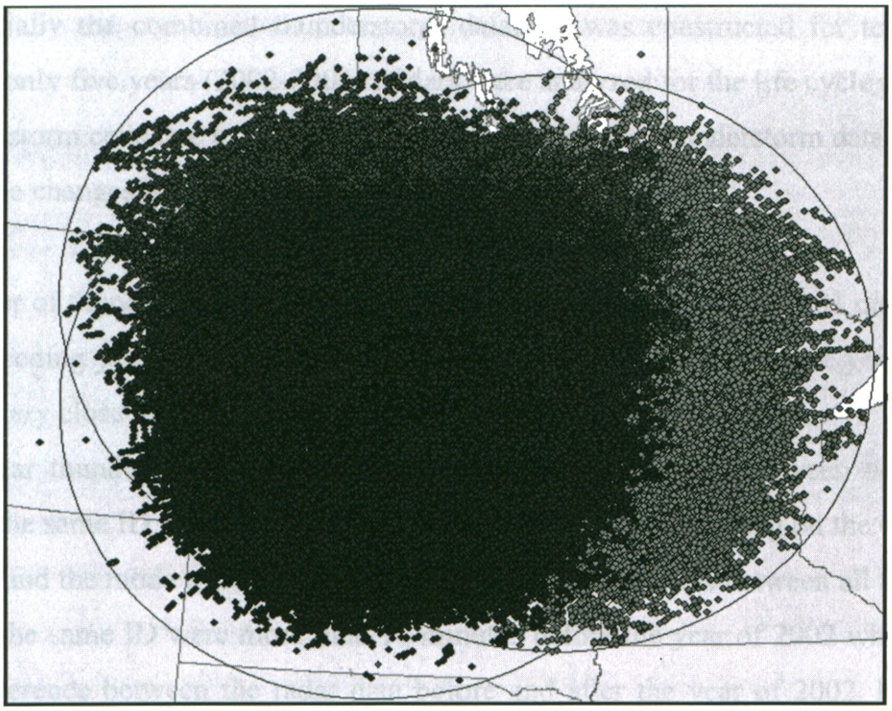


Figure 4.1: Thunderstorm cells covered by the radar stations, KBIS (bottom-left), KMBX (top-left) and KMVX (right) for 1997-2006.

Table 4.1: Number of thunderstorm data points covered by the radar stations in different years

Year	Radar station KBIS	Radar station KMBX	Radar station KMVX
1997	41377	x	40728
1998	35207	x	51702
1999	36270	x	54191
2000	38912	x	34518
2001	34404	x	22107
2002	66783	46693	x
2003	111973	138429	127915
2004	139663	33101	163188
2005	169839	196627	270048
2006	95094	131394	145572

Although initially the combined thunderstorm database was constructed for ten years (1997-2006), only five years (2002-2006) of data were analyzed for the life cycle patterns of the thunderstorm cells due to some significant changes in the thunderstorm data pattern after 2001. The changes in the data pattern include the following:

- The number of thunderstorm cell data points doubled after the year of 2001 compared to the preceding years. Again, the number of storm cell data points in the years after 2001 are very close to each other (Table 4.1).
- In the radar thunderstorm data after 2001, the time differences between two data points of the same ID storm cell were around 5 to 6 minutes depending on the weather condition and the mode of radar. On the other hand, the durations between all the data points of the same ID were more than 15 minutes before the year of 2002 which is a major difference between the radar data before and after the year of 2002. For this reason, the radar data before 2002 were ignored for the life cycle analysis.
- There is no thunderstorm data available for the station KMBX before the year of 2002. A combined thunderstorm database was developed from all the three radar stations for the same time period so that data from individual radar stations can be compared with one another and thus the credibility of the database can be increased.
- The data archiving philosophy was changed after the year 2001.

After analyzing the life cycle characteristics for the thunderstorm data for 2002-2006, it was found that the combined radar storm track database consists of 255,409 individual thunderstorm cell tracks. Of those 80,605, 76,559 and 98,245 thunderstorm cell tracks were detected by KBIS, KMBX and KMVX radars respectively during the five year time period. On average 16,121, 15,312 and 19,649 thunderstorm cell tracks were identified per year for the radar stations KBIS, KMBX and KMVX respectively.

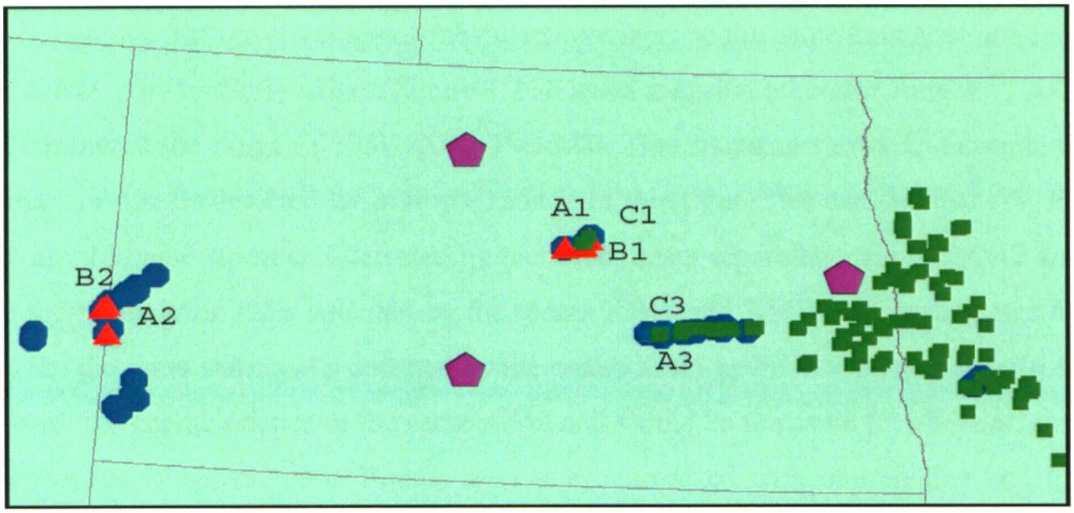


Figure 4.2: **Snapshot of storm cells detected by three radars at a specific time: by KBIS (red triangle), KMBX (blue circle) and KMBX (green rectangle) for the time 19:01:00 to 19:15:00 on 26/06/2005.**

Table 4.2: **Comparison of a thunderstorm cell detected by multiple radars**

Characteristics	Storm cell, A1 (by KBIS)	Storm cell, B1 (by KMBX)	Storm cell, C1 (by KMVX)
ID	U9	E0	P2
Date	26/06/2005	26/06/2005	26/06/2005
Time	19:11:47	19:12:14	19:12:36
Latitude	47.77657°	47.76136°	47.78435°
Longitude	-99.67062°	-99.67638°	-99.68658°
Max. reflectivity	51 dBZ	51 dBZ	46 dBZ
VIL	13 kg/m^2	11 kg/m^2	4 kg/m^2
Base height	<7.8 k-ft	<5.3 k-ft	16.2 k-ft
Top height	18 k-ft	17.6 k-ft	25.2 k-ft
Height of max. ref.	14.1 k-ft	11.7 k-ft	16.2 k-ft
Range	75	61	97
Azimuth	36	128	280

Figure 3.1 shows that the coverage of the radars overlaps, so the same thunderstorm cells can be detected by multiple radars. Figure 4.2 shows a snapshot taken for June 26th, 2005 for a 15 minute time range of 19:01:00 to 19:15:00. This snapshot shows an example of the same storm cells detected by multiple radars. In this figure, we can see that A1, B1 and C1 are the same storm cell detected by the three radars separately. Similarly, A2 and B2 are the same storm cells detected by the radars KBIS and KMBX separately and A3 and C3 are the same storm cells detected by the radars KBIS and KMVX separately. In an ideal word, the characteristics of the same storm cell would be the same for all radars, but in practice this is not the case. Radars are not synchronized with one another and the capacity of the radars depends on the distance of the storm cell from the radar station. These two matters lead to the same cells with slightly different characteristics in different radars. The comparative differences in the characteristics of a storm cell detected by three radars are given in Table 4.2. This table shows that the storm ID, exact time and location, maximum reflectivity, VIL and other cell characteristics differ slightly for same storm cell for different radars. Thus it can be stated that there are a certain number of storm cells which were counted multiple times by different radars. Figure 4.2 also shows that many of the storm cells are not covered by more than one station. Figure 3.3 also shows that one radar is not sufficient to detect all the thunderstorm cells at a distant location from a radar station and if more than one radar station is considered simultaneously, all the thunderstorms are covered. In order to avoid this repetition of the same storm cell in different radars with different characteristics, it would be preferable to start with the level-II data from multiple radars before merging and processing those in a consistent fashion, but that is beyond the scope of this thesis.

4.3 NUMBER OF THUNDERSTORM DAYS PER YEAR

The number of thunderstorm days per year and thunderstorm days with peak wind reports was calculated for different locations in North Dakota for 2002-2006. From Fig. 4.3 and Table 4.3, it can be seen that the average number of thunderstorm days each year varies from 19 to 35 days per year at any particular location in the state. It was also found that the average number of thunderstorm days all over North Dakota is 29 days per year. This

result for the number of thunderstorm days per year is a perfect match with the estimate of the number of thunderstorm days given by Alexander (1934) for the whole of North Dakota for the 30 year period 1904-1933 which was also 29 thunderstorm days per year. This number also matches with the value given by Changnon (1988b), 29 thunderstorm days per year for 1948 to 1977 and falls within the range given by Court and Griffith (1981), 20-30 thunderstorm days per year for 1951 to 1975. From Table 4.3, it can be seen that the radar based database shows that the number of thunderstorm days per year is 30 in Bismarck (KBIS), 21 in Grand Forks (KMVX) and 19 in Minot (KMBX). Table 4.4 shows the number of total thunderstorm days per year and the number of thunderstorms days per year with peak wind reports with the number of thunderstorm days between March and September in the bracket. From the comparison of Tables 4.3 and 4.4, it was found out that the number of thunderstorm days per year at Bismarck is almost the same for the radar and surface data. Thus it can be stated that the radar data provides a highly reliable accuracy of thunderstorm coverage at a location.

Of all the thunderstorm days in North Dakota, it was found that on average 35% – 60% of all the thunderstorm days are caused by high wind speeds (wind speeds of more than 25 knots) and the rest are due to heavy rainfall, large hail or lightning. The number of thunderstorm days with peak wind reports varies from a minimum of 9 to a maximum of 14 days per year (Fig. 4.3) and the average for the entire state is 13 windstorm days per year. It was also found that 1.7% of all the thunderstorms with peak wind speed reports in North Dakota are severe thunderstorms (wind speeds of more than 93 km/hr).

Table 4.3 Average number of thunderstorm days each year at different locations of North Dakota for 2002-2006 for the radar data

Radar station	Number of thunderstorm days per year
KBIS	30
KMBX	19
KMVX	21

Table 4.4 Average number of thunderstorm days each year at different locations of North Dakota for 2002-2006 for the surface data

Surface station	Number of thunderstorm days per year (in whole year and between March and September)	Number of thunderstorm days with peak wind speed per year (in whole year and between March and September)
KBIS	29 (28)	14 (13)
KJMS	33 (32)	13 (12)
KDIK	31 (30)	13 (13)
KFAR	19 (18)	10 (9)
KGFK	35 (31)	12 (11)
KHEI	23 (22)	14 (14)
KISN	35 (34)	14 (14)
KMOT	25 (24)	9 (9)
Overall average	29 (27)	13 (12)

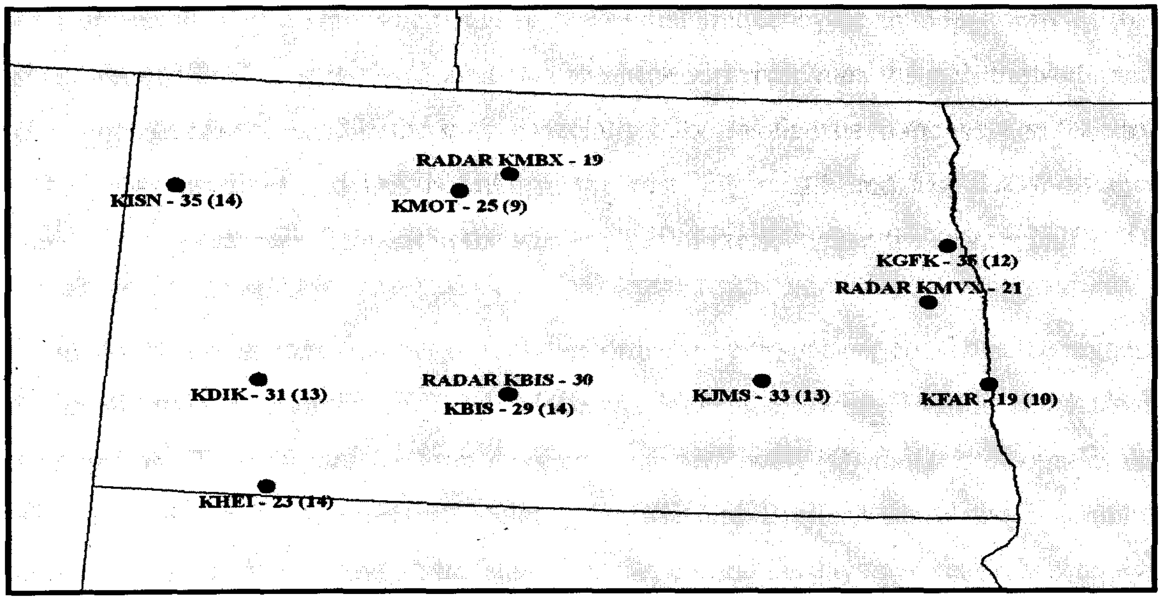


Figure 4.3: Number of thunderstorm days per year at different locations in North Dakota in 2002-2006. The numbers of thunderstorm days due to peak wind speeds are indicated within brackets.

4.4 SPATIAL DISTRIBUTION

The spatial distribution of thunderstorms in North Dakota is discussed in this section. All previous researchers who worked in the field of the climatology of thunderstorms in different regions of the USA, including Kelly et al. (1985) and Klimowski et al. (2003), have suggested the usage of radar or satellite data rather than surface data or damage report based data for better accuracy in examining the spatial distribution of thunderstorm events.

Figure 4.4 shows the names and locations of different counties in the state of North Dakota while Fig. 4.5 shows a shaded relief figure of the underlying topography pattern of the state. Figure 4.5 shows that the western parts of the state are highlands while the eastern parts are comparatively low lands. The average height of land in the western part of North Dakota varies from 1800 feet to 4500 feet above sea level while the average height in the eastern part ranges from 600 feet to 1800 feet above sea level. The topographic conditions in North Dakota and the variation in the angle of the solar heating for that reason play a significant role in the spatial frequency of thunderstorms in this state. From Fig. 4.5, it is also found that the Missouri river runs through the state and some big lakes are situated in the state, especially Lake Sakakawea in the west on the way of the Missouri river and Devils Lake in the east. Figure 4.6 and Fig. 4.7 show that thunderstorms are more frequent in the western half of the state than the eastern half.

Figure 4.6 shows that the number of thunderstorm days per year per county is the highest in the mid-western counties of Ward, McHenry, Mclean, Burleigh, Morton and Kidder ranging from 71 to 80 thunderstorm days per year per county. Of those, the counties on the banks of the Missouri river, Mclean, Morton and Burleigh show the maximum number of thunderstorm days in the state with 79, 76 and 76 days per year respectively. Besides, the southern counties of Grant, Sioux and Emmons, the western counties of Mountrail, McKenzie, Dunn, Start and Stark, the eastern counties of Griggs, Stutsman etc. also face considerably high number of thunderstorm days per year. On the other hand, the south-eastern border counties of Richland, Sargent, Ransom and the county of Pembina in

the north-east observe the lowest number of thunderstorm days with 18, 20, 24 and 20 days per year respectively. From the comparison of Fig. 4.6, 4.7 and 4.8, it was found that the spatial distributions for the number of thunderstorm days and the number of thunderstorm cells are very similar. The counties showing the higher frequency of thunderstorm days per year in Fig. 4.6 also show higher number of thunderstorm cells in Fig. 4.7 and Fig. 4.8. The number of thunderstorm cells is the highest in the counties of Griggs, Stutsman, McHenry, Burleigh, Mclean, Morton and Kidder with 11.8, 2.9, 2.2, 2.2, 2.0, 1.9 and 1.9 thunderstorm cells per sq. km per year. Again, the number of thunderstorm cells is the lowest in the counties of Richland, Pembina and Bowman with 0.1, 0.2 and 0.2 thunderstorm cells per sq. km per year. This estimation for spatial distribution of thunderstorms is in agreement with Klimowski et al. (2003) that mid-western region (around the Missouri river) and a zone in the east (Griggs and Stutsman) is the most thunderstorm prone region in the state.

Although radar data exhibit much more accurate spatial distribution results than other types of conventional data, it has two limitations:

1. As discussed in the sections 2.8.2 and 2.8.4, the efficiency of radar for detecting a weather event is higher at shorter distances and with increasing distances, its efficiency decreases gradually. Figures 4.8, 4.9 and 4.10 showing the number of total thunderstorm cells per county, the number of thunderstorm initiation points per county and the average maximum reflectivity for individual radars prove that the efficiency of individual radar is high around its location and the efficiency decreases with an increasing distance of thunderstorm cells from the radar station.
2. The coverage of radars overlap. As described in section 4.2, some of the thunderstorm cells in the common coverage region are counted more than once, each time by different radars. To avoid this discrepancy, individual radar data were also investigated (Fig. 4.8, 4.9, 4.10) along with the combined radar for this work.

But these two limitations are not necessarily the governing forces in the spatial distribution of thunderstorms all the time. For example, the spatial frequencies of thunderstorms are considerably high in the counties of McKenzie, Dunn, Emmons and

Grant in Fig. 4.7, while they are at some reasonably long distances from the nearest radar stations. On the other hand, the frequencies of thunderstorms are relatively low in the eastern counties like Nelson, Steele, Trail, Barnes, Grand Forks and Cass although they are very near to the radar station KMVX. Figure 4.7 and Fig. 4.8 also show that the frequencies of thunderstorms are also relatively low in the northern counties like Renville and Rollette although they are very near to the radar station at Minot (KMBX). Although located in the middle of three radar stations, there is a very low thunderstorm frequent zone in the mid-eastern counties of Eddy and Foster. Thus it can be understood that these two limitations are not always the governing factor in the spatial distribution of thunderstorms in this state.

As discussed in section 2.4 in chapter 2, the presence of large lakes or rivers supply the necessary warm and moist air for the development of thunderstorm cells and the presence of hills or mountains and the topographic condition of lands also facilitate the creation of thunderstorm cells at a place. Figures 4.5, 4.9(a) and 4.9 (b) show that the presence of hilly areas on the western bank of the Missouri river and the presence of the Lake Sakakawea and the Missouri river itself leads to a major thunderstorm initiation belt in the counties on the two banks of the Missouri river running through the state, McKenzie, Mountrail, Ward, Mclean, Dunn, Mercer, Morton, Burleigh, Sioux and Emmons. Figures 4.9(b) and 4.9(c) show that the presence of Devils Lake has also lead to the presence of another thunderstorm initiation zone in the counties of Ramsey and Benson in the north-eastern region of the state. From Fig. 4.9(c), it is also found that a considerable number of thunderstorms also initiate in the eastern border counties of Grand Forks, Trail and Cass. Figure 2.15 (d), given by Klimowski et al. (2003), is also in agreement with the current finding described in Fig. 4.9(a) and 4.9(b) that the mid-western region (the region around Lake Sakakawea and the Missouri river) is the most frequent thunderstorm-initiation-zone in the state.

Figure 4.10 shows that the average maximum reflectivity of storms is higher for the counties furthest from the radar stations. This can be explained by the fact that radar can detect all the thunderstorms near to it and its efficiency decreases with longer distances

and at longer distances, a radar can detect only the stronger thunderstorms. For this reason, the average maximum reflectivity in any county at a longer distance from the radar stations is higher than that for closer counties.

If level-II data from the three radar stations might be merged together at the beginning of the database creation process, those two limitations could be overcome, but that is beyond the scope of this thesis. For this current research work, although radar data have those two limitations for spatial distributions, it shows a much better spatial distribution than shown by a surface station. Since there is no surface stations available in some of the most thunderstorm frequent counties like Mclean, Grant, Sioux and Emmons, Benson, Ramsey or Griggs, it is not possible to detect thunderstorms in those counties by the surface data and thus it is not possible for surface data to find out a state wide spatial distribution pattern of thunderstorms. The thunderstorm initiation zones also cannot be detected by the surface data. Considering these matters, it can be concluded that radar data, although having those two discrepancies, provides a much more accurate and much widely distributed spatial distribution of thunderstorms in North Dakota. But from Fig. 4.6 and 4.7, it was also found that the inclusion of data from few more radar stations in the adjacent states of Montana, Minnesota and South Dakota would certainly increase the completeness of the thunderstorm database created in this research.

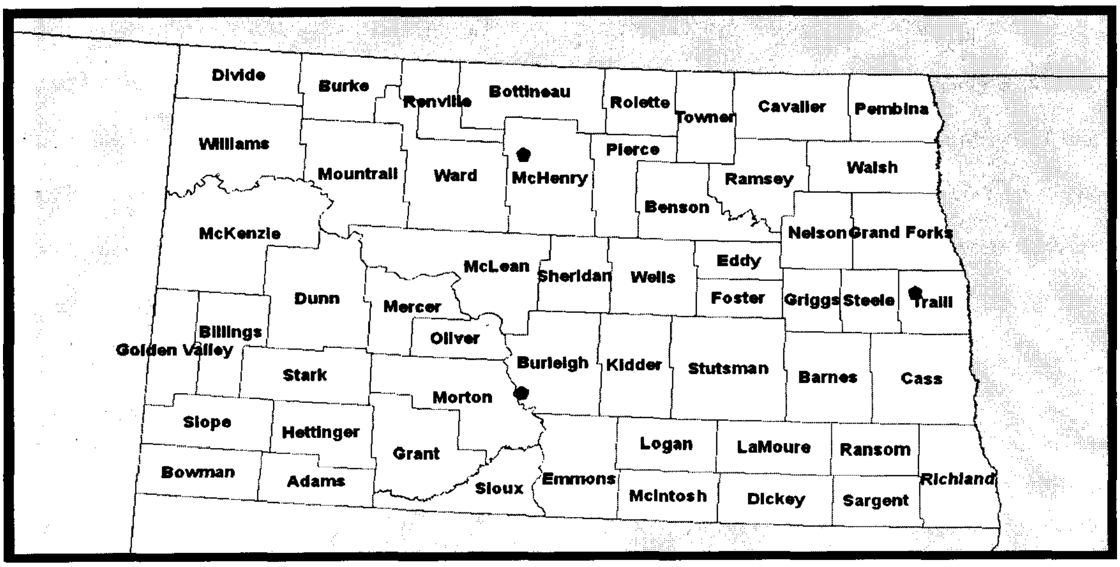


Figure 4.4: Names and locations of different counties in North Dakota.

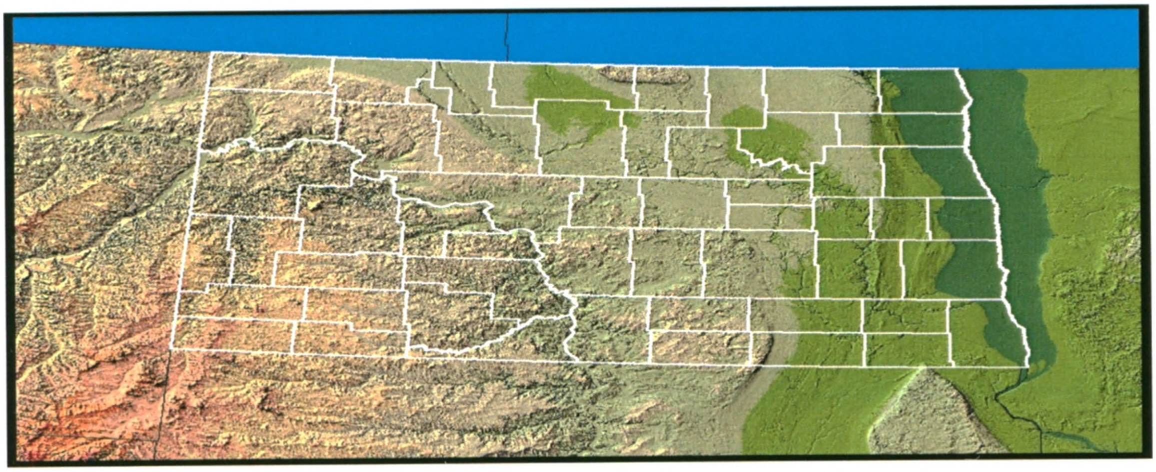


Figure 4.5: Land topography pattern all over North Dakota.

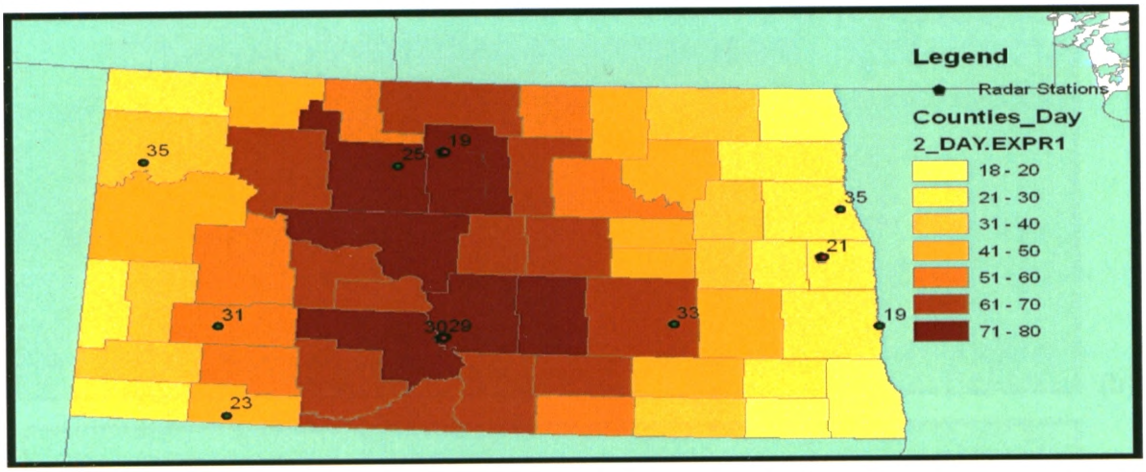


Figure 4.6: Spatial distribution for number of thunderstorm days per year in North Dakota for 2002-2006.

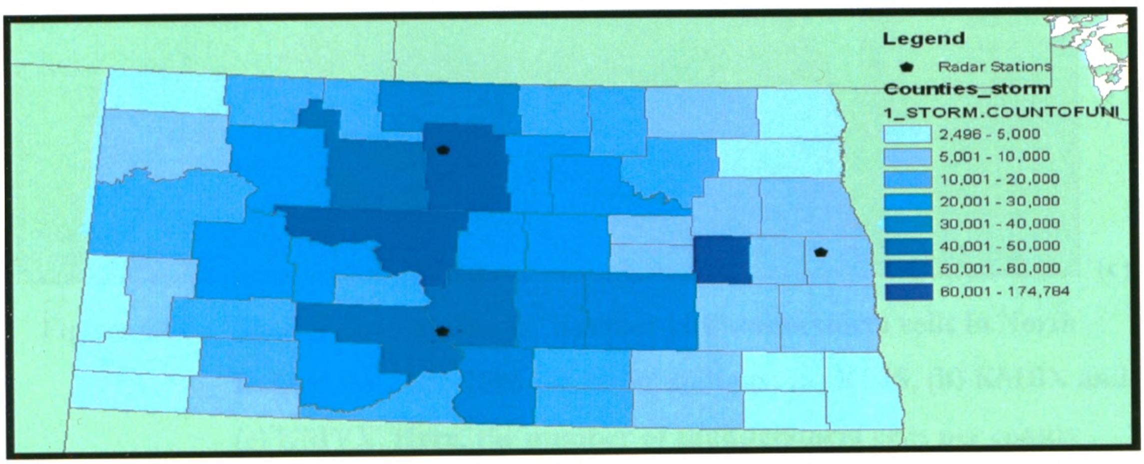


Figure 4.7: Spatial distribution for the total number of thunderstorm cells in North Dakota between 2002 and 2006.

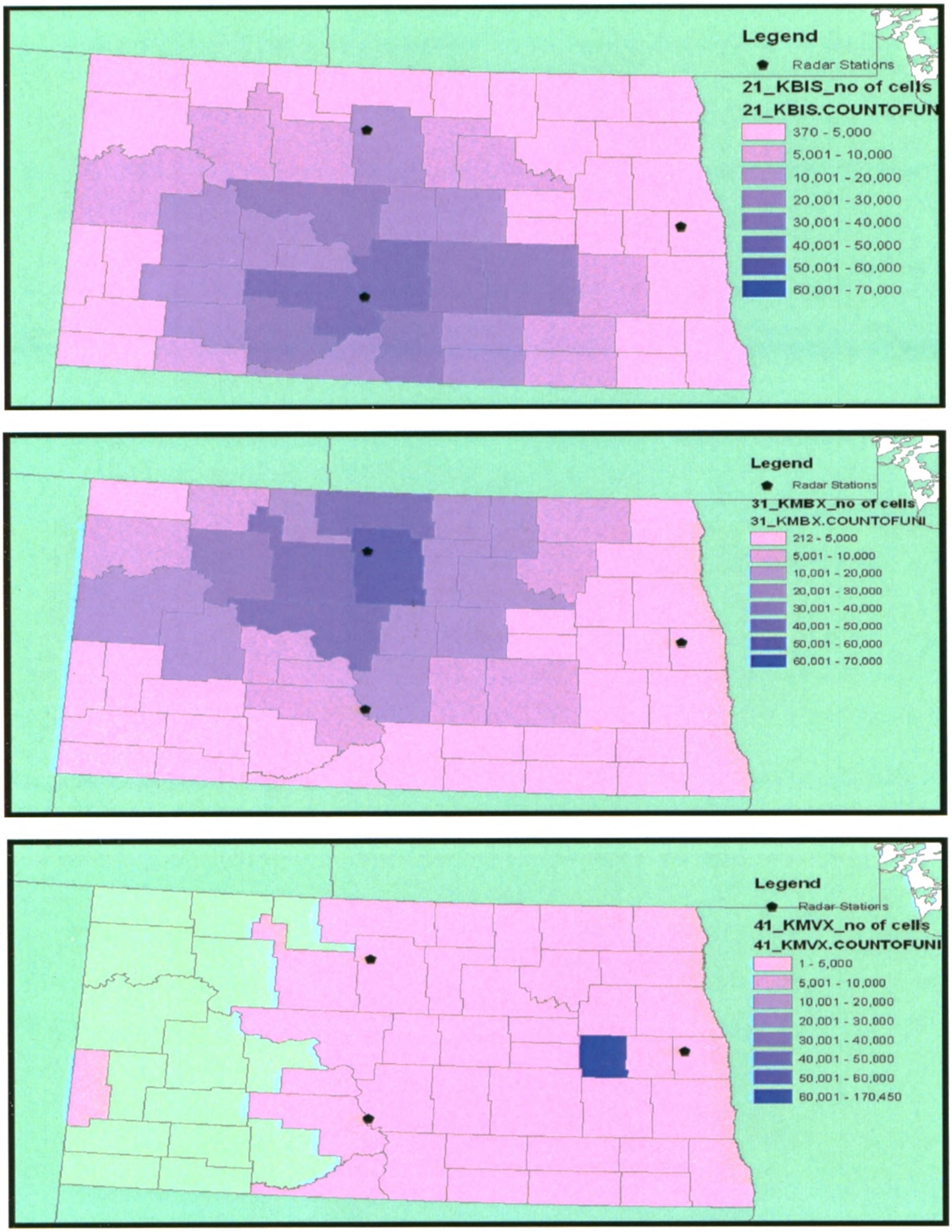
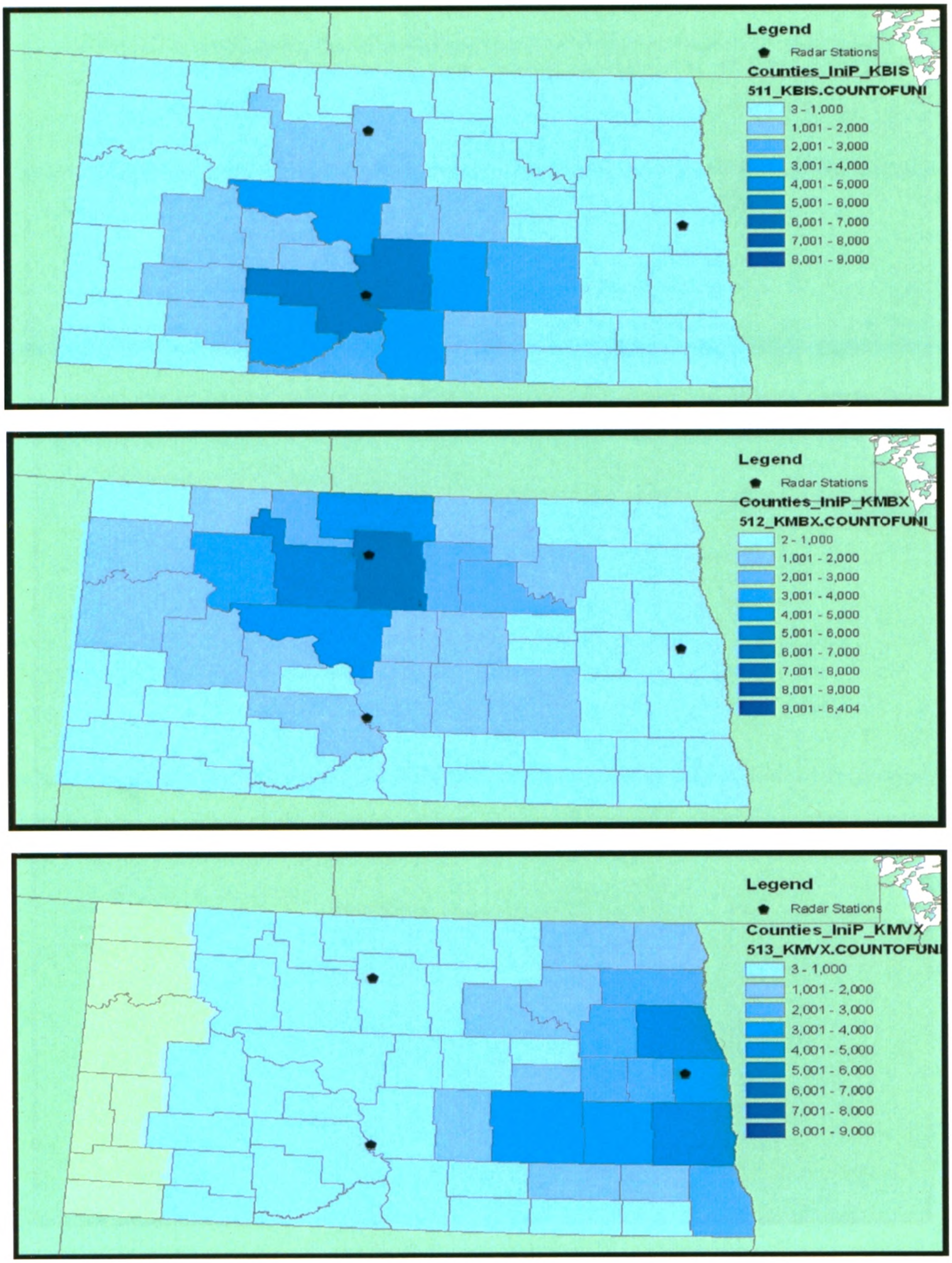


Figure 4.8: Spatial distribution for number of thunderstorm cells in North Dakota for 2002-2006 for radar stations: (a) KBIS, (b) KMBX and (c) KMVX. Here, the number of thunderstorm cells per county per five year time period is shown.

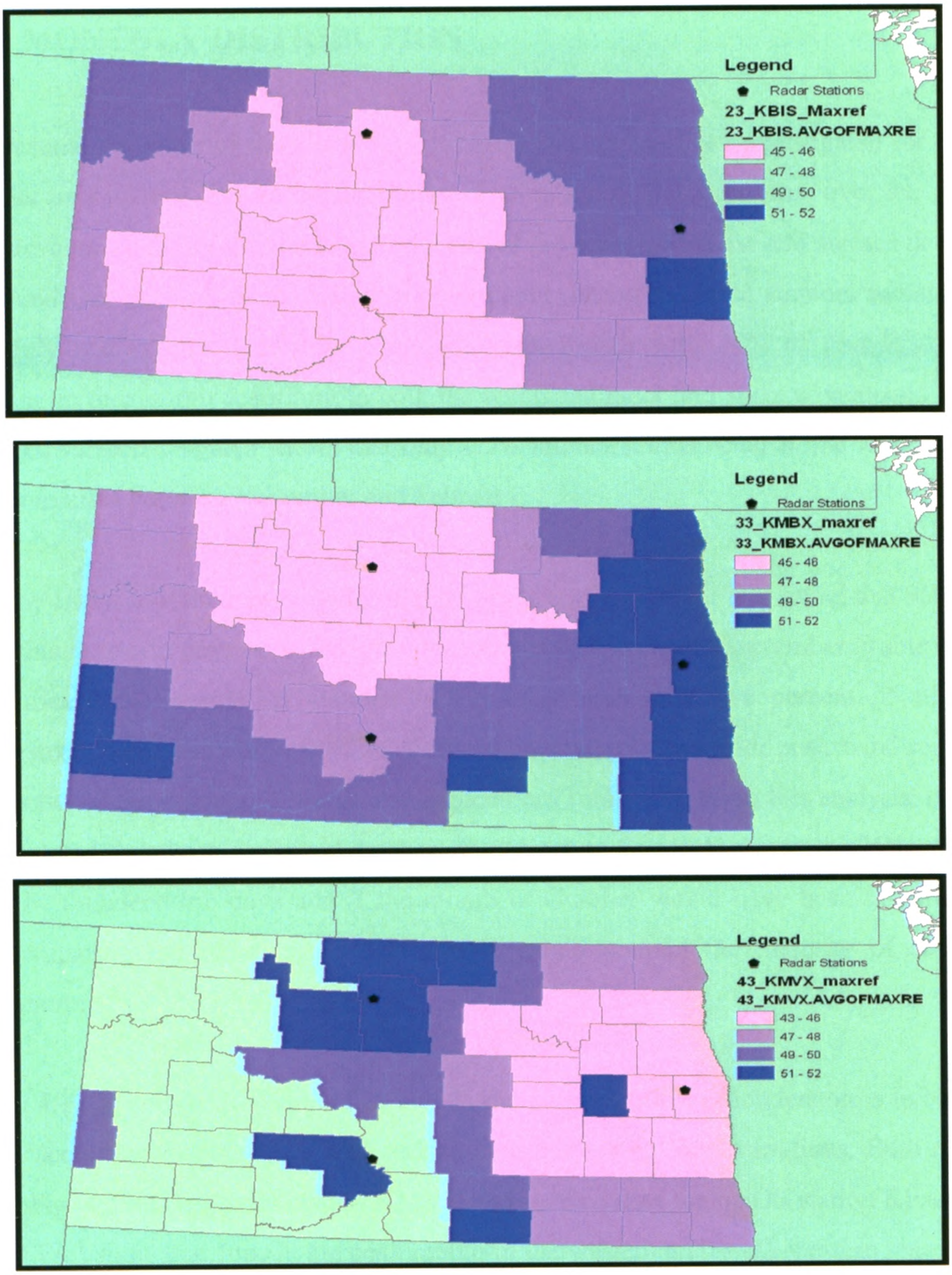


(a)

(b)

(c)

Figure 4.9: Spatial distribution for the initiation points of thunderstorm tracks in North Dakota for 2002-2006 for radars: (a) KBIS, (b) KMBX and (c) KMVX. Here, the number of thunderstorm tracks per county per year is shown.



(a)

(b)

(c)

Figure 4.10: Spatial distribution for average maximum reflectivity (in dBZ scale) of the thunderstorms in counties in North Dakota for 2002-2006 for radars: (a) KBIS, (b) KMBX and (c) KMVX.

4.5 MONTHLY DISTRIBUTION

The seasonal variation of thunderstorms in North Dakota has been investigated for both the radar and surface data to document the distribution of thunderstorms over the year. From the analysis of all the thunderstorm cells of the combined radar and surface data, it was found that 74% of all the thunderstorms occur during the three summer months of June, July and August with July being the peak month with 26% of thunderstorms occurring in this month according to both the combined radar and surface databases. The combined surface data also shows that only 1.5% thunderstorms occur in the winter over the four months between November and February.

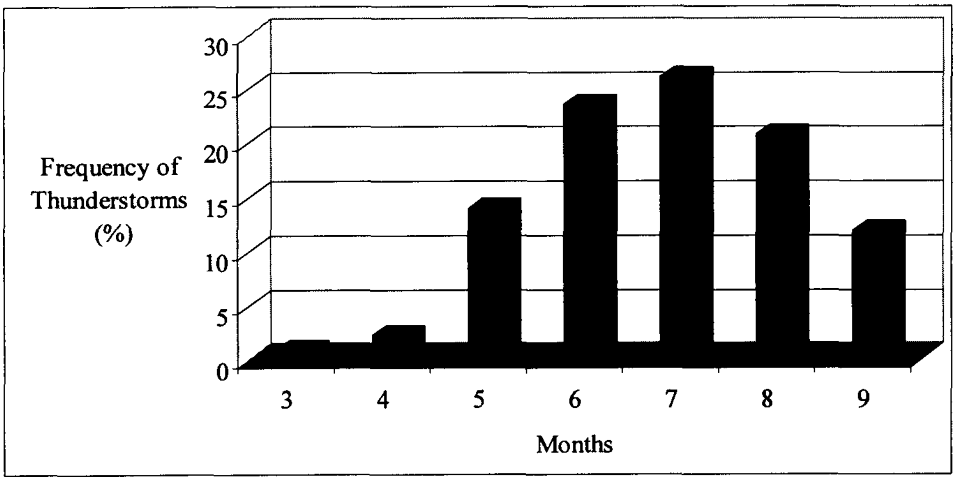
From the analysis of the monthly distribution of the surface data, it was found that 95% of all the thunderstorm days occur between the months of March and September (Table 4.3), which means the months of October to February have only five percent of all the thunderstorm days. Similarly, 96% of all the thunderstorm days with peak wind reports occur between the months of March and September (Table 4.3). From this analysis, it can also be stated that the radar based database for March to September contains 95% - 96% of all the thunderstorm days and if the month of October would have been considered while preparing the radar based database, it would contain the majority of all the thunderstorms.

Figures 4.11(a) and 4.11(b) show that July is the peak month for thunderstorms in North Dakota according to both radar and surface data with some local variations. Both radar data in Fig. 4.12(c) for radar station KMVX and surface data for ASOS station KFAR in Fig. 4.13 (c) show that June is the peak month in the western and south-western region of the state. From the surface data in Fig. 4.13, it was also found that the peak is distributed among the three summer months – June, July and August in Minot (KMOT) while June has a slight peak in some locations like Dickinson (KDIK) and Fargo (KFAR) and July has peak in the rest of the state. Except for the western region of the state and some localized weathers like Minot and Dickinson, both radar and surface data shows that July is the peak month all over North Dakota.

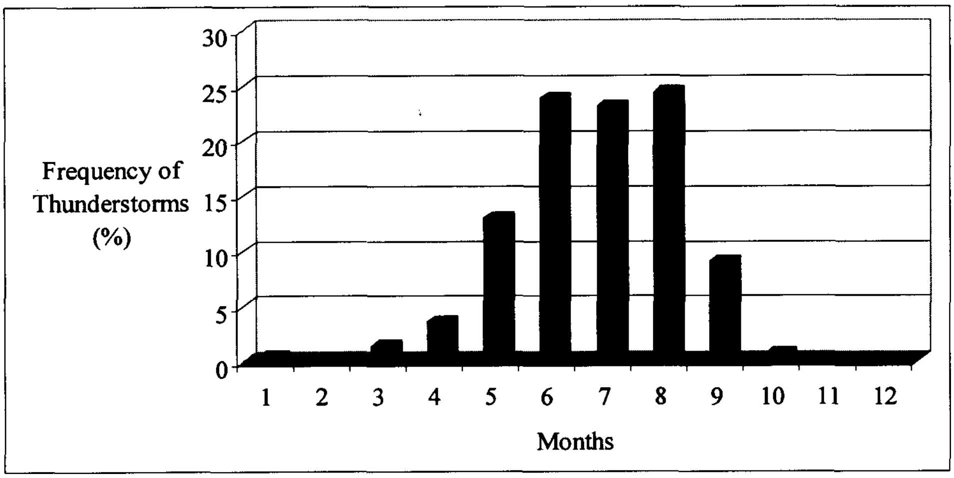
Figures 4.11(a) and 4.12 show that the combined and the three individual radar databases show a normal distribution for the monthly distribution of thunderstorms with a gradual decline in the frequency of thunderstorms from the peak months of June, July and August to the months of May and September while Fig. 4.11(b) shows that the combined surface data shows a sharper decline in the frequency of thunderstorms in the months of May and September compared to the radar data. Location-wise, Fig. 4.13 shows that some of the surface stations exhibit a gradual decrease in frequency for places like Grand Forks (KGFK) and Jamestown (KJMS), while in some regions there is a sharp drop in the frequency of thunderstorms beyond the peak period of June, July and August. From Fig. 4.13, it can be seen that in the Williston (KISN), Minot (KMOT) and Hettinger (KHEI) region, 84%, 79% and 77% of all the thunderstorms occur in these three months and there is a sharp drop in number of thunderstorms in May and September. In some areas like Fargo (KFAR), September sees a considerable number of thunderstorms, 15% of all the thunderstorms occur in September in this location.

The analysis of the surface data also indicates that in some regions of North Dakota like Jamestown (KJMS), Hettinger (KHEI) and Dickinson (KDIK), there was no thunderstorm activity at all during the five year period (2002-2006) during the winter four months between November and February, while in some eastern regions in North Dakota like in Grand Forks (KGFK), as high as 8% of all the thunderstorms occur in the four winter months of November to February. The storm frequency in winter months is also considerable in Fargo (KFAR), Minot (KMOT) and Bismarck (KBIS) with 3%, 2% and 2% of storms occurring over the four winter months in these locations.

From the monthly analysis of thunderstorms in North Dakota, it was found that radar and surface data show exactly the same results and that result is in good match with the previous researchers' results.

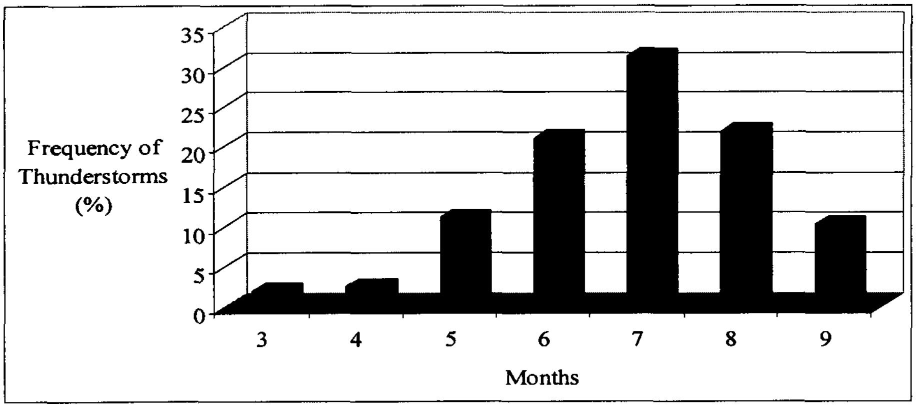


(a)

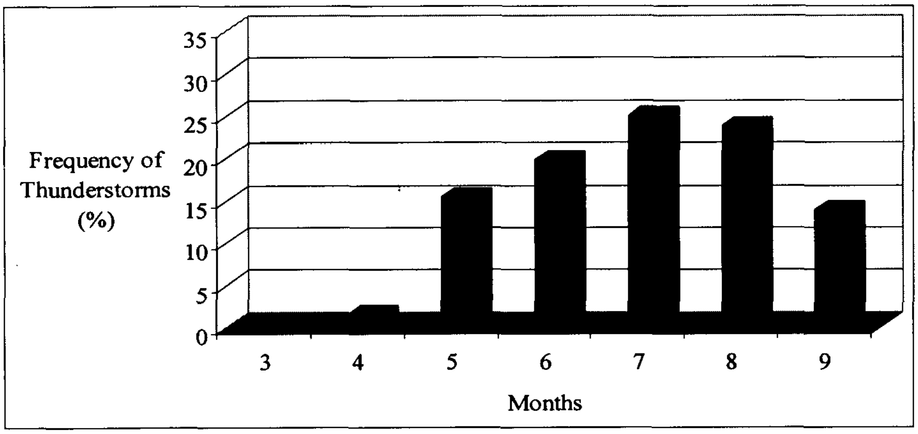


(b)

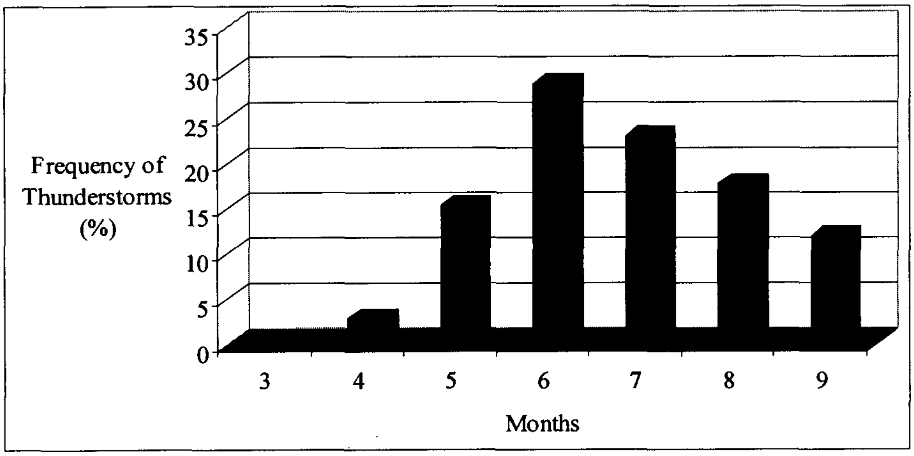
Figure 4.11: Monthly distribution of thunderstorms for 2002-2006 for (a) combined radar data and (b) combined surface data.



(a)



(b)



(c)

Figure 4.12: Monthly distribution of thunderstorms for 2002-2006 for radars: (a) KBIS, (b) KMBX and (c) KMVX.

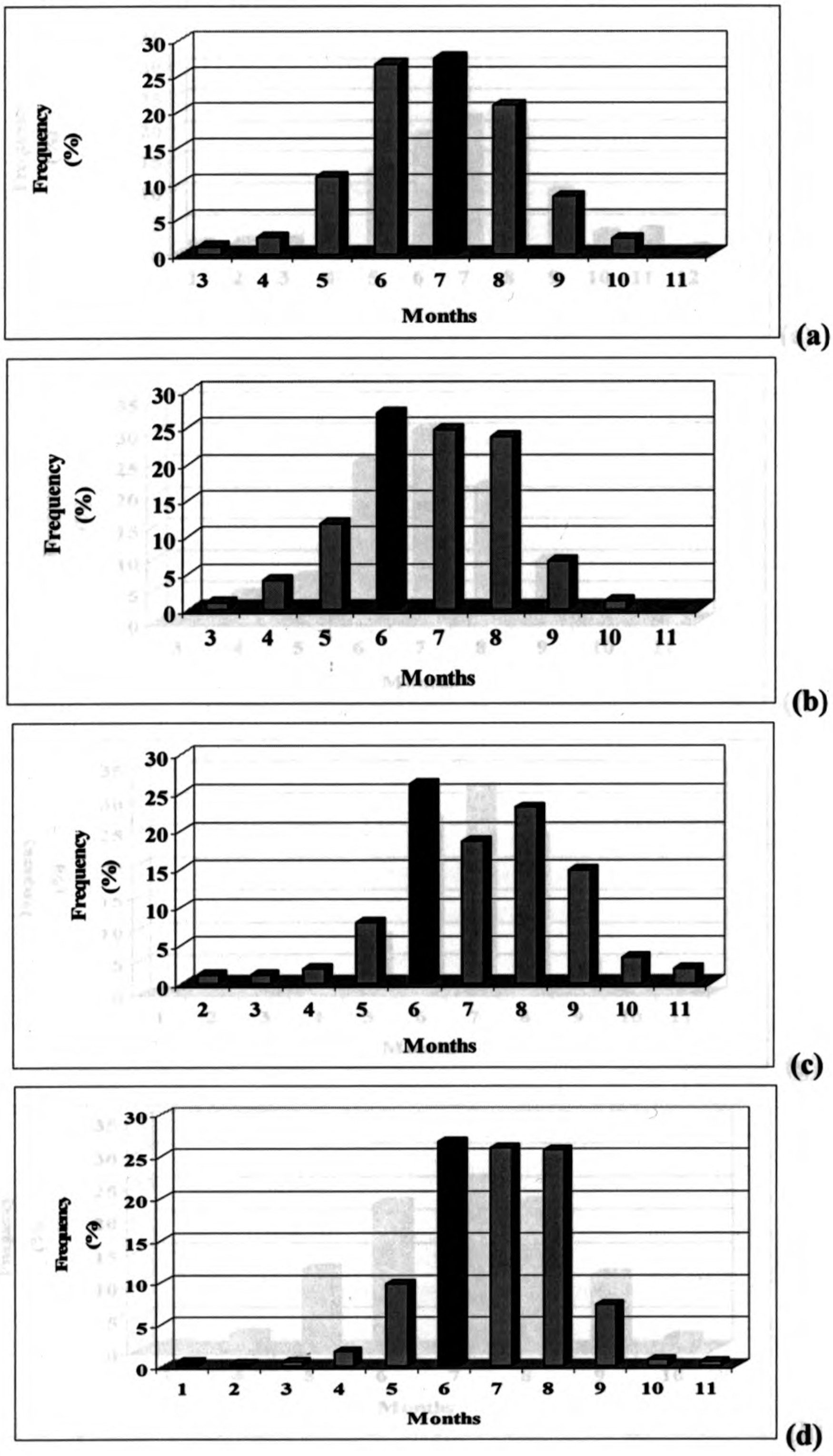


Figure 4.13: **Monthly distribution of thunderstorms for 2002-2006 for surface stations (a) KBIS, (b) KDIK, (c) KFAR and (d) KMOT.**

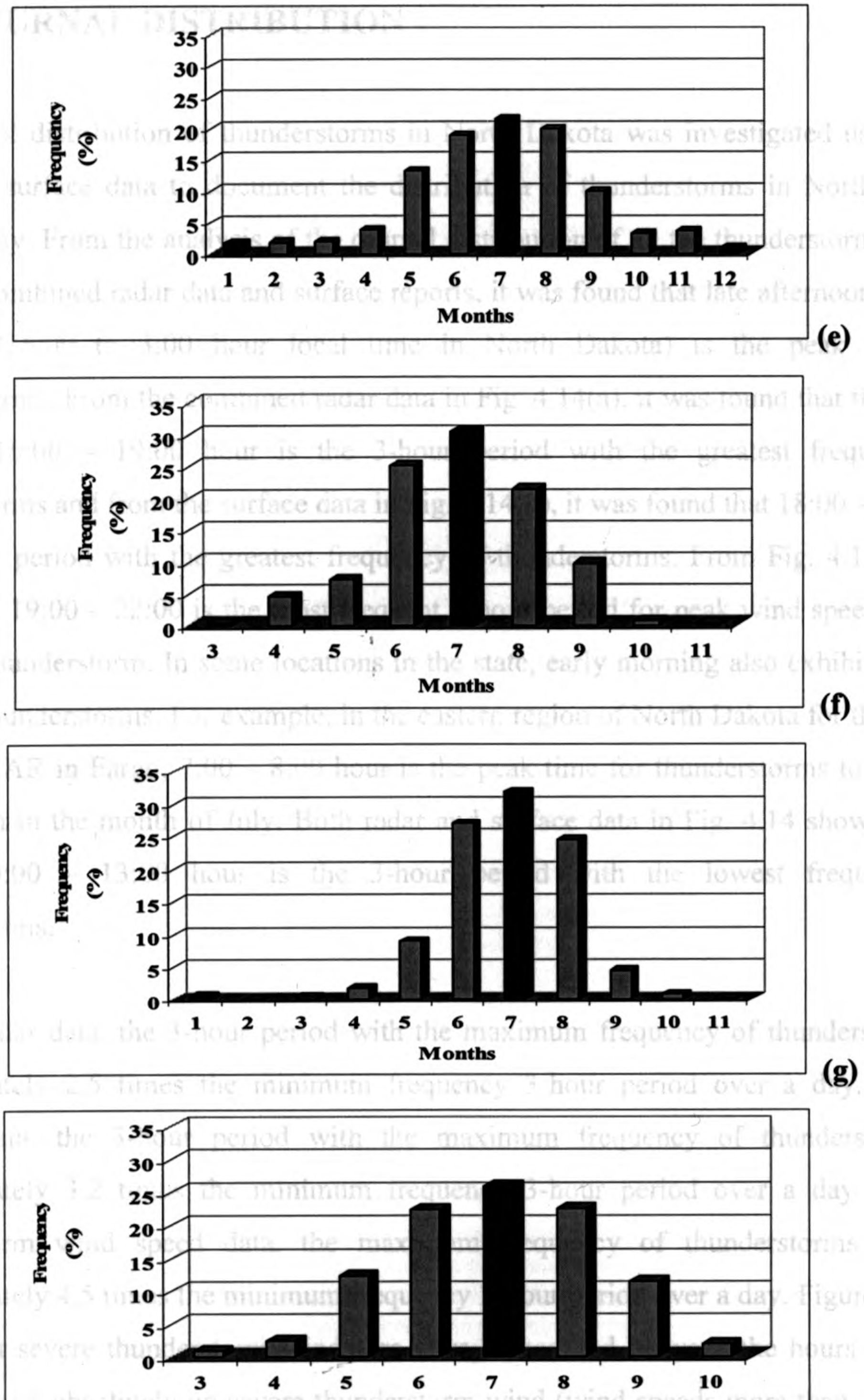


Figure 4.13: (Contd.) **Monthly distribution of thunderstorms for 2002-2006 for surface stations: (e) KGFK, (f) KHEI, (g) KISN and (h) KJMS.**

4.6 DIURNAL DISTRIBUTION

The diurnal distribution of thunderstorms in North Dakota was investigated using both radar and surface data to document the distribution of thunderstorms in North Dakota over the day. From the analysis of the diurnal distribution of all the thunderstorm cells of both the combined radar data and surface reports, it was found that late afternoon to early morning (16:00 to 3:00 hour local time in North Dakota) is the peak time for thunderstorms. From the combined radar data in Fig. 4.14(a), it was found that the period between 16:00 – 19:00 hour is the 3-hour period with the greatest frequency of thunderstorms and from the surface data in Fig. 4.14(b), it was found that 18:00 – 21:00 is the 3-hour period with the greatest frequency of thunderstorms. From Fig. 4.14(c) it is found that 19:00 – 22:00 is the most frequent 3-hour period for peak wind speed reports due to a thunderstorm. In some locations in the state, early morning also exhibits a peak time for thunderstorms. For example, in the eastern region of North Dakota for the ASOS station KFAR in Fargo, 7:00 – 8:00 hour is the peak time for thunderstorms to occur in that region in the month of July. Both radar and surface data in Fig. 4.14 show that the period 10:00 – 13:00 hour is the 3-hour period with the lowest frequency of thunderstorms.

For the radar data, the 3-hour period with the maximum frequency of thunderstorms is approximately 2.5 times the minimum frequency 3-hour period over a day. For the surface data, the 3-hour period with the maximum frequency of thunderstorms is approximately 3.2 times the minimum frequency 3-hour period over a day. For the thunderstorm wind speed data, the maximum frequency of thunderstorms exhibits approximately 4.5 times the minimum frequency 3-hour period over a day. Figure 4.14(d) shows that severe thunderstorm winds are always recorded between the hours of 19:00 and 4:00 with absolutely no severe thunderstorm wind (wind speeds more than 50 knots) reports between 6:00 and 15:00 during the daytime within the five year period between 2002 and 2006. These indicate that both radar and surface data shows the same diurnal variations for the thunderstorms. These results also show that the difference between the maximum and minimum frequency is higher in the surface data, especially for the surface

wind reports than the radar data. Figures 4.15(a) and 4.15(b) show that the combined radar data is well correlated with both the combined surface data and the surface data with all peak wind reports, since both of them represent straight lines in these figures. On the other hand, Fig. 4.15(c) shows that combined radar data do not relate with the severe thunderstorms with wind reports of more than 93 km/hr. Figure 4.16 shows that all the three radars exhibit similar diurnal variations which suggest that all over North Dakota, the diurnal variations are similar. Figure 4.17 shows the diurnal variation of thunderstorms for different months over the year for the different radars and thus for different regions of the state. From Fig. 4.17(a), it was found that early morning (4:00 – 9:00) is the most frequent time for thunderstorms in March. March is also the only month when the three radars exhibit different diurnal variation patterns although they all show the basic pattern of exhibiting the peak time in the early morning. Since there is only few number of thunderstorm cells present in March, data for higher number of years would give more confidence in the results for March. From Fig. 4.17(b) and 4.17(c), it was seen that during the months of April and May, there is very little variation with the time of the day and there is no definite peak time for thunderstorms over the day. With advancement in months, the peak time for thunderstorms moves towards the late afternoon to early evening. Table 4.6 shows the most frequent 3-hour time period for thunderstorms to start over the day in different months of the year.

Table 4.6: Most frequent diurnal time for thunderstorms in North Dakota for 2002-2006 in radar data

Month	Most frequent 3-hour time for thunderstorms to start
March	7:00 –10:00
April	23:00 – 2:00
May	16:00 – 19:00
June	17:00 – 20:00
July	1:00 – 4:00
August	0:00 – 3:00
September	18:00 – 21:00

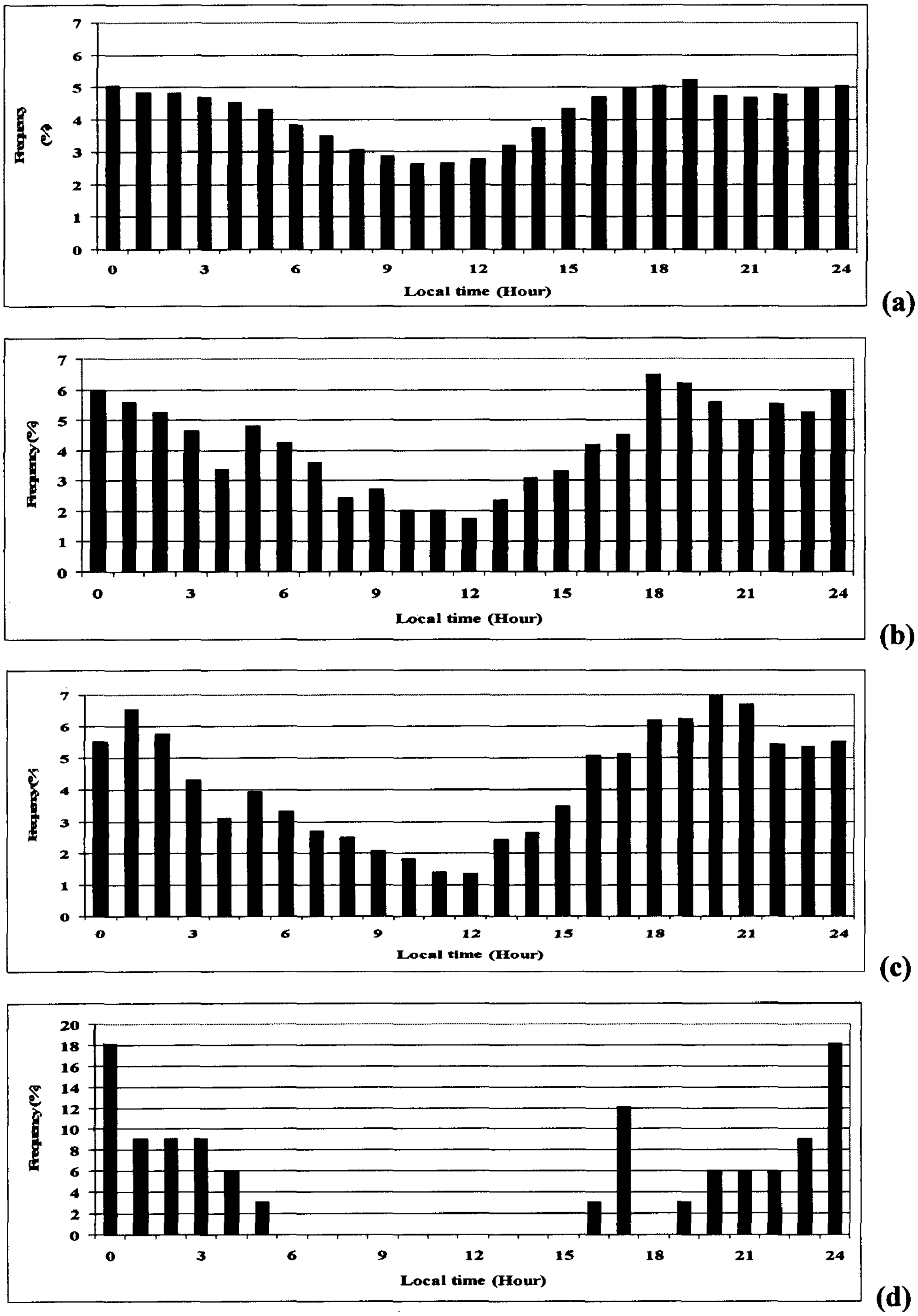


Figure 4.14: Diurnal distribution of thunderstorms for 2002-2006 for (a) combined radar data, (b) combined surface data, (c) combined surface data having peak wind reports and (d) severe storms (wind speed more than 93 km/hr)

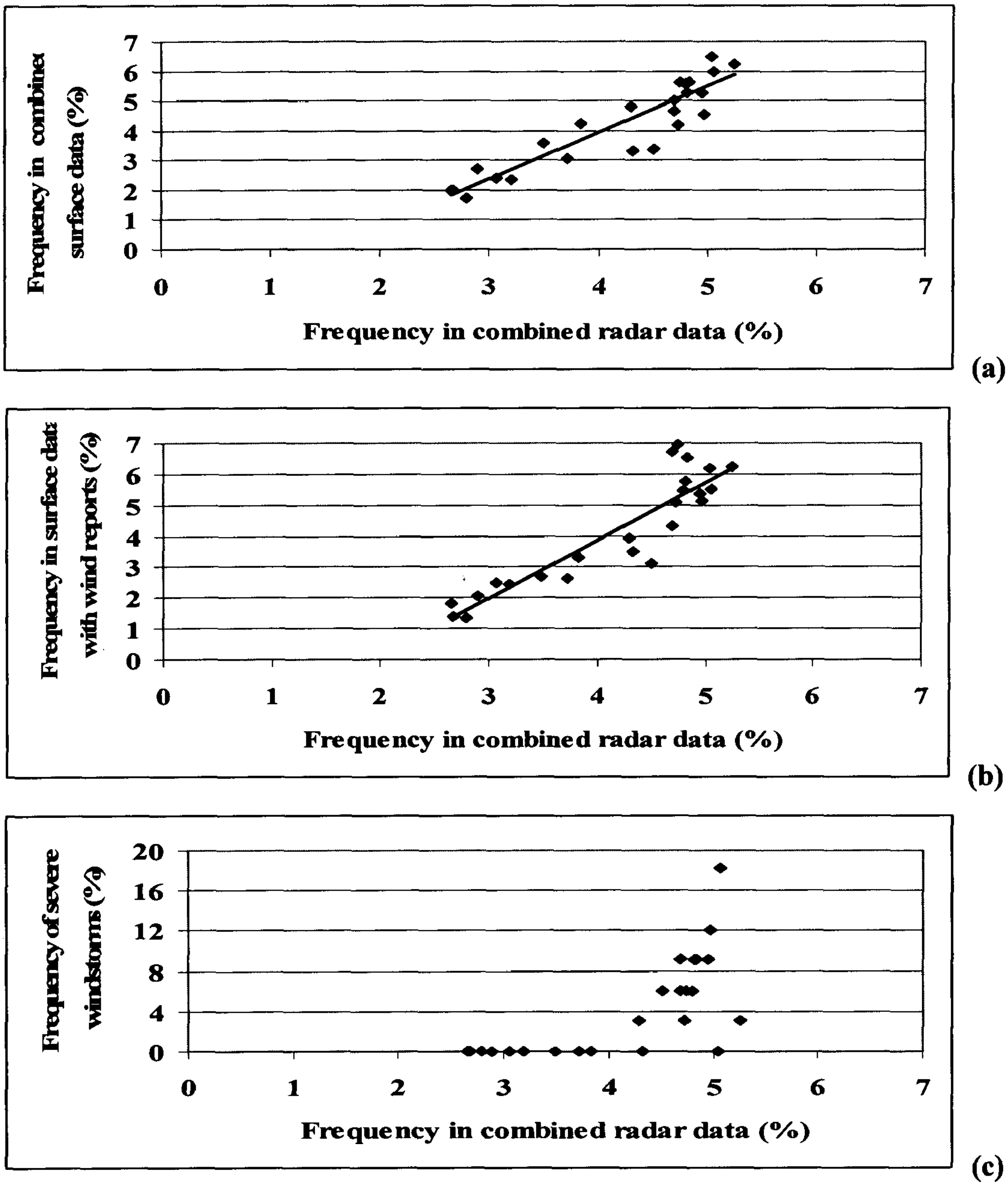


Figure 4.15: **Relationship of diurnal frequency of combined radar with (a) combined surface data, (b) surface data with peak wind reports (wind speed of more than 46 km/hour) and (c) surface data for severe wind storms (wind speed of more than 93 km/hour).**

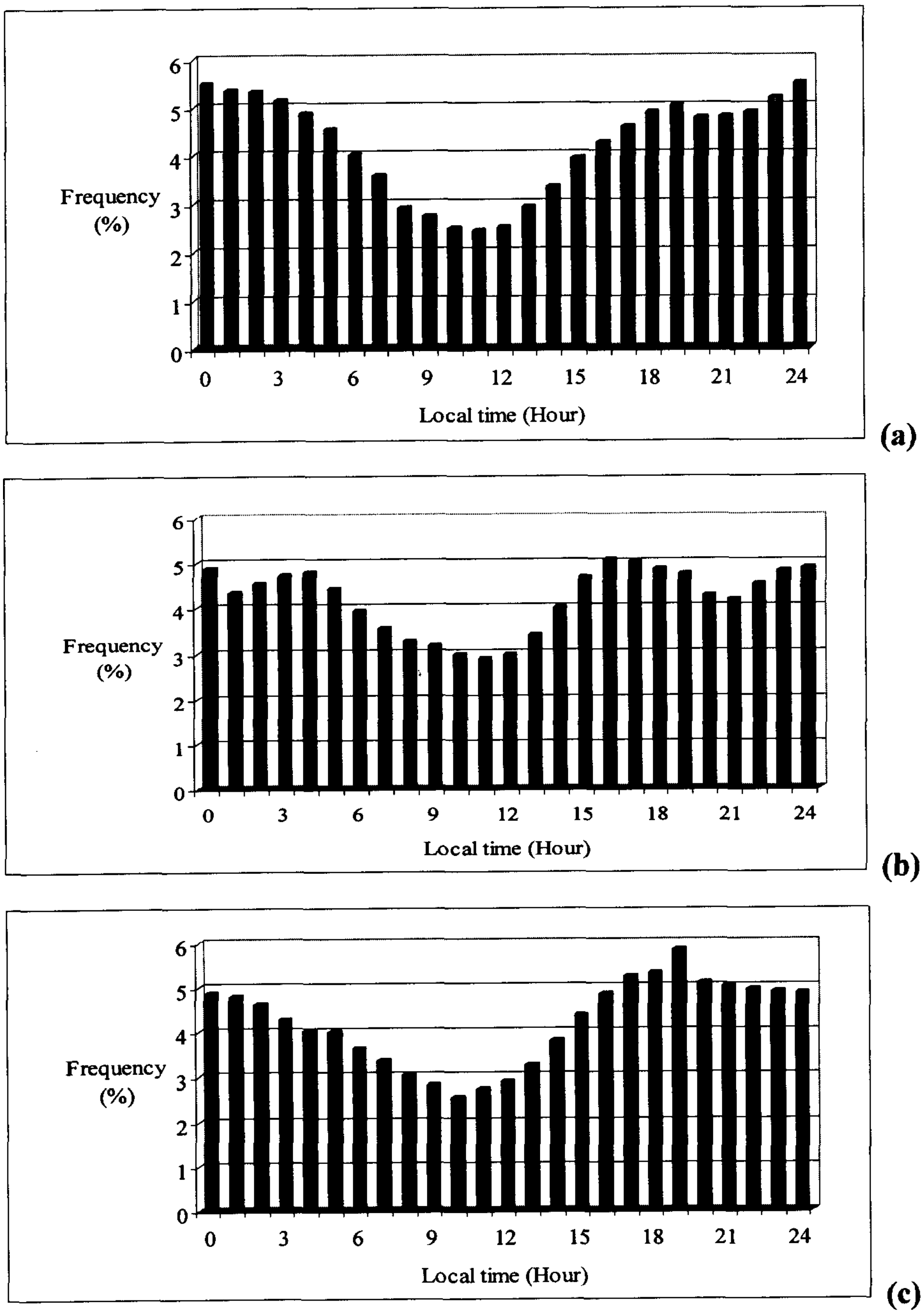


Figure 4.16: Diurnal distribution of thunderstorms for 2002-2006 for radars: (a) KBIS, (b) KMBX and (c) KMVX.

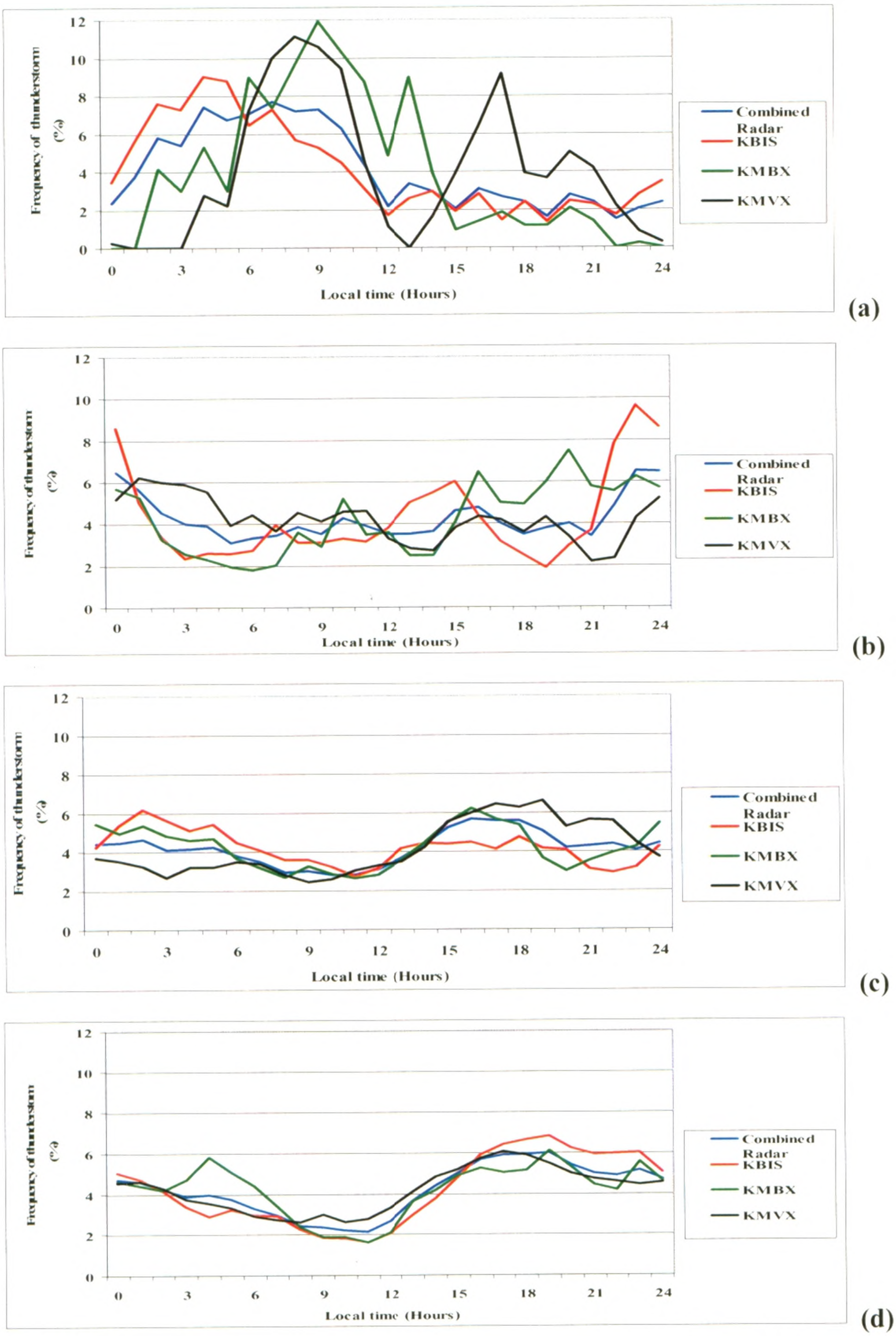
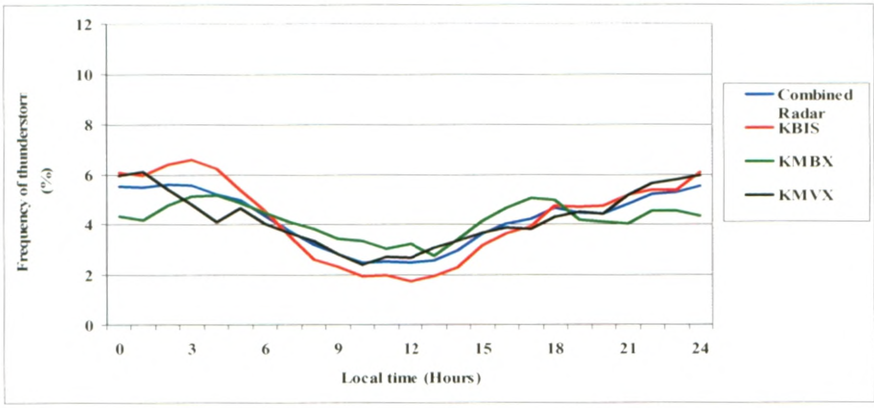
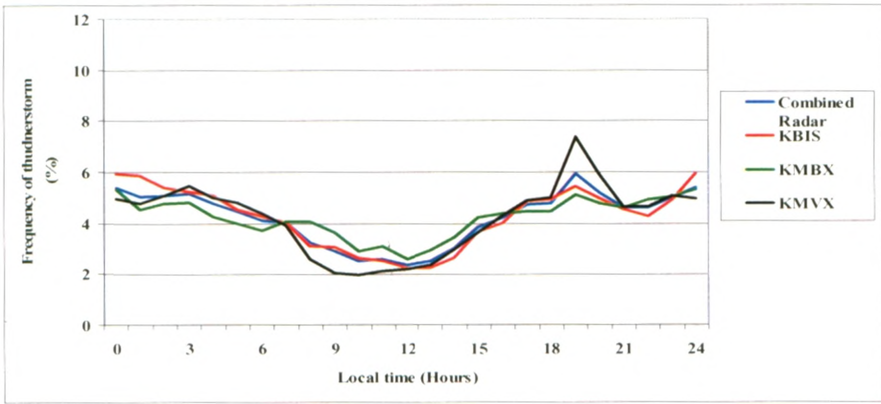


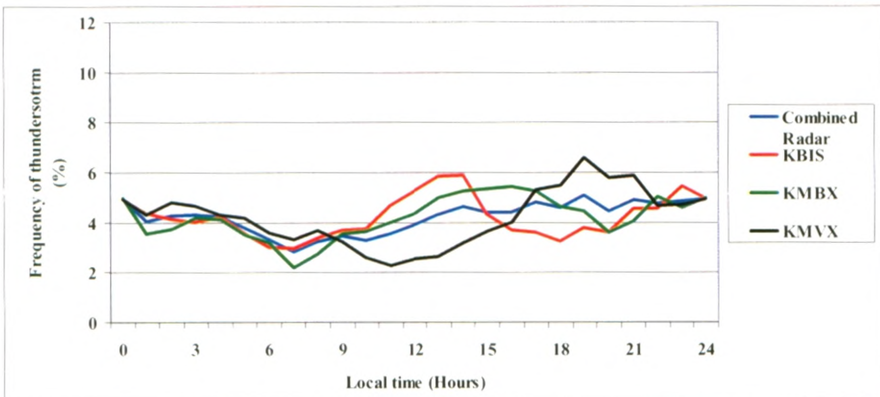
Figure 4.17: Diurnal distribution of thunderstorms for 2002-2006 for different radars for different months: (a) March, (b) April (c) May and (d) June.



(e)



(f)



(g)

Figure 4.17: (Contd.) **Diurnal distribution of thunderstorms for 2002-2006 for different radars for different months: (e) July, (f) August and (g) September.**

4.7 LIFE TIME, DISTANCE TRAVELLED AND SPEED OF THE THUNDERSTORM CELLS

The lifetimes of the individual thunderstorm cells in North Dakota for the period 2002-2006 were investigated to find out the average duration of thunderstorms all over the state and also for different months of the year and for different times of the day. From the analysis of all thunderstorm cells between 2002 and 2006 all over North Dakota, the average duration of thunderstorm cells was found to be 23.6 minutes. Again, according to the definition of thunderstorms by NCDC, the start time of a thunderstorm is recorded as soon as thunder is heard or lightning is seen and the end time is recorded as the time after 15 minutes of the last thunder or lightning. With this definition, the minimum possible duration of a thunderstorm cell is 15 minutes. So considering 15 minutes as the minimum duration, the average duration of thunderstorms all over the state was found as 41.3 minutes. Again, for all thunderstorms with duration more than 30 minutes, the average is 59.8 minutes.

Figure 4.18 (a) shows that the monthly distribution patterns of the average durations of thunderstorm cells are similar for all the three radar stations and thus all over the state. But for longer duration thunderstorms (thunderstorms with > 15 minutes, > 30 minutes and > 60 minutes), it was found that in the middle and southern region of North Dakota, the average duration are significantly higher than the northern and western regions. Among the thunderstorm cells with more than 30 minutes duration, Fig. 4.18(b) shows that the storms covered by radar at Bismarck, KBIS (middle, southern and western region of the state) have an average duration of 86.2 minutes comparing to 60.3 minutes and 59.4 minutes for the thunderstorm cells covered by radars at Minot, KMBX (northern region of the state) and at Grand Forks, KMVX (western region of the state) respectively. The duration of thunderstorm cells obtained in this research, 23.6 minutes fall in the limit for duration of thunderstorm cell given by Ackerman and Knox (2006), 20-30 minutes. The durations of thunderstorms obtained in this research are for individual thunderstorm cell, not for big thunderstorm events, that's why this duration does not match with the duration of thunderstorm events given by Changnon (1988a) and Klimowski et al. (2003).

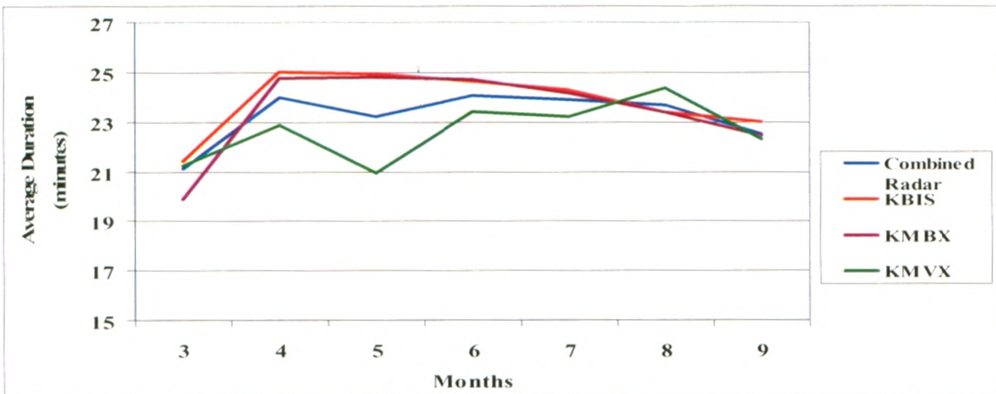
The average life-times of the thunderstorm cells are shorter in duration in the months of March (21.1 minutes) and September (22.5 minutes) than the summer months of April (24.0 minutes), May (23.2 minutes), June (24.0 minutes), July (24.0 minutes) and August (23.7 minutes). Although the average duration of thunderstorms is less than half an hour, there was storm cell that lasted as long as 514.8 minutes (8 hours 35 minutes). Figures 4.18 and 4.19 show that the average duration of thunderstorms are very near to each other between the months April and August. Figure 4.18 also shows that in the western region (radar KMVX region), August sees thunderstorms with higher average duration and May sees storms with less duration in this region. Again, the longest duration thunderstorms detected by radar KBIS and KMVX were also in August. The longest duration in the northern region (radar KMBX region) was in July. Figure 4.19 also shows that the storms starting between the late afternoon and early morning usually have more durations than storms originating in other times of the day.

It was found that 24% and 8% of all the thunderstorms have durations of more than 30 minutes and more than 60 minutes respectively. It was also found that only 0.3% of all the thunderstorm cells have duration of more than 180 minutes (3 hours) comparing to Changnon's (1988a) result of 6% of all the thunderstorm events having more than 180 minutes of duration. The huge amount of data used in this research (2.2 million data points) has led to this difference in the percentage in results compared to that of Changnon.

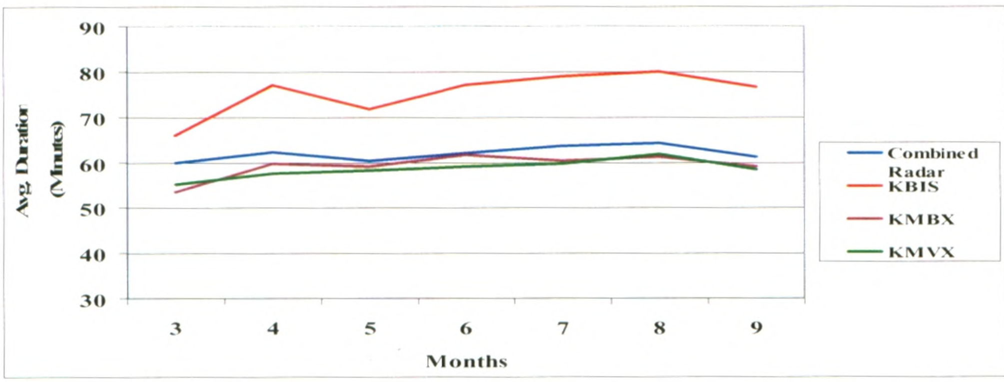
Of all the thunderstorms in North Dakota between 2002 and 2006, 10.2% are both more than 30 minutes in duration and more than 50 km in track-length. It was also found that the average maximum reflectivity and VIL values of the thunderstorm cells with more than 30 minute of duration and 50 km of track-length are 53.9 dBZ and 25.8 kg/m^2 respectively which are much larger than the overall average maximum reflectivity and VIL values of 47.7 dBZ and 13.2 kg/m^2. Those storm cells have an average forward speed of 64.9 km/hr that is also higher than the overall average (47.6 km/hr). Again for thunderstorm cells with more than 200 km of length and more than 30 minutes of duration, the average maximum reflectivity and VIL values are 61.5 dBZ and 45.6 kg/m^2

respectively which are much larger than both the overall average maximum reflectivity and VIL values and the values for the storm cells more than 50 km in length.

Again, from the analysis, it was also found that 86% of all the thunderstorms that have maximum reflectivity value between 30 and 50 dBZ have duration less than 30 minutes compared to MacKeen et al.'s (1999) provided value of 82% (as discussed in section 2.8.5) and 44% of all the thunderstorms that have maximum reflectivity greater than 55 dBZ have duration of less than 30 minutes compared to that of MacKeen et al.'s (1999) given value of 44%. Thus it can be stated that there is a relationship between storm duration and storm intensity and the longer lasting storms usually are more intense storms.



(a)



(b)

Figure 4.18: Average duration of thunderstorm cells for (a) all cells and (b) cells with more than 30 minute lifetime.

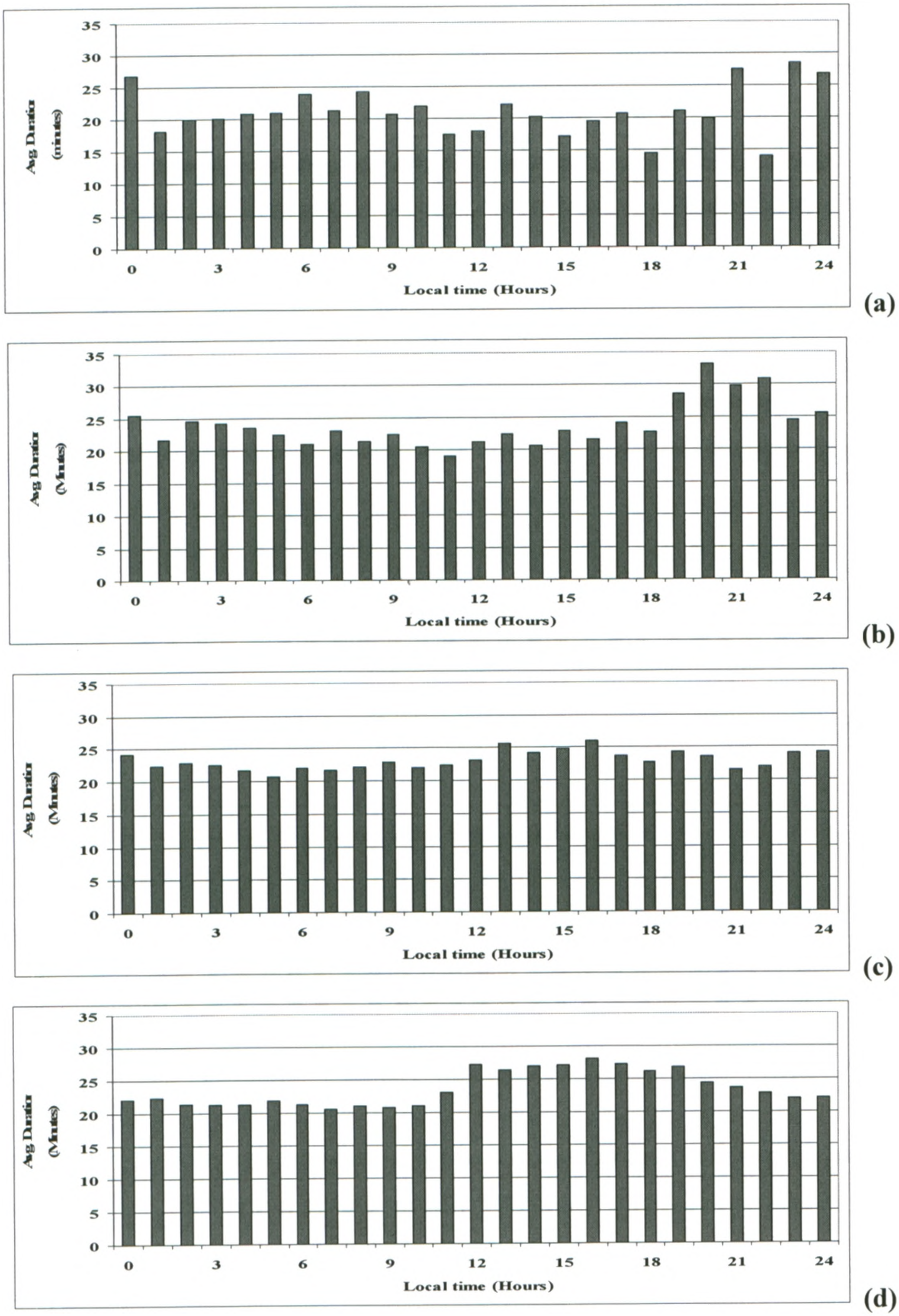
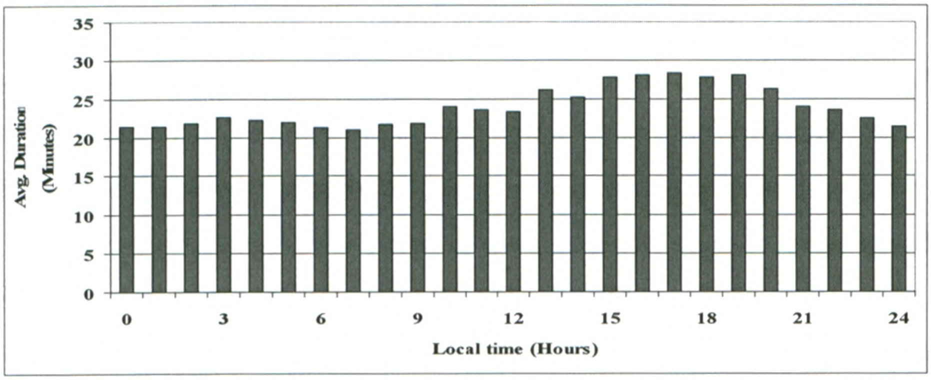
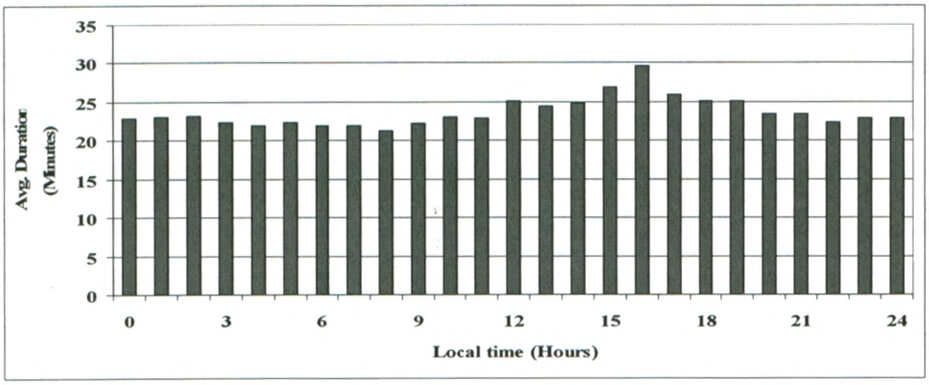


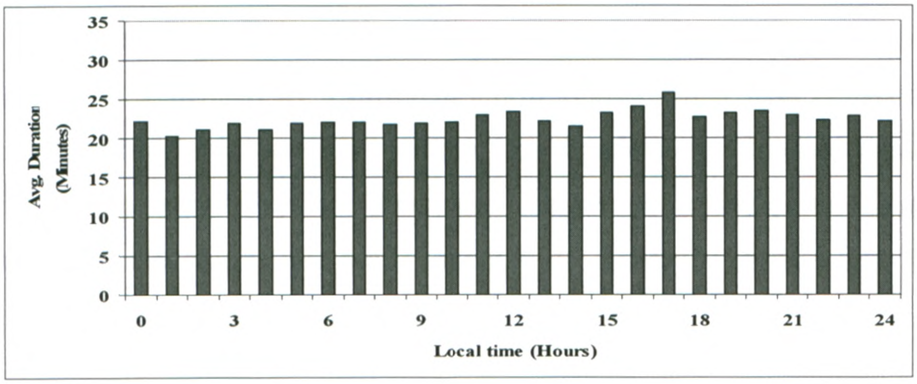
Figure 4.19: Average duration of thunderstorms in the combined radar for different months: (a) March, (b) April, (c) May and (d) June.



(e)



(f)



(g)

Figure 4.19: (contd.) **Average duration of thunderstorms in the combined radar for different months: (e) July, (f) August and (g) September.**

The overall average for the track-length of all thunderstorm cells in North Dakota is 21.8 km. The average track-length of storms are 24.7 km, 20.7 km, 21.0 km, 20.6 km, 23.3 km, 21.2 km and 23.2 km for the months of March, April, May, June, July, August and September respectively. Figure 4.20 also shows that the average track-lengths of thunderstorm cells are comparatively longer in March and September than the summer months between April and August. Again, the overall average forward speed of all the thunderstorm cells in North Dakota is 59.0 km/hr. Figure 4.21 shows that during the month of March, the forward speed of thunderstorm cells has a wide flat peak. But the forward speed has a definite peak during the months between April and August. In the month of September, the speed shows a comparatively wider peak. Again, March is also the only month when different radars show different speed patterns. In all other months except March, all the radars exhibit a very similar forward speed pattern. The average forward speeds for storms are 73.4 km/hr, 55.8 km/hr, 59.4 km/hr, 55.4 km/hr, 61.2 km/hr, 56.5 km/hr and 64.4 km/hr for the months of March, April, May, June, July, August and September respectively. This indicates that the average speed is higher in March and it again rises in September. Thus a different storm forward speed and track-length pattern in March and September (months towards the winter) indicate that the thunderstorms in these months are generated by a different storm system rather than convection (which cause thunderstorms in the summer months). The thunderstorms in these months may be originating from a synoptic system, due to the presence of a cold front in the atmosphere. It can be noted that during the winter months of January, February and March, this synoptic system has led to a higher wind speeds in these months.

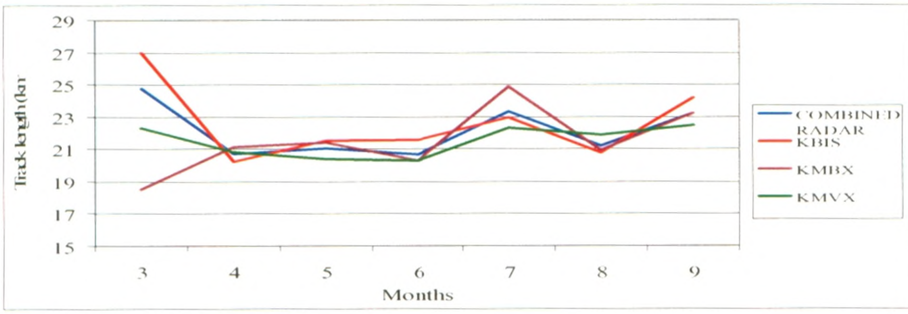
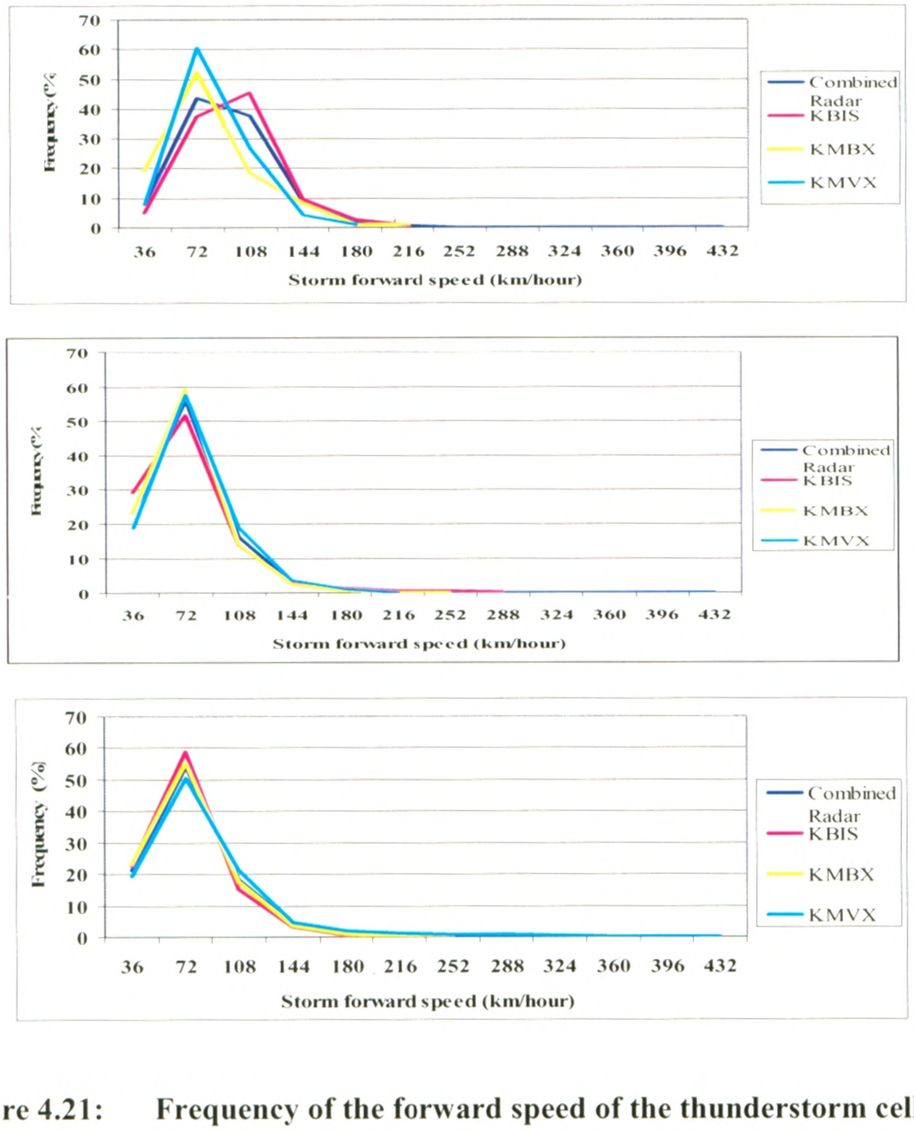


Figure 4.20: Average distances travelled by the thunderstorm cells.

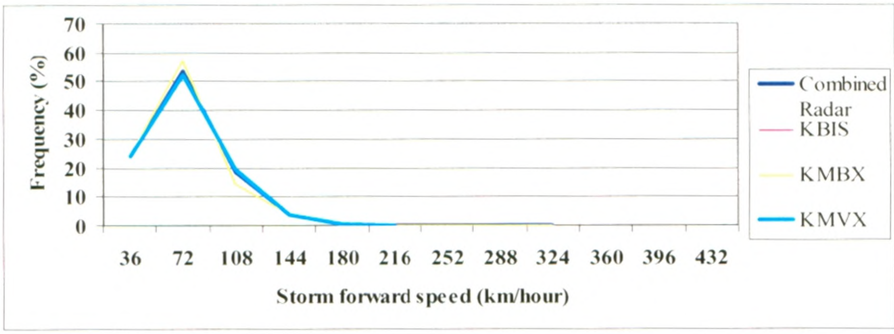


(a)

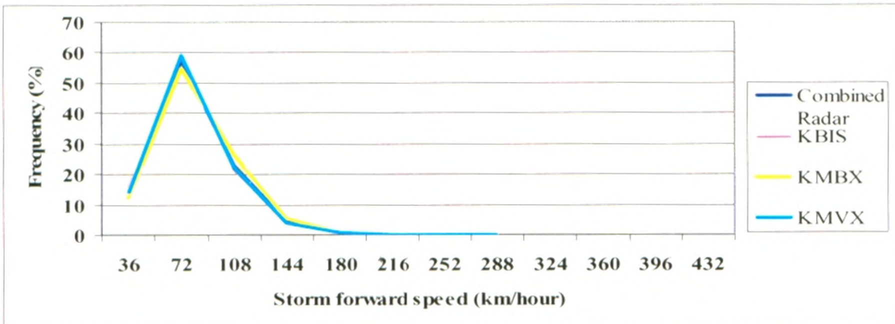
(b)`

(c)

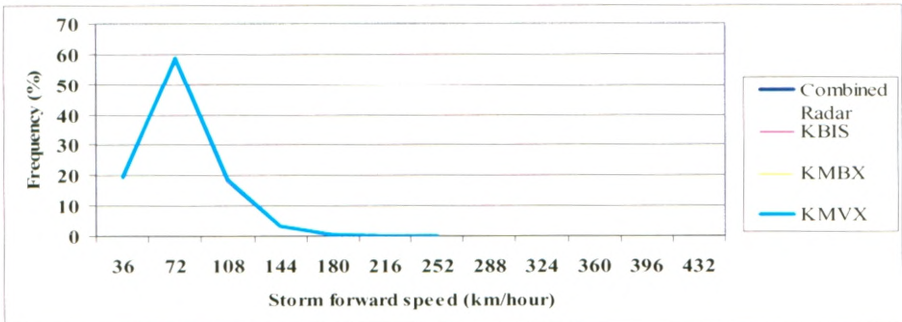
Figure 4.21: Frequency of the forward speed of the thunderstorm cells for different radars for 2002-2006 for different months: (a) March, (b) April and (c) May



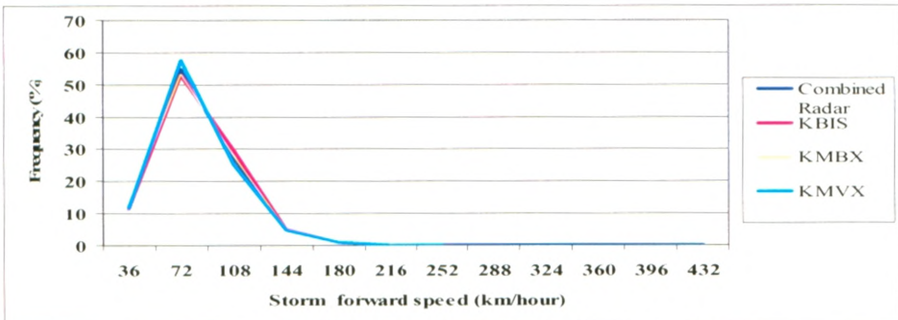
(d)



(e)



(f)



(g)

Figure 4.21: (Contd.) **Frequency of the forward speed of the thunderstorm cells for different radars for 2002-2006 for different months: (d) June, (e) July, (f) August and (g) September.**

4.8 HEADING OF THUNDERSTORM TRACKS

Figure 4.22 shows that the average heading of the thunderstorm tracks' movements are towards the west and north-west during the month of March. With time, the average heading moves towards the north and north-east in April and then becomes flat for the months of May and June and then again moves towards the north-east and east directions in July and August then again moves towards the north and north-west directions in September. Again, March is also the only month when different radars show different heading patterns in different regions of the state. Figure 4.23 also shows the heading of the thunderstorm tracks on the map of North Dakota for the months of March, May, July and September for radar station KBIS for the year 2005. Here it is also seen that the heading is towards the north-west in March, there is no definite direction in May, and the headings are towards the north-east and east in July and towards the north-east in September.

From the analysis of the heading of thunderstorm tracks with more than 30 minutes, it was also found that March is a different month when the headings do not match smoothly for different radars which indicates that the heading varies with location in March. This figure also shows that storms move towards the west and north-west in March, the heading becomes flat for the months of May and June and then the average heading is changed towards the north-east and eastern directions in July, towards the north-east in August and again towards the north and north-west in September. Since there is only few number of thunderstorm cells present in March, data for higher number of years would give more confidence in the results for March for the heading of thunderstorm cells in this month.

The overall average heading for all thunderstorms all over the year is towards the north-east direction which is a match with Klimowski et al.'s (2003) given heading for overall heading for severe thunderstorms in the state.

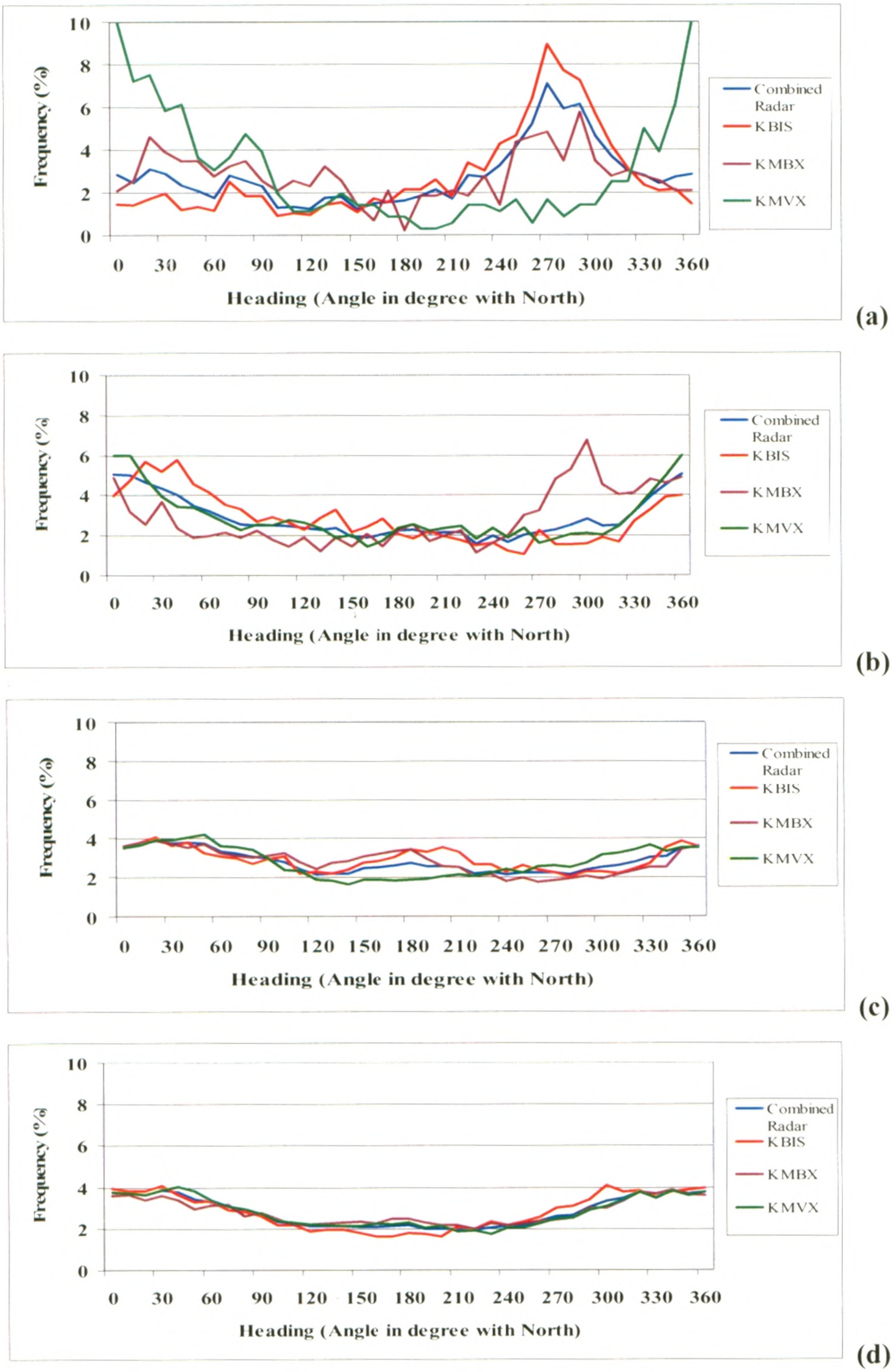
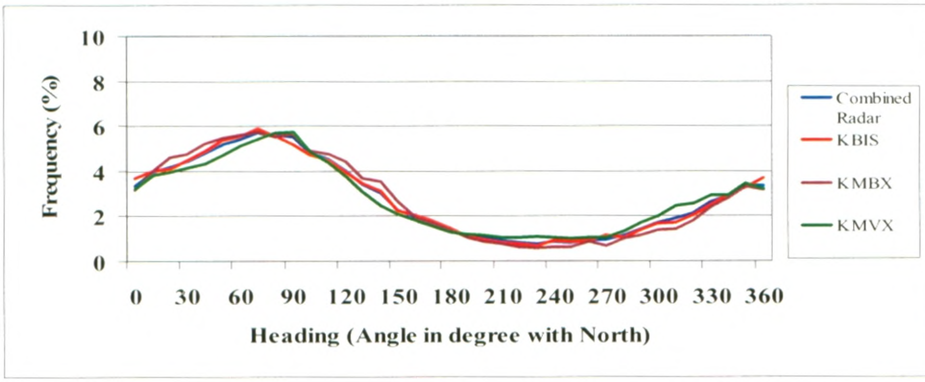
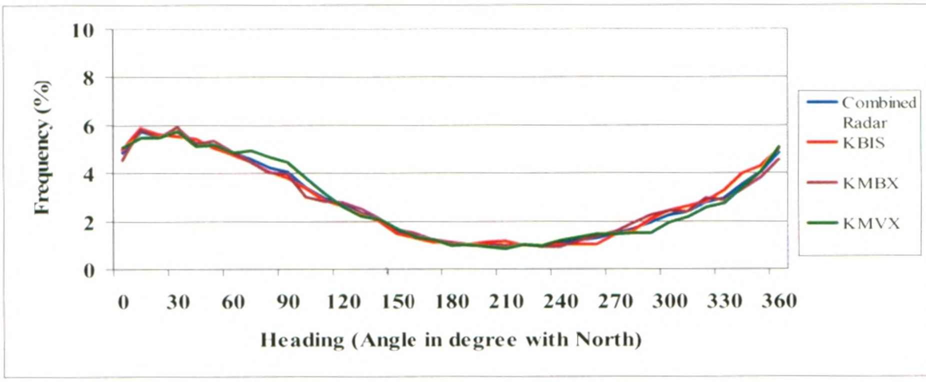


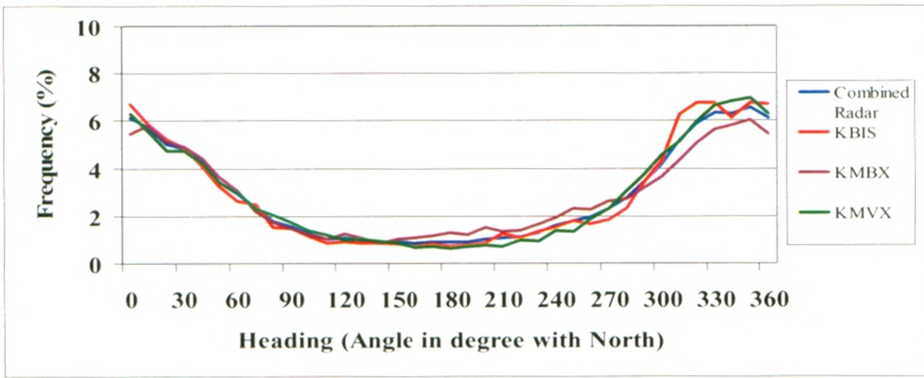
Figure 4.22: Heading of thunderstorm cells for different radars for 2002-2006 for different months: (a) March, (b) April, (c) May and (d) June.



(e)

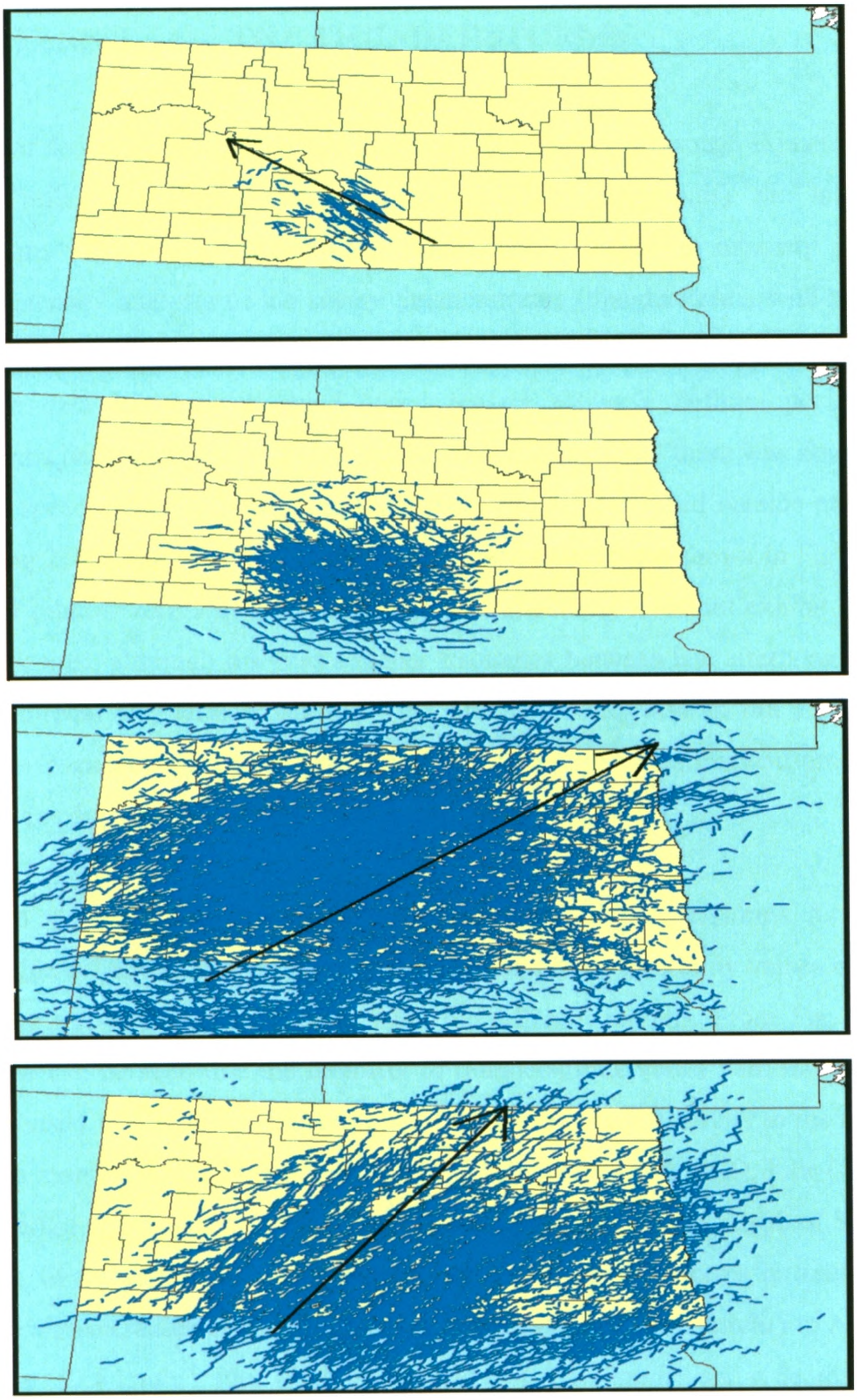


(f)



(g)

Figure 4.22: (Contd.) **Heading of thunderstorm cells for different radars for 2002-2006 for different months: (e) July, (f) August and (g) September.**



(a)

(b)

(c)

(d)

Figure 4.23: Snapshot of thunderstorms' headings for radar KBIS for 2005 for different months: (a) March (North-West), (b) May (no definite direction), (c) July (North-East) and (d) September (North-East).

4.9 INTENSITY OF THE THUNDERSTORMS

For the radar data, since VIL is related to maximum reflectivity through Equation 2.1, the maximum reflectivity is the only parameter available to identify the intensity of thunderstorms while in the surface data, wind speed is the storm intensity parameter. From the intensity analysis of the severe thunderstorms (thunderstorms with peak wind speed of 50 knots or more) in surface data as indicated in Fig. 4.24(b), it was found that the surface data in terms of wind speed reports shows a definite peak-time for thunderstorms between the late afternoon and early morning and there was absolutely no peak wind speed report with more than 50 knots (93 km/hr) speed outside of this time range during 2002-2006. On the other hand, in case of radar data shown in Fig. 4.25, the intensity of thunderstorms in terms of maximum reflectivity does not exhibit any sharp diurnal peak time, although it shows a higher frequency between late afternoon and early morning. So radar and surface data show the similar diurnal patterns, but the difference between the frequency during the most frequent time and the least frequent time is lower than that in the diurnal distribution of severe surface winds.

Figure 4.26 shows the frequency pattern of intensity of thunderstorms for different months. Table 4.7 shows that all three radars exhibit closely proximity values of average maximum reflectivity of thunderstorm cells for different months. From Fig. 4.26 and Table 4.8, it can be seen that the intensity of thunderstorms varies with month and the average intensity of thunderstorms in terms of the maximum reflectivity in the radar data increases as months advance from March (45.1 dBZ) to May (45.8 dBZ), June (48.0 dBZ), July (48.6 dBZ) and August (48.8 dBZ) and it decreases again in the month of September (46.1 dBZ). In the surface data, the average intensity of thunderstorms in terms of peak wind speed also increases as the months advance from March (54.3 km/hr) to April (55.6 km/hr), May (57.4 km/hr), June (60.0 km/hr) and July (61.3 km/hr) and it decreases again from August (59.4 km/hr) to September (59.0 km/hr), October (56.4 km/hr), November (54.6 km/hr) and December (53.7 km/hr) and then rises again to 61.0 and 57.4 km/hr in January and February respectively. Thus, it can be understood that the most intense storms are present usually in the months of June, July and August. From the surface data,

it was also found that the overall average peak wind speed in North Dakota is 59.4 km/hr (32 knots). For most of the months, the frequency of storms versus the maximum reflectivity distribution are skewed distributions but for June and August (either side of the peak month of July), they are almost uniform distribution. The tails of these distributions are also significant. Although the average and the most frequent values for all the months are below 50 dBZ, the peak values at the end of the tail are significantly higher which indicates the presence of few thunderstorms with much higher intensity. The peak maximum reflectivity values are as high as 80 dBZ and 79 dBZ in June and July comparing to the average value of only 48.0 dBZ and 48.6 dBZ respectively. So the investigation of the return periods of such highly intense thunderstorm should be a future research work, Table 4.8 also shows the minimum, maximum and most frequent value of maximum reflectivity of thunderstorms for different months between 2002 and 2006.

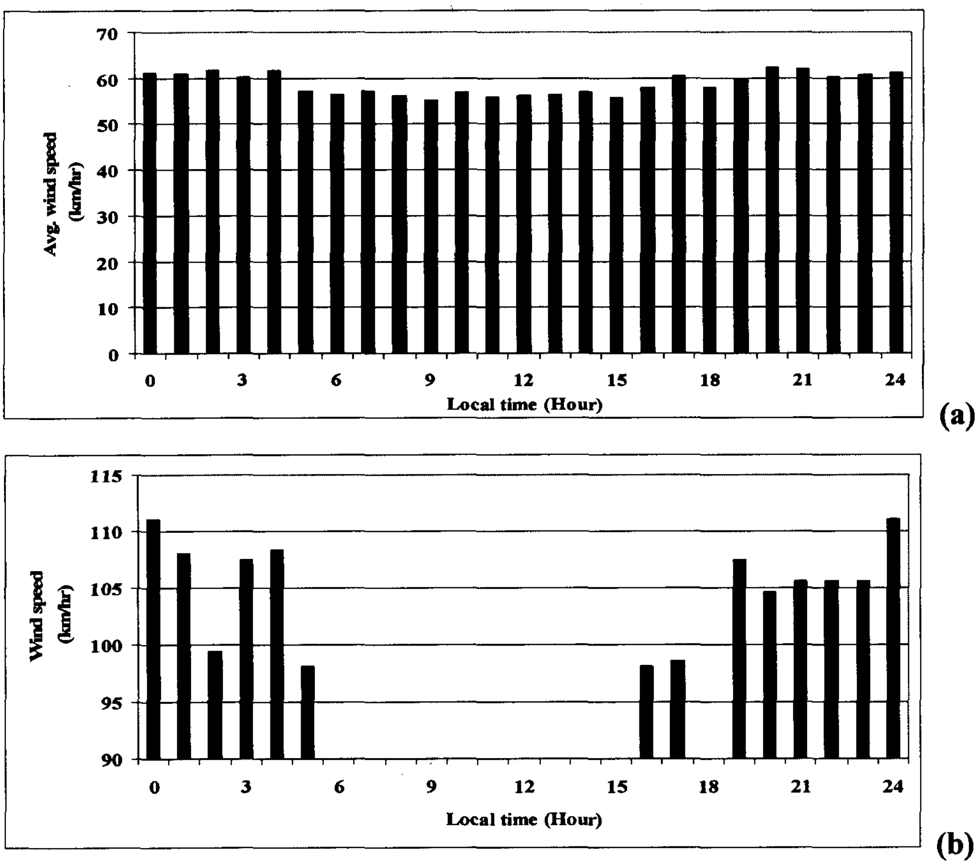


Figure 4.24: Average wind speed of thunderstorms for: (a) all storms (wind speeds > 46 km/hr) and (b) severe storms (wind speeds > 93 km/hr).

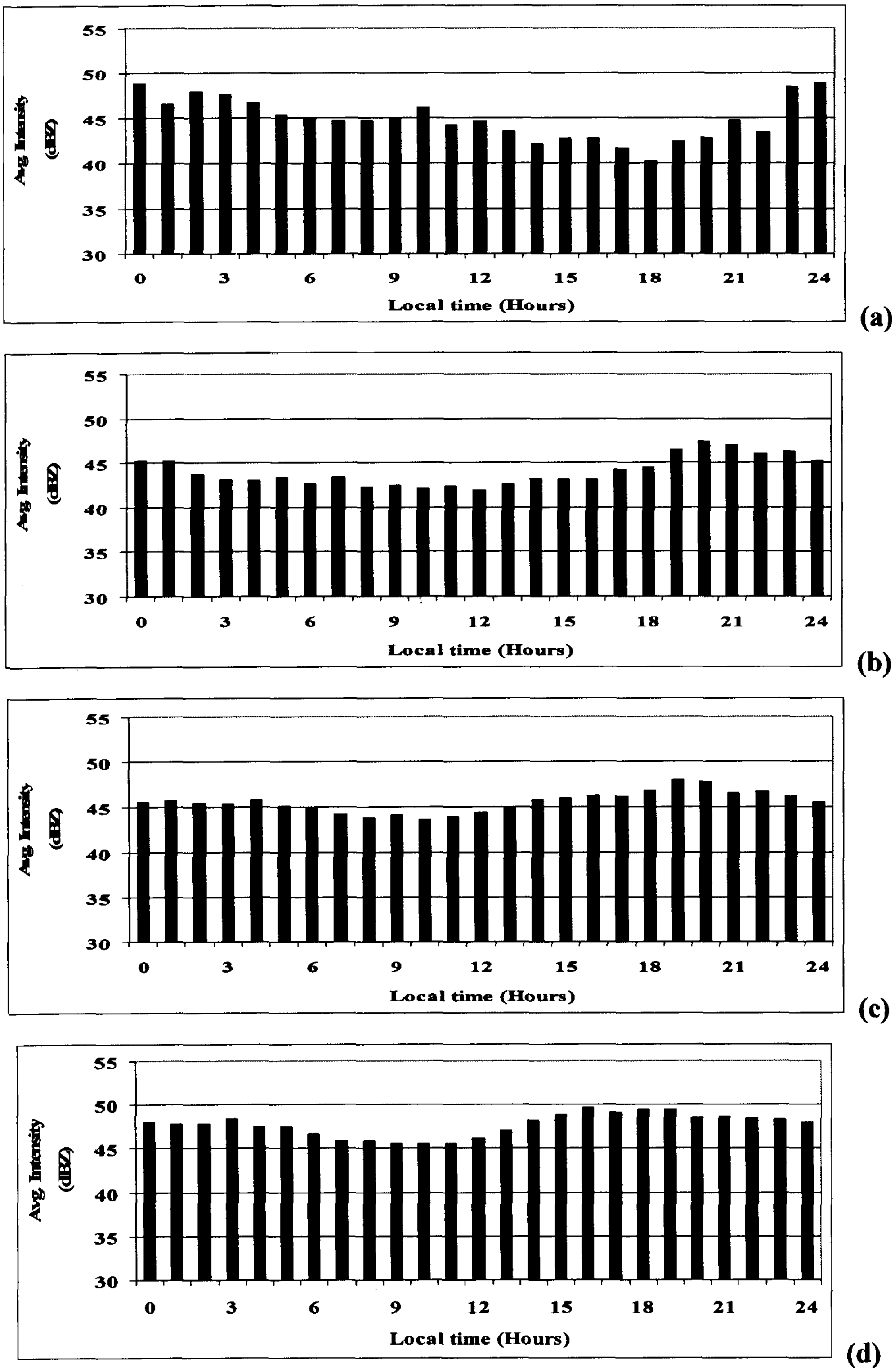


Figure 4.25: **Average intensity of thunderstorm cells over the day in the combined radar data for 2002-2006 for different months: (a) March, (b) April, (c) May and (d) June.**

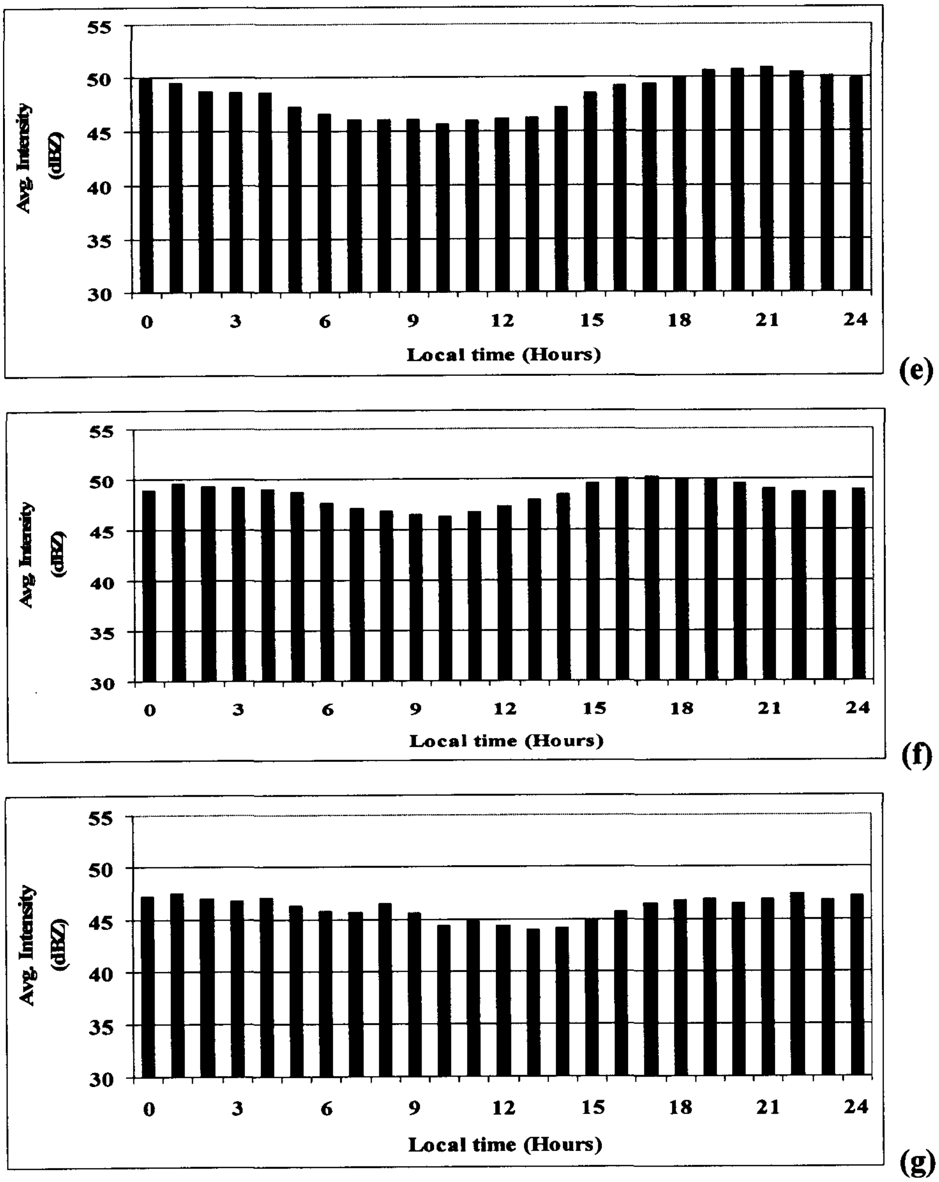


Figure 4.25: (Contd.) **Average intensity of thunderstorm cells over the day in the combined radar data for 2002-2006 for different months: (e) July, (f) August and (g) September.**

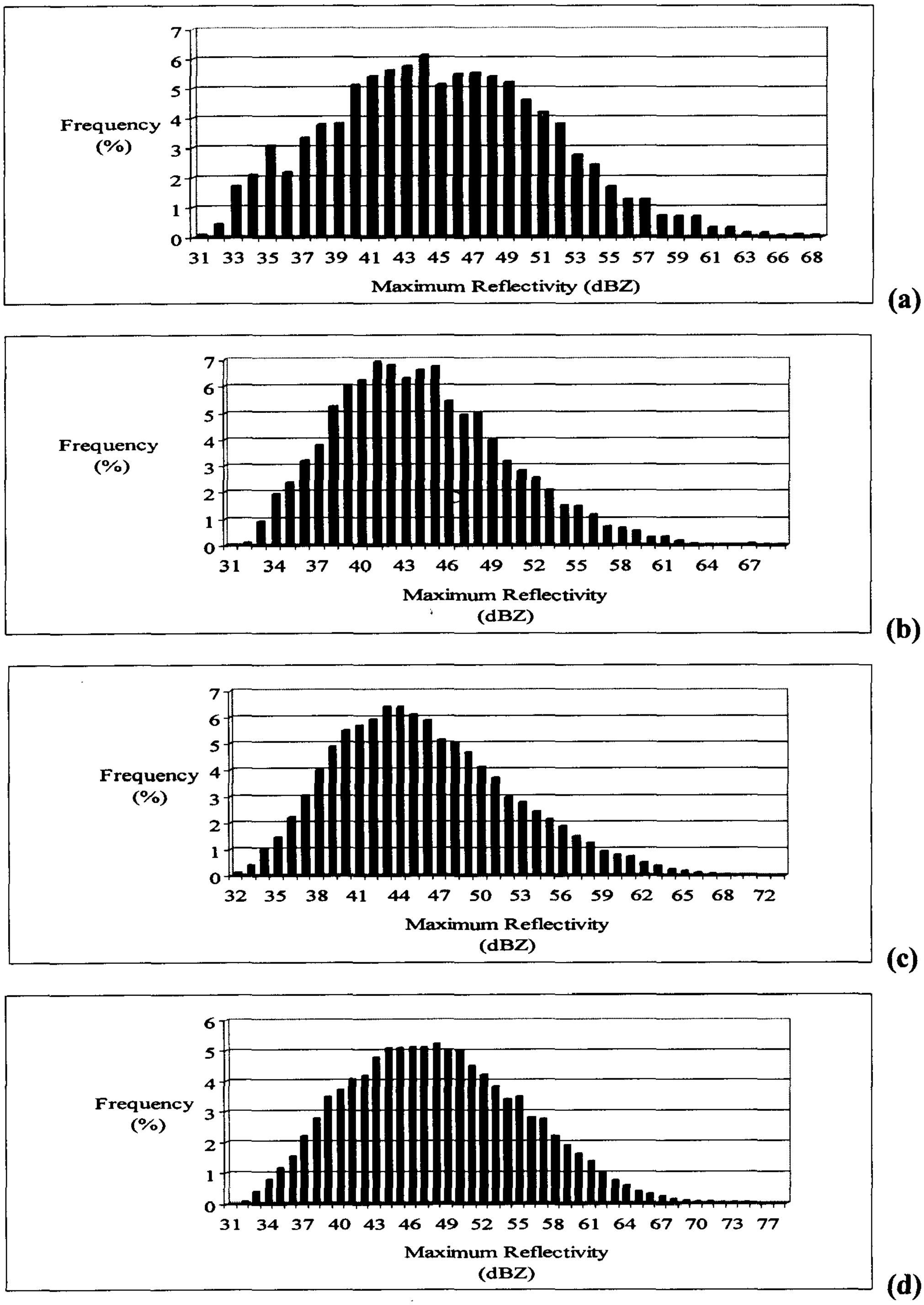
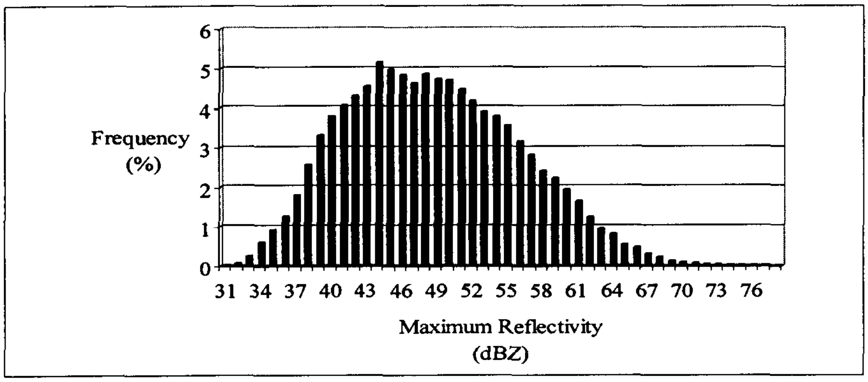
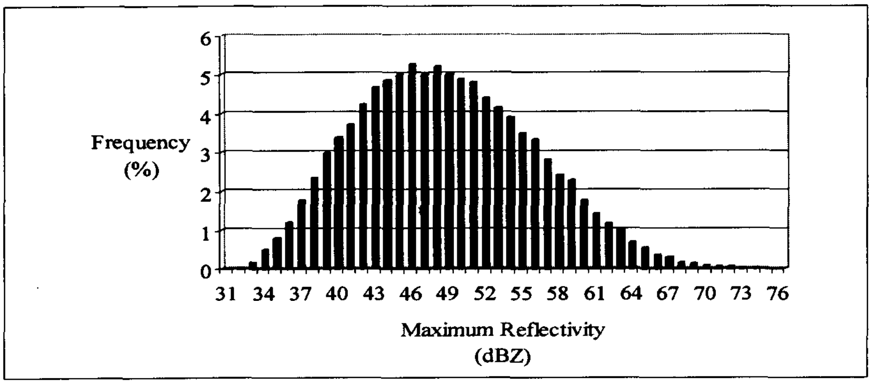


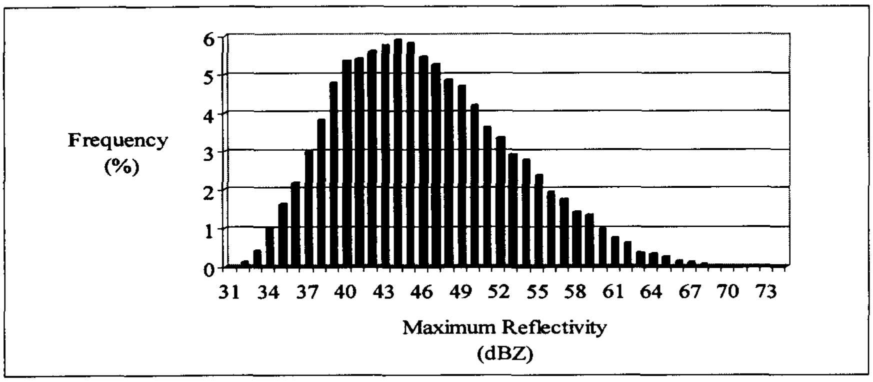
Figure 4.26: Frequency of Maximum Reflectivity of thunderstorm cells for the combined radar for 2002-2006 for different months: (a) March, (b) April, (c) May and (d) June.



(e)



(f)



(g)

Figure 4.26: (Contd.) **Frequency of Maximum Reflectivity of thunderstorm cells for the combined radar for 2002-2006 for different months: (e) July, (f) August and (g) September.**

Table 4.7 Comparison of the average of the maximum reflectivity values of the thunderstorm cells in dBZ covered by different radars for different months between 2002 and 2006

Month	Average maximum reflectivity (dBZ)			
	Combined radar	KBIS	KMBX	KMVX
March	45.1	46.4	42.0	42.8
April	44.1	43.5	45.1	44.1
May	45.8	45.2	46.5	45.5
June	48.0	47.8	48.8	47.8
July	48.6	48.4	48.8	48.8
August	48.8	48.3	49.3	48.7
September	46.1	45.7	45.7	46.8

Table 4.8 Statistical analysis of the maximum reflectivity values of the thunderstorms in the combined radar data in 2002-2006 in dBZ

Month	Maximum reflectivity (dBZ)				
	Mean	Min	Max	Most Frequent	Standard Deviation
March	45.1	31	68	42	6.4
April	44.1	31	69	40	5.9
May	45.8	32	73	43	6.4
June	48.0	31	80	44	7.1
July	48.6	31	79	44	7.4
August	48.8	31	76	44	7.2
September	46.1	31	77	44	6.7

4.10 SUMMARY

From the discussion of the analysis results in this chapter, a few matters regarding the climatology of thunderstorms in North Dakota became clear. It was found that June and July are the most frequent months for thunderstorms in North Dakota and late afternoon to early morning is the most frequent time for thunderstorms. The average number of thunderstorm days is 19 to 35 days per year depending on the location of the place with 29 days per year being the overall average for the entire state. The number of thunderstorm days due to peak wind speed is 9 to 14 days per year with 13 days per year as the average for whole state. It was also found that the heading of the thunderstorm cells is towards the north-west in March and it moves towards the north and then to north-east and east with advancing months and then moves back to the north and north-west in September. It was also found that March is a different month in North Dakota with several different climatological characteristics when compared to the other months of the year. It was also found that the average duration of thunderstorm cells in North Dakota is 23.6 minutes for all thunderstorms and 41.3 minutes and 59.8 minutes for the thunderstorms with more than 15 minutes and more than 30 minutes durations respectively and the average duration of thunderstorm cells are higher in the western and southern region of the state. Lastly, all the results were compared both by radar and surface data. Both radar and surface data indicates the same pattern of monthly, diurnal and spatial variations and same number of thunderstorm days and similar patterns for the life cycle characteristics. So it can be stated that radar data can be used for future research works for the development of thunderstorm climatology. The only significant matter between radar and surface data is the lack of any concrete relationship between the two thunderstorm intensity parameters in the two types of data – wind speed and maximum reflectivity. And finding a relationship between these two can be a future research work.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY AND CONCLUSIONS

For the investigation of the thunderstorm data from three WSR-88D radar stations and eight ASOS surface stations in North Dakota, the following steps were taken:

- Radar data from the three WSR-88D radar stations (KBIS, KMBX and KMVX) in North Dakota for 1997-2006 were downloaded, processed and merged into a combined radar-based thunderstorm database.
- Surface data for the eight ASOS surface stations in North Dakota for 1997-2006 were downloaded, processed and then the radar and the surface data were compared. Thus the accuracy and the completeness of the combined radar database were verified and confidence was built up in the analysis results.
- The individual and the combined radar databases and surface databases were investigated for the life cycle patterns of the thunderstorm cells for the time period of 2002-2006 to find out the climatology of thunderstorms in North Dakota.

From the aforementioned analysis of the individual and the combined databases as mentioned in chapter 4, the following conclusions about the climatology of thunderstorms in North Dakota were reached:

- The climatological characteristics shown by the radar data are very good match with that provided by the surface data and also with the climatological information obtained by the previous researchers. So this research shows that radar based database can be used to develop thunderstorm climatology.
- 95%-96% of all the thunderstorms in North Dakota occur between the months of March and September and 98.5% of all the storms occur between March and October.

The frequency of thunderstorms varies with month. In both the radar and surface data, June and July are the peak months for thunderstorm activity in North Dakota.

- The frequency of thunderstorms varies with local time. Both radar and surface data show that thunderstorms are most frequent between late-afternoon and early morning and least frequent between late morning and noon.
- According to the surface data, there is a clear diurnal peak during the late afternoon to early morning for thunderstorms with high wind speeds (wind speeds exceeding 25 knots or 46 km/hr) and for the severe thunderstorms (wind speeds exceeding 50 knots or 93 km/hr). It can be noted that there were no severe thunderstorm reports at all beyond that time range in 2002-2006 in North Dakota.
- There are around 19-35 thunderstorm days per year at any given location in North Dakota, with the average for the entire state being 29 thunderstorm days per year. This estimation of the average number of thunderstorm days per year is in agreement with all previously published values.
- According to the surface data, 35%-60% of all the thunderstorm days are associated with high wind speeds. The number of thunderstorm days with peak wind reports varies between 9 and 14 thunderstorm days per year at any place and the overall average for the entire state being 13 windstorm days per year. 1.7% of all the thunderstorms with peak wind speeds in North Dakota are severe thunderstorms.
- The presence of the Rocky Mountains and Lake Sakakawea in the western part and Devils Lake in the eastern part of the state and the passage of the Missouri river through the state lead to the presence of some high frequency thunderstorm initiation zones in the state. Mclean, Morton, Burleigh, Griggs, Stutsman, McHenry etc. are the most thunderstorm prone counties in North Dakota.
- The average heading of thunderstorm cell track-lines varies with month. The average heading is towards the north-west in March and it swings through northerly, north-easterly and easterly directions with the advance of months from April to August. In September, the average heading again moves towards the north and north-west.
- The average duration of thunderstorm cells in North Dakota is 23.6 minutes for all thunderstorms and is 41.3 minutes for thunderstorms with durations more than 15

minutes. The average duration of thunderstorm cells are comparatively higher in the western and southern regions of the state.

- The overall average forward speed of thunderstorm cells in North Dakota is 59.0 km/hr. The frequency distribution of the forward speed of thunderstorm cells is broad in March but there are definite peaks for other months between April and August. The average forward speed of the storms is also higher in March (73.4 km/hr) and September (64.4 km/hr) compared to the summer months.
- The overall average track-length of thunderstorm cells in North Dakota is 21.8 km. The average track-length of the thunderstorm cells is higher in March and in September, when compared to the summer months.
- The overall average peak wind speed in North Dakota is 59.4 km/hr.
- The intensity of thunderstorms varies with month. The average intensity of thunderstorms in radar data (in terms of maximum reflectivity) increases as months advance from March to August and after reaching a peak, it decreases again during the month of September. The average intensity of thunderstorms in surface data (in terms of peak wind speed) also increases as months advance from March to July and after reaching a peak, it decreases again from August to December.
- Longer lasting storms are more intense storms. Thunderstorms of more than 30 minutes duration and 50 km track-length have higher average maximum reflectivity values than storms with smaller duration and length.

This new radar-based database has some limitations. These limitations arise due to the SCIT algorithm limitations used to identify and track storm cells as described in chapter 2 and also due to the unavailability of data for some months within the research time period as described in chapter 3. Besides these issues, some other radar data limitations became apparent during this research:

- The spatial analysis results clearly show that the efficiency of radars depends largely on the location of the radar and the distance of the storm cells from the radar. The efficiency of radars decreases with distance. To rectify this, the combined radar data was used for all the analysis in this research. In spite of this drawback, radar data

show more accurate and more widely distributed spatial distribution pattern for thunderstorms than surface or any other traditional data. The usage of the usage of satellite data can increase the completeness of a thunderstorm database in terms of spatial distribution over a big state.

- Radar data overlap with each other. From the comparison of radar and surface data in an overlapped region, it was found that one radar is not sufficient to detect all the thunderstorm cells at longer distances. Again, if more than one overlapping radar data are considered together, all the thunderstorm cells in that place are covered by the combined radar data. But in that case, same storm cells can be counted more than once by different radars, with slightly varied cell characteristics. To rectify this drawback, individual radar data were analyzed in each steps of this research.

- Although the radar data in terms of maximum reflectivity and the surface data in terms of surface wind speed show very similar patterns of thunderstorm intensity for both monthly and diurnal distributions, there is no obvious relationship between the two storm intensity parameters – the radar oriented maximum reflectivity values and the surface wind speed values.

- Although the maximum range of radars cover the whole of North Dakota and most of the regions of South Dakota and southern Manitoba, it was found from this research that inclusion of data from two or three radar stations from adjacent states of Montana, Minnesota and South Dakota would increase the accuracy and completeness of the database created in this research.

5.2 RECOMMENDATIONS FOR FUTURE STUDY

A reliable radar based database for thunderstorm cells along with the surface based wind speed reports in North Dakota was developed. In terms of developing a parametric risk model for thunderstorms for the power transmission lines of Manitoba Hydro, the following are the recommendations for future study:

- An investigation should be carried out to find out a possible relationship between the surface wind speed parameter and the maximum reflectivity parameter in the radar data, possibly by vertical profiling of the atmospheric conditions and incorporating other data like balloon data. The relationship between wind speed and storm cell forward speed can also be compared extensively to investigate any possible relationship between these two.

- The database developed in this research can be further analyzed to understand the behaviour of thunderstorm systems as clusters of individual storm cells in terms of their direction, duration, track and intensity.

- A study to investigate the return period of the extreme thunderstorm events should also be a future research work. But in that case, a longer period of data would be required to obtain a reliable result.

An investigation can also be carried out to investigate the reason behind the different characteristics of thunderstorm cells (i.e. different heading, higher and flat forward speed pattern, higher track-length, different diurnal distribution etc.) during the month of March comparing to the other summer months and the reason behind the high average wind speed value during the winter month of January, February and March compared to the Fall and the Spring months.

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