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Atmospheric Conditions Associated with Lightning during Snow and Ice Events

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THE ATMOSPHERIC MECHANISMS ASSOCIATED WITH LIGHTNING DURING SNOW AND ICE EVENTS

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Abstract
The purpose of this research was to find the atmospheric mechanisms associated with lightning in snow and ice events. The specific mechanisms that were examined were low-level wind shear, upper level divergence, surface temperature, low-level temperature, the -10 degrees c level, and precipitable water. A chi-squared dependency test showed the strong association of low-level wind shear to each precipitation type (snow, sleet/freezing rain, rain) in two separate studies. Surface temperature appeared to have a relationship to lightning in all preciptation categories, while no significant relationship to lightning in all precipitation categories, while no significant relationship was found with upper level divergence, the -10 degree C level, or the precipitable water. From examination of the vertical soundings, temperatures above freezing are found in the low levels for all precipitation types meaning that different types of hydrometeors are present in the clouds. The mixing of these due to the turbulent effects of low-level shear may explain how the thunderclouds (mostly stratiform) are charged. Graupel and snow pellet interaction are also believed to be mechanisms for cloud charging.

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SNOW AND ICE EVENTS

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Randall J. Haeberle

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Abstract

The purpose of this research was to find the atmospheric mechanisms associated with lightning in snow and ice events. The specific mechanisms that were examined were low-level wind shear, upper level divergence, surface temperature, low-level temperature, the -10° C level, and precipitable water. A chi-squared dependency test showed the strong association of low-level wind shear to each precipitation type (snow, sleet/freezing rain, rain) in two separate studies. Surface temperature appeared to have a relationship to lightning in all precipitation categories, while no significant relationship was found with upper level divergence, the -10° C level, or precipitable water. From examination of the vertical soundings, temperatures above freezing are found in the low levels for all precipitation types meaning that different types of hydrometeors are present in the clouds. The mixing of these due to the turbulent effects of low-level shear may explain how the thunderclouds (mostly stratiform) are charged. In most cases, imbedded convection appears to be the predominant cause of lightning in snowstorms. Graupel and snow pellet interaction are also believed to be mechanisms for cloud charging.

THE ATMOSPHERIC MECHANISMS THAT TRIGGER LIGHTNING DURING SNOW AND ICE EVENTS

I. Introduction

1.1) Background

The mechanisms that cause lightning in snow or ice storms, otherwise known as thundersnow, have not been thoroughly studied. Since most wintertime thunderstorms in the United States are elevated meaning they are formed over a frontal inversion (Colman 1990a), the main emphasis will be the mechanics involved with these particular storms. Several scientists have studied the dynamics of winter storms, while others studied the electrical nature of thunderstorms. No study has been done to examine the mesoscale dynamics involving the production of lightning during wintry precipitation. Work has also been done to study specific cases of thundersnow or ice, particularly in Japan, but no broad study has been done. In Japan, thundersnow forms mostly from the instability created from Siberian air masses moving over the Sea of Japan (Kitagawa 1992), which is a different situation compared to the Great Plains (except the Great Lakes region) of the United States where thundersnow is most common in the U.S. This thesis will examine topics related to thundersnow, which will entail the winter storm mechanics, frontal circulations, the electrical nature of the wintertime clouds, and previous case studies of individual events.

1.2) Problem Statement

Lightning occurs at or near Air Force bases many times each year during snow or ice events (based on observation). Lightning in snowstorms may seem insignificant to the average person, but not to the individual in charge of sensitive equipment such as aircraft and computers on base. Since lightning is a costly and dangerous weather phenomenon, the threat of lightning strikes should be forecasted when conditions are favorable to protect the sensitive equipment on base, and more importantly, any personnel who must be outside during the storm.

1.3) Research Objectives/Questions/Hypotheses

1.3.1) Objectives

1.) To find the atmospheric conditions (divergence aloft, low-level jet, etc.) necessary for lightning to occur during snow and/or ice events.

2.) To find the level of the -10° C line in the cloud and determine its significance.

3.) To locate the areas within the winter storm where lightning occurs, and where snow is common relative to the storm.

1.3.2) Questions

1.) What is different between a thundercloud that produces snow and one that produces rain?

2.) What is happening in a mesoscale snow storm to produce the strong lift necessary to create a strong electrical charge separation?

3.) What is the significance of the -10° C level within the thundercloud?

4.) What is the significance of graupel or snow pellets interaction on charge separation?

5.) What is the difference between a cloud that produces lightning while snow is falling versus a cloud that does not produce lighting while snow is falling?

6.) Why is the average peak of the temperature inversion above the surface during thundersnow events above freezing?

1.4) Research Focus

The focus of this thesis will be on the mechanisms involved with the atmospheric conditions conducive to thundersnow. Since data were only used from synoptic charts and radar data, the focus can only be on the large-scale features of storms. An attempt will be made to find some of the smaller scale conditions, but again, the focus will be on the large-scale phenomenon.

1.5) Assumptions/Limitations

Due to the lack of completely accurate data, the following are assumed:

1.) The flashes observed in the lightning data are assumed to be cloud to ground flashes. Since the flashes are occurring from low clouds during wintertime thunderstorms, some cloud-to-cloud and intra-cloud flashes may be recorded in the data set.

2.) The wind, temperature, and surface analysis data on synoptic charts are considered accurate. Because some upper-air observations are recorded from balloon measurements, the position of the wind direction and wind speed will not be directly over the observed station.

3.) The locations of the lightning flashes in the lightning data are considered to be accurate. Factors such as different localized air density pockets (thermals) and ducting may slightly change the time of arrival of the electromagnetic pulse towards different sensors. This should only inhibit the precise location of the flash by less than one mile, which is insignificant for a mesoscale synopsis, but for a microscale study could be detrimental.

4.) The upper-air processes are estimated for thundersnow occurrences between observational readings. Since many cases did not occur within an hour of the 00Z and 12Z sounding times, interpolating the time of occurrence with the previous and post occurrence charts will give an approximation of winds and processes. With this, the storm's fronts and low pressure centers are assumed to move concurrent with the radar and satellite information, so calculating the winds can be done assuming that the processes will be the same as the storm moves over the area.

The limiting factors of this thesis are as follows:

1.) The limited availability of data is the number one inhibitor of this thesis. Because of the numerous small-scale errors, the exact nature of the microscale processes cannot be found with the synoptic data. Because no equipment is available for measuring cloud features, microscale features cannot be found. However, a hypothesis of the mesoscale conditions present during thundersnow can be formed based on the synoptic data.

2.) Since thundersnow is a large-scale problem, only a fraction of the problem can be analyzed and studied by this work.

3.) The knowledge of the nature of electrical storms is still not completely understood. This lack of support works against this thesis in that proving something involving the electrical nature of the storm will be difficult, if not impossible with no equipment or source of data for the electrical attributes of the storms (except location, current strength, and polarity of the flashes).

1.6) Preview

This thesis examines the synoptic atmospheric conditions present when lightning occurs in snow and/or ice events. Previous work relating to wintertime thunderstorms, electrical cloud structure, and strong convective dynamics from other scientists will be examined first, followed by an overview of the methodology used. Next are the results from the approaches used and the analysis of those results. Finally, a conclusion is given as to whether the results are satisfactory in determining the conditions present when lighting occurs during snow and ice events.

II. Literature Review

The mechanisms that cause lightning in snow or ice storms, otherwise known as thundersnow, have not been thoroughly studied. Since most wintertime thunderstorms in the United States are elevated, meaning they are formed over a frontal inversion (Colman 1990), the main emphasis will be the mechanics involved with these particular storms. Several scientists have studied the dynamics of winter storms and the electrical nature of them, but not the dynamics involved with lightning in the wintry precipitation. Much work has also been done to study specific cases of thundersnow, but no broad study in the United States has been done. For example, in Japan thundersnow forms mostly from the instability created from Siberian air masses moving over the Sea of Japan. This literature review will examine the topics related to thundersnow, which will entail the winter storm mechanisms, the electrical nature of the clouds, and the previous case studies relating to thundersnow.

2.1) Previous Work

2.1.1) Winter Storm Mechanisms

For a strong winter storm to develop, certain parameters including sub-freezing air must be in place. Parameters such as moisture, moisture transport, a mechanism of lift, and upper-level support are needed to create the strong vertical velocity and the higher number of hydrometeors required to cause lightning.

First, a moisture source must be available. The availability of moisture is key to not only providing a storm with the moisture to produce precipitation, but to add to the instability of the atmosphere. Johnson and Downey (1976) showed that latent heat release is a major factor in enhancing mass circulations and cyclogenesis. Water vapor is also less dense enabling it to rise easier than dry air in its environment.

Next is the moisture transport mechanism. For thundersnow and for lightning with freezing rain and sleet, that mechanism is the low-level jet stream (LLJ) found about 800 meters above the ground (Bluestein 1992). LLJs can be found ahead of fronts and flow parallel to them. A LLJ has a diurnal variation that is strongest at night, which may help explain why thundersnow occurs more often at night and in the morning. Colman (1989) showed that 635 of 1093 (58%) elevated thunderstorm cases studied occurred closer to 1200 UTC rather than 0000 UTC. In the Plains States, the moisture is transported from the Gulf of Mexico. Moisture is transported from the Great Lakes and Gulf of Mexico in the Northern Plains and Great Lakes region. Along the Eastern Seaboard, the moisture is brought in from the Atlantic Ocean.

Next is the lifting mechanism. This is typically a frontal boundary or surface wind shift for lightning with wintry precipitation (to be shown in this thesis). As the LLJ or low-level flow flows over the cold air entrenched at the surface, the flow along the surface of the cold air mass forces the moisture the LLJ carries upward creating lift for cloud development. Along the East Coast of the United States and the coastline of the Great Lakes, a phenomenon called the coastal front develops. Bjerknes and Solberg (1921) proposed that surface convergence due to frictional differences of land and sea helps to enhance this front. The coastal front acts like a warm front oriented tens of kilometers inland and parallel to the coastline. The coastal frontal boundary sends the easterly low-level flow coming off the Atlantic (for the East Coast of the United States) up and over the cool air entrenched to the west of the wind shift.

Finally, upper tropospheric support aids in vertical development of clouds. This support can be in the form of a jet streak circulation as seen in Figure 1 (Kocin and Ucellini 1991) or a divergent mechanism like diffluence or speed divergence. When coupling the upward vertical motion derived from upper tropospheric support with the upward vertical motion on the backside of the rotating, ascending LLJ, a moist parcel would be allowed to rise.

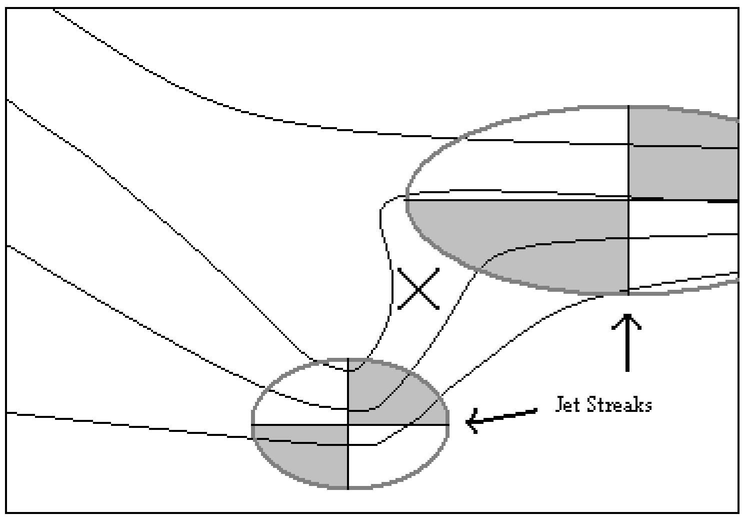

Figure 1. Jet streak positioning for Uccelini's proposed jet streak circulation. The shaded parts of the jet streaks indicate rising motion from the circulation. The X on the figure marks the area where the influence of rising air due to both jet streak circulations is present (after Kocin and Ucellini 1991).

In conclusion, moisture, moisture transportation, a lifting mechanism, and upper-level support are needed to develop a strong winter storm. Snow and ice can be created by a combination of these conditions, but heavy snow from a mid-latitude cyclone needs all of these.

2.1.2) Frontal Circulation

Emanuel (1985) studied frontal circulations with small moist symmetric instability. He found the circulations to have a strong, concentrated sloping updraft that occurs slightly to the warm side of the region of maximum geostrophic compression of the isotherms (in other words, slightly to the warm side of the maximum temperature gradient). He also suggests the effects of melting or evaporation of the falling precipitation, in that they likely occur in the downdraft below the 0 m/s vertical velocity surface, thus modifying the solution in the direction of a stronger downdraft. However, in terms of frozen precipitation, evaporation and melting would likely be a less significant effect because latent heat exchange is minimal. He also noted that when potential vorticity was decreased, the slope on the updraft side of the circulation deepened, thus updraft speed increased (Figure 2). Finally, he suggests that condensation appears to rapidly sharpen the potential vorticity gradient.

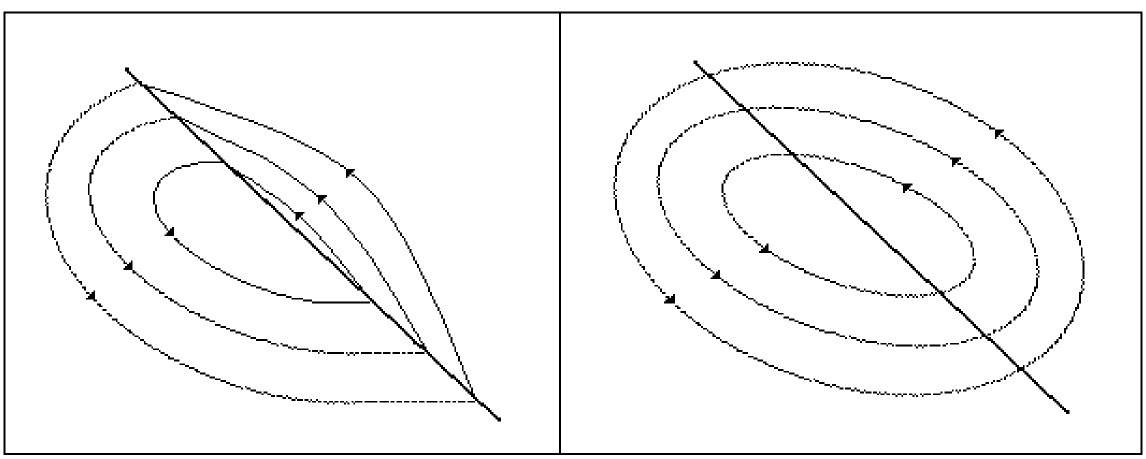

Figure 2. The cross-front circulations in the presence of low potential vorticity (0.01) (left side), and uniform potential vorticity (1) (right side). The heavy solid line denotes X=constant, where X=x+Vg/f and x is the coordinate orthogonal to the isotherms, Vg is the geostrophic wind along isotherms, and f is the coriolis paramter. (from Emanuel 1985).

Sanders and Bosart (1985) studied the mesoscale structure of a snowstorm in the Northeastern United States. Frontogenetical forcing and symmetric instability were proposed as possible explanations of the intense snow bands that form. They found a prominent circulation below 500 mb, with a maximum vertical velocity greater that 12 m/s. They also noted that the dividing line (0 m/s line) sloped toward the northwest from 940 mb near Cape Hattaras, NC to 700 mb between Washington, D.C. and Pittsburgh, PA. Another important aspect to note is that updraft speeds were near 4 m/s above the 500 mb surface. Finally, they note that there was an intense tranverse frontal circulation below the 500 mb level that showed pronounced lower tropospheric confluence.

2.1.2) Electrical Nature

Wintertime thunderstorms tend to have a similar electrical structure as a summertime thunderstorm (Magono 1980). Although the clouds may be as shallow as 5000 meters, they still produce lightning and have been characterized by Takeuchi et al.. (1978) to have higher lightning peak discharge currents than in summer storms and produce a high percentage of positive discharges to the ground. The different heights of different types of hydrometeors make it more challenging to examine the wintertime thunderstorm. Magono (1980) found that winter clouds have nearly the same polarity as summer clouds, but with the negative charge layer at a lower height for wintertime clouds, especially when high vertical shear was present. He also found that the negative charge layer existed above the radar bright band while the positive charge layer existed beneath it.

Graupel effects are very important in the charging process. Graupel is defined as "soft hail" between 2-5 millimeters in diameter that forms in a convective cloud when supercooled water droplets collide and freeze on impact (Geer 1996). Snow pellets (formerly called graupel) are a type of frozen precipitation consisting of soft, spherical (sometimes conical) particles of opaque, white ice having diameters of 2-5 millimeters (0.08-0.2 inches), which typically fall from a convective type cloud (Geer 1996). Since snow pellets were considered graupel in the past, it is impossible to distinguish between graupel and snow pellets from the researchers who studied graupel effects. So, the term graupel in this thesis is a general term, which includes both. Isono et al. (1966) found that graupel had very little charge when it fell over the sea, but was charged well inland with both polarities. He concluded that fewer ice crystals over the sea meant fewer collisions in the clouds, thus reduced charge exchange. Simpson (1909) noted that lightning occurred on most days when graupel was mixed with snow. Takahashi (1997) found that graupel at heights where temperatures were less than -10° C had mostly negative charge while Fukao (1991) concluded that lightning was associated with the contact and mixing of graupel and ice crystals or snowflakes. Takahashi (1984) suggested that the positively charged graupel below the -10° C level plays a critical role in the accumulation of the large negative space charge at that level.

Takahashi also shows how the strong electric charge separates through the two major charging stages in the cloud. In the first stage near the top of the cloud (-30° C) large space charges accumulate because of gravitational separation between negatively charged graupel and positively charged snow crystals (Figure 3). The next stage occurs near the -10° C level in the mature stage of the thunderstorm life cycle. In this stage, negatively charged falling graupel combines with negatively charged upward moving snow crystals to enhance the negative space charge accumulation. Positive charging of graupel below the -10° C line is the critical process in negative space charge accumulation at that level. His work in 1999 showed that graupel concentrations of one per liter of air and an average space charge on the precipitation particles of a few tenths of a picocoulomb were sufficient to produce lightning. He also noted that riming electrification was the primary charge separation process. His work then showed

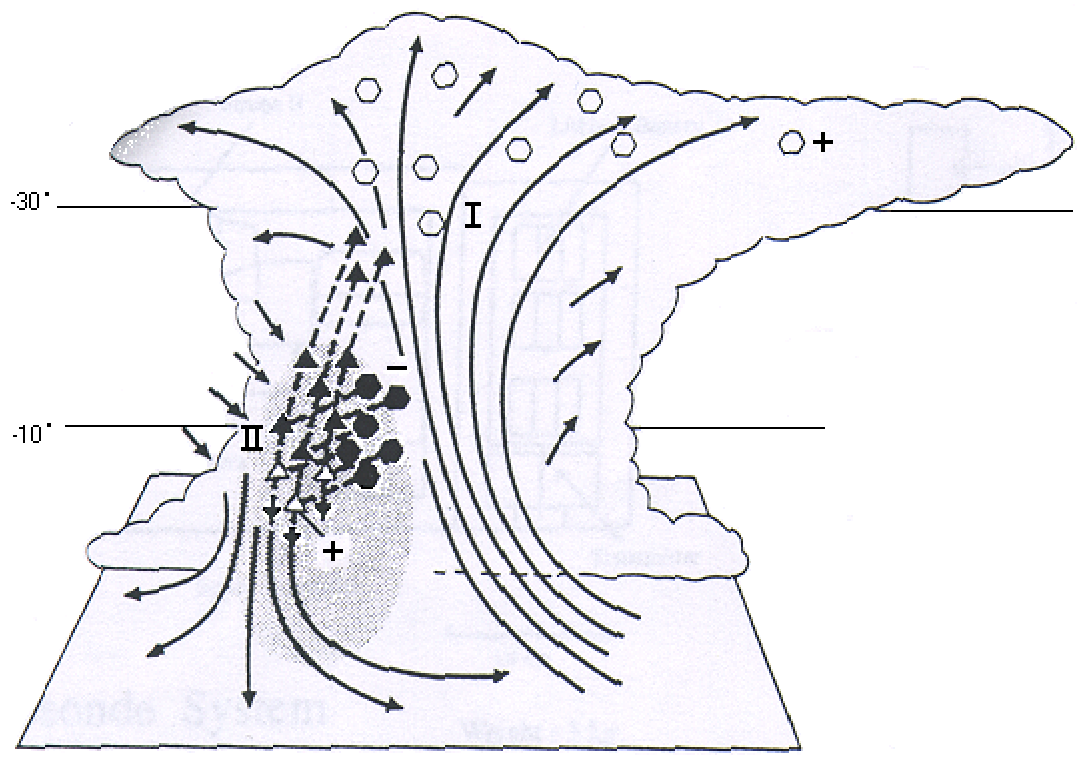

Figure 3. Cloud model of charge structure with graupel (hexagons) and ice crystals (triangles) (after Takahashi 1999). The two stages of cloud charging are denoted in Roman numerals and the temperature levels are in Celsius.

that the most active particle charging process occurred around the -20° C level, and that graupel had a charge reversal at about the -11° C level as seen in Figure 4. It is important to note that the wintertime clouds he studied were in Japan, where the effects from the Sea of Japan, similar to lake-effect snow in the Great Lakes area, differ from those found within the interior of the United States in terms of a convective source for cloud formation. However, the effects of graupel interaction should be the same since internal cloud processes (especially with space charging) should be similar.

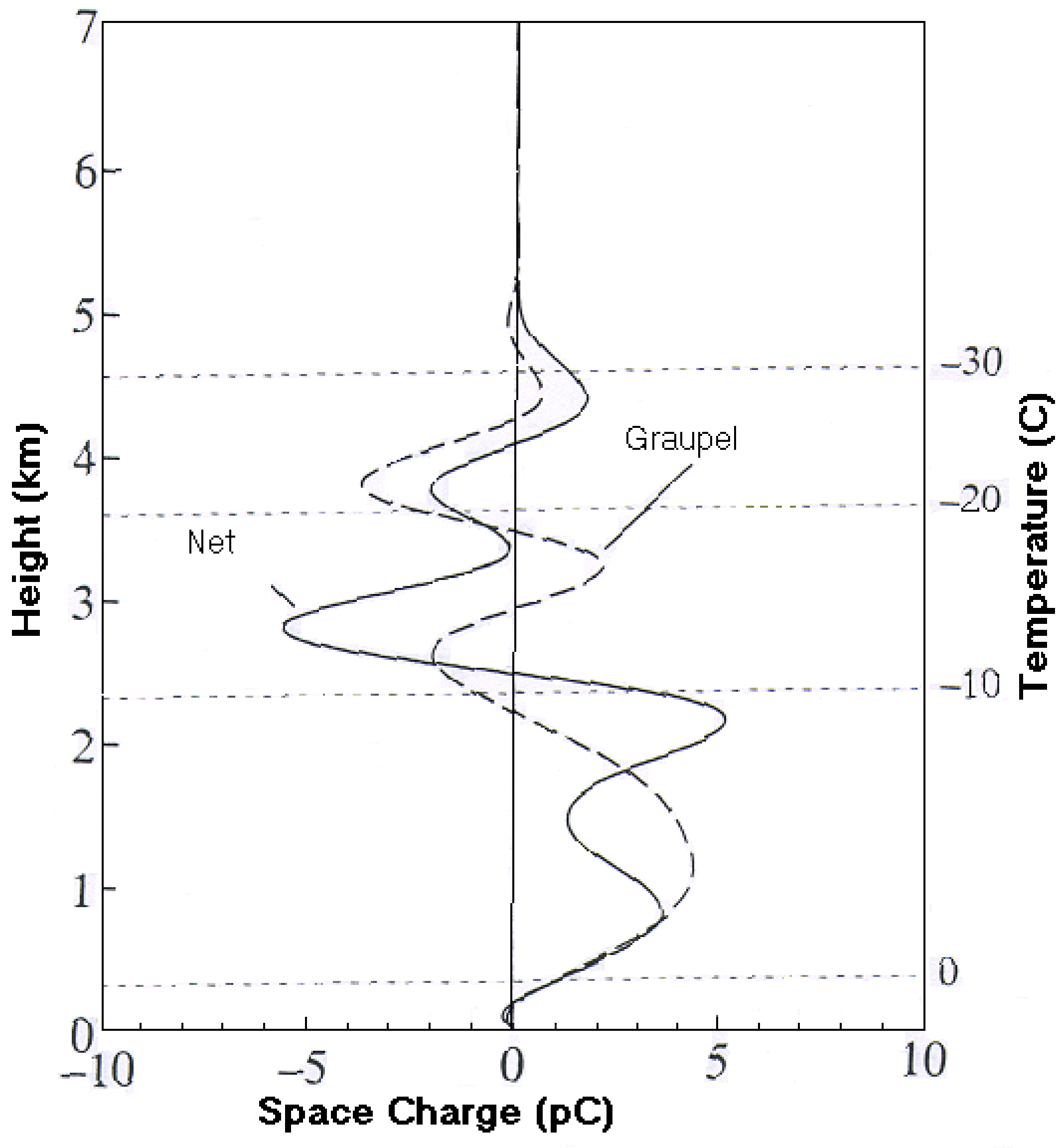

Figure 4. Charge on graupel and total net charge with height (after Takahashi 1999).

The fall speeds of particles have an influence on the charging process. Many scientists have found that larger snowflakes have faster fall speeds. The faster falling snowflakes collide with smaller ice particles and snowflakes causing a higher collision rate. The melting layer possesses a heterogeneous group of fall speeds, which may aid in the charging process. Graupel interaction appears to play a pivotal role in the charging process since graupel are large and have faster fall speeds.

In conclusion, graupel interaction may be the most important influence in cloud electrification for thundersnow. Simpson's work in 1909 showed that lightning occurred most of the time when graupel was falling with snow. The analysis and results of this thesis will help to show why and how graupel fits into the thundersnow and ice with lightning processes.

2.1.3) Previous Case Studies

Holle et al. (1998) developed a chart that showed all occurrences of thunder at certain temperatures with the accompanying surface precipitation/conditions. Their study included approximately 80% of all hourly observations from 1982-1990 for 211 stations in the 48 conterminous states. They found 458 hours with thunder and some form of wintry precipitation (averages approximately 51 per year). They showed thunder maximums in the Midwest from Missouri to SE Nebraska down to the panhandle of Texas, Utah, and the Great Lakes (Wisconsin and the Upper Peninsula of Michigan) as shown in Figure 5. In addition, Table 1 lists their categorizations of station reports.

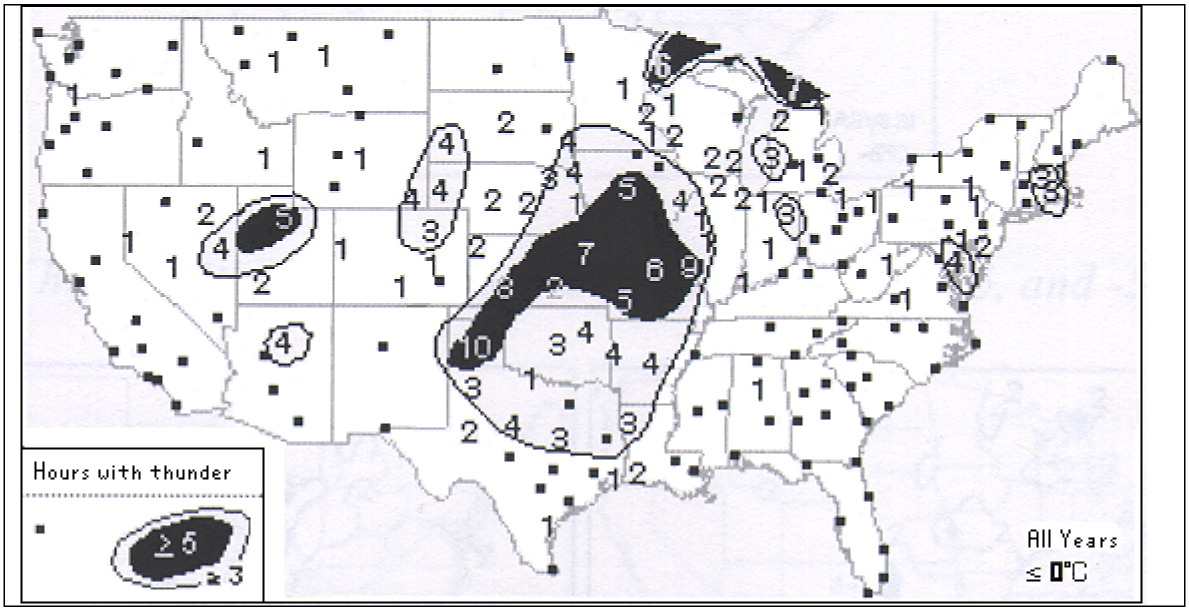

Figure 5. Number of hours reported with thunder and a surface temperature at or below freezing for a nine year period (after Holle et al. 1998).

Table 1. Categorized thunder reports and surface temperatures in Celsius for a nine year period from Holle et al. (1998).

Wx Condition	<=-5° C	-5°C to 0° C	0° to +5° C	+5° C to+10° C
Light Rain	0	0	**643**	**2567**
Moderate Rain	0	0	174	788
Heavy Rain	0	0	57	226
Drizzle	0	0	5	11
Light Snow	6	**47**	81	1
Moderate Snow	6	25	16	1
Heavy Snow	**13**	34	7	0
Light Sleet	1	6	10	1
Moderate Sleet	2	2	2	0
Freezing Rain	1	46	2	0
Mixed Precip.	2	38	92	26
Other	2	7	35	62
Thunder Only	0	7	83	423
All Hours total	33	212	1207	4106

(note: Bolded numbers represent the highest frequency of occurrences in each temperature category. Mixed precipitation refers to a combination of more than one type of precipitation except hail. Others refer to non-precipitating weather events such as fog and haze.)

No station observed thunder simultaneously with only moderate or heavy freezing rain, freezing drizzle, heavy sleet, or hail alone. However, hail was reported with thunder and some form of precipitation for 68 hours. Mixed precipitation refers to a combination of more than one type of precipitation except hail. Others refer to non-precipitating weather events such as fog and haze.

From their work, they showed that snow is the most common precipitation with thunder when temperatures are below freezing at the surface, while rain is the most common form for temperatures above freezing at the surface. Another interesting aspect to note is that 0.6% of all thunder events at or below 10° C are below -5° C, while only 4.4% of all thunder events below 10° C are below freezing.

Holle and Watson (1994) also studied lightning during two winter precipitation events and found that 59% of all flashes were positive flashes for the 10 Jan 94 case and 29% were positive flashes (52% during the first 4 hours) for the 16 Jan 94 case. They concluded that the positive flashes occurred more often on the northeast ends of precipitation lines in the Northern Hemisphere.

Curran and Pearson (1971) found the average of 76 soundings for thundersnow occurrences. The average showed an inversion around 800 mb with a magnitude of temperature and dew point temperature above 32° F as shown in Figure 6. These 76 reports came from the locations shown in Figure 8.

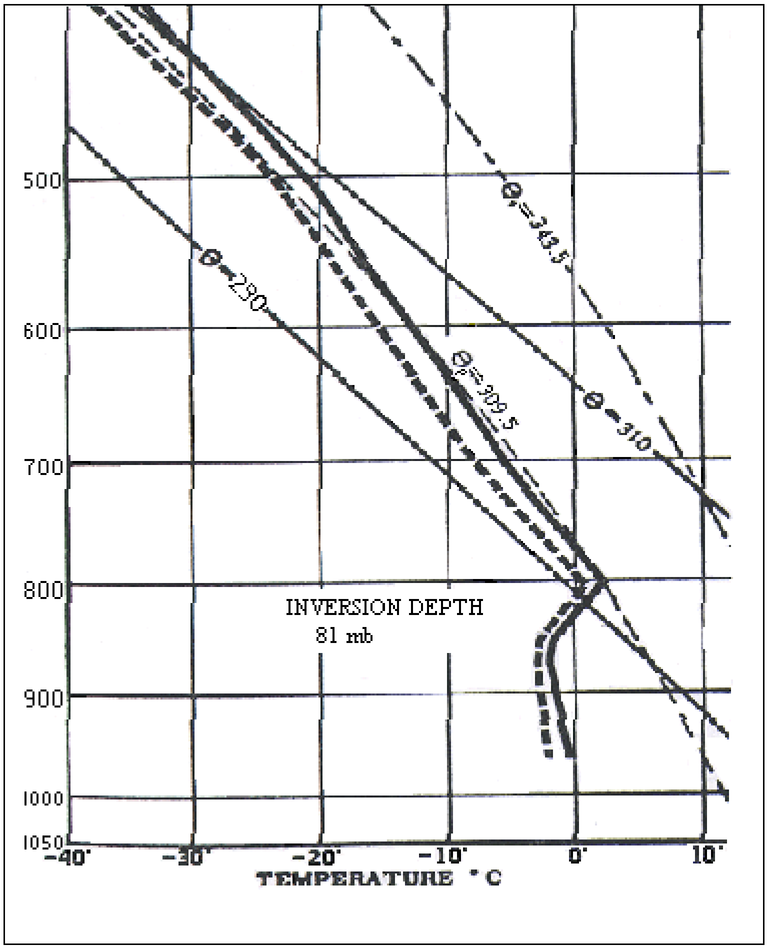

Figure 6. Average temperature sounding taken from 76 thundersnow events (after Curran and Pearson 1971).

Colman (1990a), who studied elevated thunderstorms above a front's surface in environments without CAPE (convective potential available energy), along with Holle et al. (1998), and Curran and Pearson (1971) work showed a maximum of thundersnow occurrences for the U.S. in the Midwest.

Another example of a vertical sounding pertaining to thunder with ice comes from Holle and Watson (1996) as seen in Figure 7.

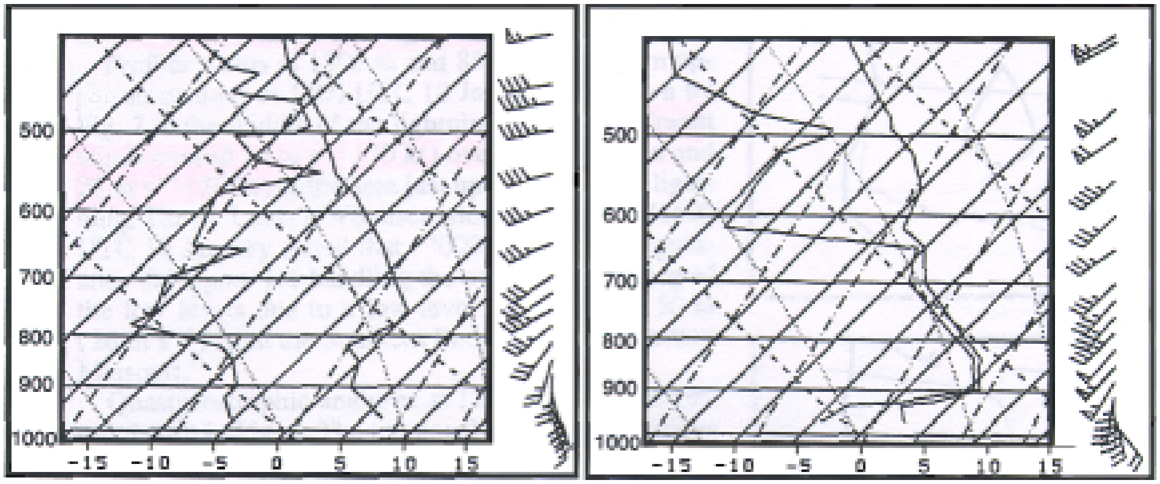

Figure 7. Vertical soundings for a freezing rain with thunder event at Monet, Missouri on 10 January 1994. The sounding on the left is for 0000 UTC and the one on the right is for 1200 UTC. The lightning occurred from 1003 to 1340 UTC (from Holle and Watson 1996).

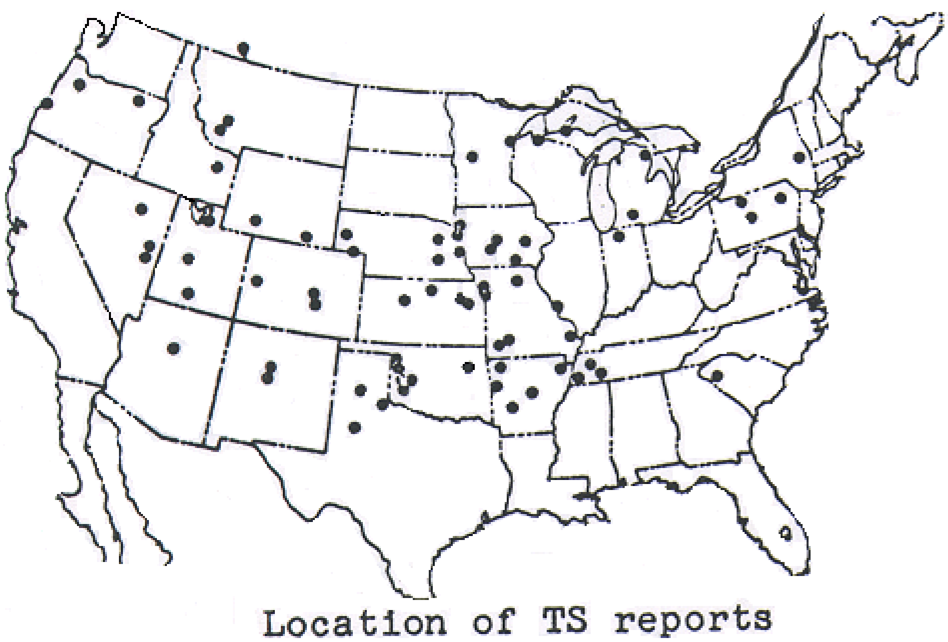

Figure 8. The locations of the 76 vertical soundings used in Curran and Pearson's (1971) average soundings for thundersnow (from Curran and Pearson 1971).

Another major factor in assuming that most thundersnow occurrences in the U.S. are associated with fronts is that nearly all thunderstorms East of The Rockies and North of Florida in the winter are elevated (Colman 1990a). Colman also found that a diurnal variation exists in winter thunderstorms (458 at 0000 UTC, 635 at 1200 UTC). This variation shows that the low-level jet could be a major factor in the formation of thundersnow/ice since the LLJ is enhanced during the nighttime hours.

In summary, previous studies have shown that the Midwest has the highest frequency of thundersnow occurrences. Holle and Watson (1996) also found that a strong southwesterly flow, hence the LLJ, exists in the above freezing layer between 800 mb and 700 mb with these storms. The significance of the strong low-level flow will be one of the major factors in the current research.

2.2) Summary

Low-level shear, different types of hydrometeors, and the creation of graupel may be the most important ingredients for thundersnow. Physically proving these will be nearly impossible for this thesis since observing clouds that produce thundersnow is not possible. Support can be found that low-level shear plays a role by statistically showing the association of shear as a factor. Showing the presence of sub-freezing and super-freezing air within the cloud can show the different types of hydrometeors. Graupel, on the other hand, will be next to impossible to prove as a factor because it may be occurring in between stations or in between observations. Since the graupel may be falling out just to the south of the lightning zone, it may not be reported with the thundersnow observation. Again, based on previous research and the preliminary observations in the current research, these two factors appear to be necessary ingredients for thundersnow.

III. Methodology

This thesis is more qualitative than quantitative due to the lack of accurate numerical data and the fact that the goal of this thesis is to find the physical mechanisms associated to thundersnow and thunder with ice. Some statistics are used for showing the dependency (chi-squared test) of certain mechanisms to lightning generation and trying to find a surface temperature correlation for thundersnow. In terms of the rest of the thesis, most of it is qualitative in the sense that upper air maps, radar data, and visual comparisons are the main sources of the data analysis. This section will examine the process that was used in searching for the mechanisms for thundersnow.

3.1) Overview

Again, this thesis was mainly a qualitative thesis. Since no one has done a comprehensive thundersnow study over land, all of the data had to be found via surface observations from AFCCC reports, or by searching for them on over two-dozen compact discs full of 100's of charts each. Though a lengthy process, finding the cases was easy once a strategy was developed. In terms of choosing the mechanisms to be studied, a hypothesis for the main physical mechanisms for vertical velocity had to be found. With the belief that the low-level jet stream or low-level flow had something to do with thundersnow, several hypotheses were made. When noticing that that the difference between the low-level flow and the surface wind was low-level wind shear, the idea for categorizing shear took place. After reading Kocin and Uccelleni's (1990) work and seeing a pattern of diffluence at upper-levels, the idea then was to classify diffluence. After noticing speed divergence, and in some cases, the presence of Uccellini's jet stream circulations, the plan switched to overall divergence instead of diffluence. When noticing that most events occurred near the rain-snow line, the idea to examine temperature effects was added. Finally, other less comprehensive tests involving the precipitable water values and the vertical soundings were done to see any other possible correlations of physical processes.

3.2) Data

Most of the data used in this study are in the form of daily lightning plots, surface observations, radar images, the surface analyses, upper air analyses, radar depictions, skew-T maps, and precipitable water maps. The process of finding the data and analyzing it was the most tedious part of this thesis.

3.2.1) Collecting the Data

The first part in this process was developing a plan for gathering occurrences of thundersnow. Since several influences from terrestrial effects are likely, the sites for which the data were to be collected was divided into three regions: East Coast, Midwest, and Rocky Mountains. From these regions (A-Atlantic region, M-Midwest region, Mtns-Rocky Mountains), bases from each were chosen to get a good representation for each region. The Air Force bases selected were Hanscom (A), Andrews(A), McGuire(A), Wright-Patterson(M), Scott(M), Offutt(M), Tinker(M), Grand Forks(M), Hill(Mtns), and Peterson(Mtns). After deciding which bases to use, AFCCC (Air Force Combat Climatology Center) searched for all observations at these locations of thunder with a temperature at or below 37° F with the hope of finding at least 20 occurrences (time and date) of thundersnow and ice with thunder. The idea was also to gather a few cases of rain at low temperatures to see if there is a difference in the lightning mechanisms between the different precipitation types. After gathering the times and dates, the next step was to use them to gather the charts and radar data from websites <weather.unisys.com/archive> and <www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwnexrad~images2>. AFCCC also sent 72 compact discs (24 months) from NCDC (National Climatic Data Center) which had the surface maps, upper air charts, composite moisture/precipitable water charts, and radar summaries. Because these CDs had more and better quality surface analyses than those archived at the website, they were used as the predominant source of information (the website was used only when the 00 UTC or 12 UTC surface chart was missing).

After obtaining the synoptic data, the next task was to write a computer program (Appendix A) to plot the cloud-to-ground lightning strikes. These plots were used to find more cases of thundersnow and lightning during freezing precipitation events. By examining the location of the lightning strikes across the country each day, any day that had lightning in snow prone areas was noted. Next, the synoptic charts and radar mosaics were examined for those days in conjunction with the locations of the lightning. From examining the temperatures and precipitation types on the surface analyses for the lightning area using the radar loop as the time basis for when the lightning happened, the cases were then selected for future study. Figure 9 shows an example of the lightning plots.

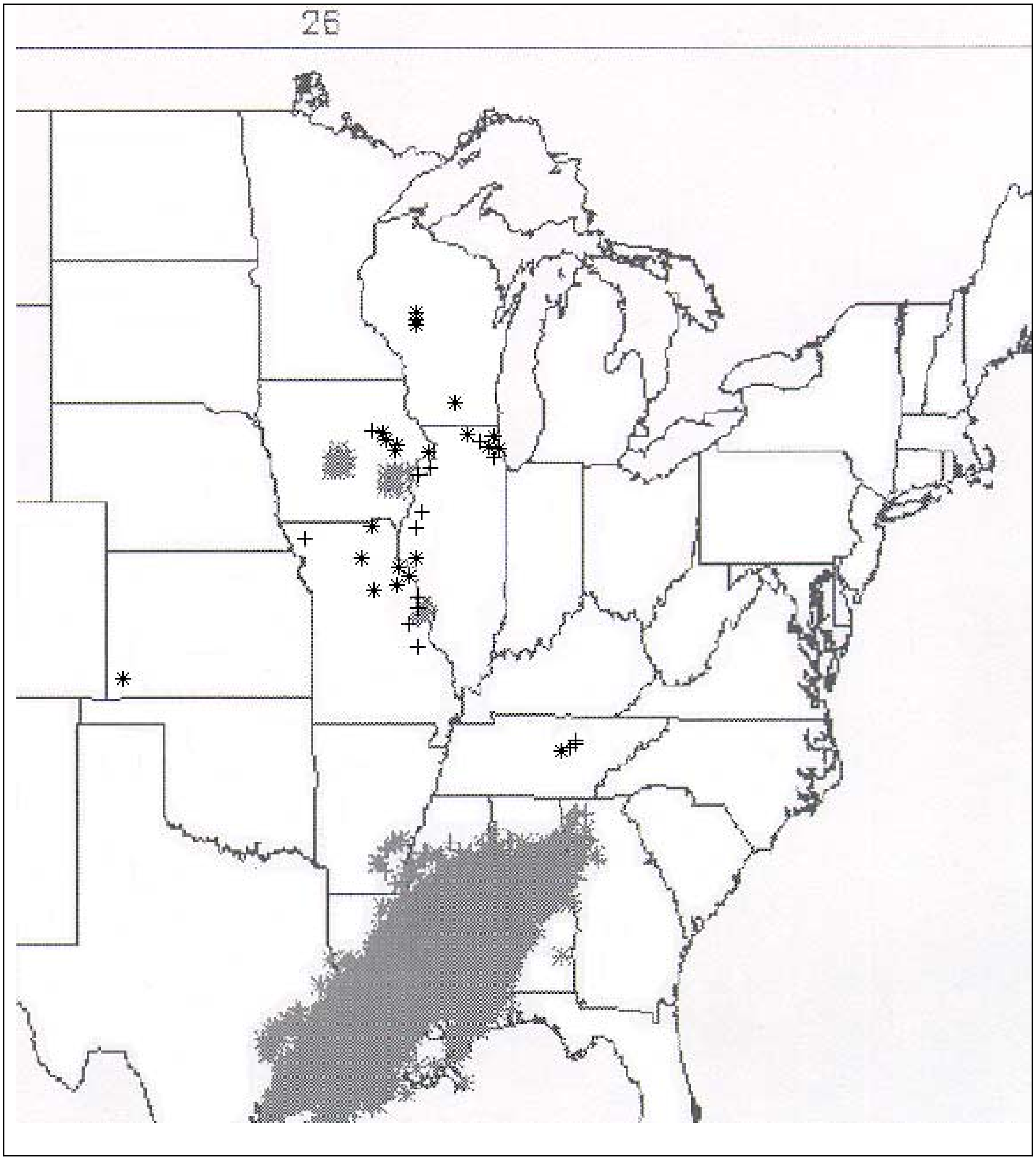

Figure 9. A daily lightning plot used for disseminating locations of cloud-to-ground flashes (asterisk denotes negative flash, plus sign denotes positive flash). The lighter shades indicate dense regions of lightning strikes. This example is the lightning data for 26 January 1996.

To find the no lightning cases, every 00 UTC and 12 UTC surface synoptic chart was scanned in the location of the storm where thundersnow is prone (see Figure 12 in

Chapter 4 for the prone areas) and for stations reporting moderate or heavy precipitation within the thundersnow-prone zone. The only difficulty with this process was determining the intensity of freezing rain since it has only one surface symbol for all intensities (except for freezing drizzle). For those cases, the radar loop was used to judge the intensity. The times and dates were then recorded for future study.

For the temperature correlation, more data were requested from AFCCC to include the temperature at the surface, dew point, wind, and remarks. Since many of these are from before 1995, only a few (the occurrences after 1994) were added to the low-level shear study.

Finally, the skew-T's were examined for any possible correlation of the -10º C level and to examine the intensity of the low-level temperature inversion. Since many processes can occur over a few hours that could greatly change the vertical sounding, only those within an hour were taken. Also, since low-level horizontal temperature gradients along fronts tend to be strong, only the sites that archived vertical soundings were used.

3.2.2) Analyzing the data

Once all of the data were collected, they were studied for any synoptic patterns. One of the first patterns noticed was a strong area of convection in certain locations of the storm in the form of embedded thunderstorms within stratiform precipitation (Appendix C). Finding the causes for this convection should help to find the mechanisms for thundersnow. After reading a few more articles about processes in major winter storms, the hypotheses began to unfold as evidence for them were presented. The articles and theories also stimulated a few ideas as to some possible mechanisms, and a synthesis of the knowledge unfolded.

The next tasks were to examine the divergence at the 300 mb level and the vertical wind shear between the surface wind and the 850 mb wind above the surface observation. Every 850 mb and 300 mb chart was examined for the intensities of low-level shear and upper-level divergence. The shear for each case was calculated empirically by taking the velocity difference from the surface wind and the 850 mb level wind as seen in Figure 10, then classified into weak (<25 knots), moderate (25-39 knots) and strong (40+ knots) categories.

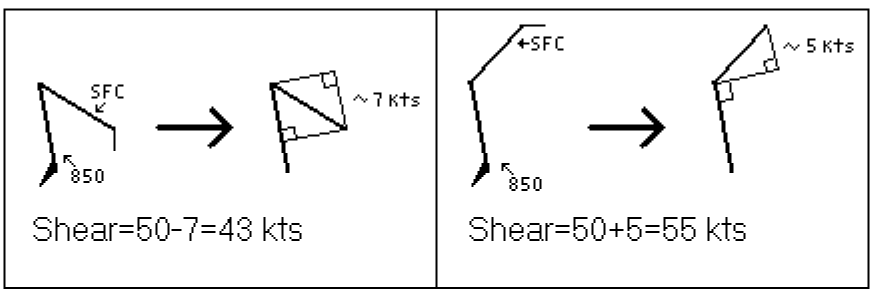

Figure 10. Empirically calculating low-level wind shear. By subtracting the component of the surface wind that is in the same direction as the 850 mb wind to the 850 mb wind, a close approximation to the shear is determined. In this case on the left side, the 10 kt wind at the surface has a component in the 850 mb wind's direction of about 7 kts. If the surface wind opposes the direction as seen on the right side, the component is added since subtracting a negative number is equal to adding a positive number.

To estimate a divergence, a ratio proportionate to divergence was calculated using the differences in velocity both along the path and normal to the path. Divergence is measured in units of 1/second. In this study, the measurement is in knots because the distances between wind measurements were not calculated (the distances between wind measurements are close enough to each other east of the Rocky Mountains to assume them approximately the same). Therefore, a measurement proportional to divergence, which be called divergence for the sake of this study, will be approximated by adding the components of speed change in the direction of flow and the speed change normal to the flow (Figure 11). The divergence cases were calculated empirically by finding the diffluent part and speed divergent part of the 300 mb (shown in Figure 13) wind then classified in to weak (<20 knots over a 250 km radius), moderate (20-29 knots over a 250 km radius), and strong (30+ over a 250 km radius) categories. The major difficulty associated with classifying divergence is the subjectivity imposed by estimating the intensity of divergence and the distance between observations. Mechanisms like jet streak circulations, curvature around a trough, and entrance regions to jet streaks contribute to divergence. Any case that observed one of these but did not have 20+ knots of divergence over a 250 km radius (roughly the distance between observations) was classified into the weak category.

After concluding that the mountainous regions have other local terrestrial factors that help to create strong lift, all cases in the mountainous areas were discarded. Also, any case with uncertainty as to when it produced lightning (e.g. if heavy rain moved through a lightning area in the morning but changed to snow in the afternoon, or if the temperature was above 37 degrees during the questionable period) was thrown out.

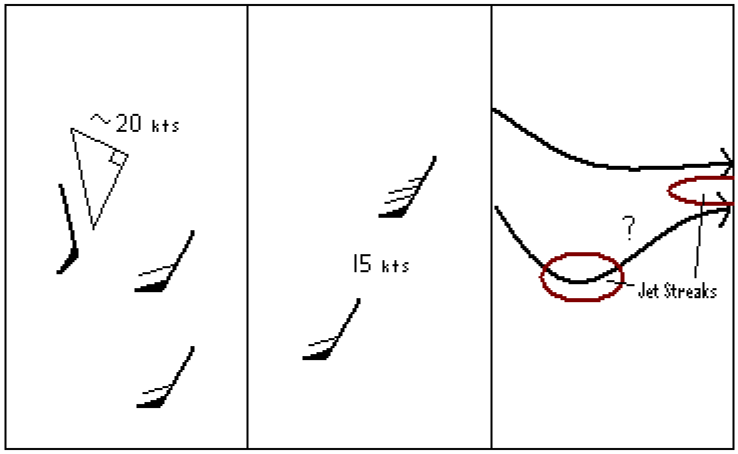

Figure 11. Empirically calculating the divergence for this study (in knots for this study). The left side shows the diffluent part where the divergent speed is approximately calculated by trigonometry by finding the component normal to the main flow. The speed divergence (middle) was calculated by the difference in wind speed in the same direction as the mean flow. The right side shows the divergence associated with a jet streak and the divergence of the jet streak circulations. The calculation for a jet streak circulation was not possible.

With so many charts gathered for each case, the idea was then to superimpose everything onto one map for each case. This would have helped to show the processes involved with each storm, but after determining that superimposing hundreds of maps and charts would not be worth the time invested considering their significance toward the solution, the idea to draw the generalized storm structures was used. With a strong similarity shown between the storm structures in most of the cases, the main causes for thundersnow/ice over land can be better studied. When learning about a website that shows the vertical soundings for the cases, the focus then was to see a few examples of vertical profiles and support Curran and Pearson's (1971) study.

3.2.3) False Alarm Cases

Since thundersnow/ice only developed within certain locations in a mesoscale storm, the plan for finding the false alarm cases (those cases similar in storm structure, but with no lightning) was fairly simple. The radar loop (taken once every 24 hours) over the winter months helped to show most meso-scale systems throughout the winter months. To find the most cases possible, each 00 UTC and 12 UTC surface map was analyzed to find any moderate or heavy precipitation events. From finding several storms, a good estimation of the occurrences of thundersnow/ice verses non-occurrences with similar conditions should be found. These false alarm cases were categorized according to their structure and the precipitation type that occurred in the areas within the storm similar to the lightning cases.

3.2.4) Analyzing the Results

Once all of the cases were found, they were all categorized by their low-level wind shear intensity, divergence intensity, and storm's mesoscale structure. The lightning cases were then compared to the non-lightning cases using a chi-squared dependency test. This test shows the dependency of lightning to wind shear or divergence. The only limit to this test is the small number of cases.

In order to alleviate the problem of having too few cases, and in order to verify the results, additional months were thoroughly examined into a follow up study for more cases of thundersnow, ice with thunder, and moderate/heavy snow/ice events without lightning. A second chi-squared test was done on the new cases to compare the results to the first data set to support the results of the first test. The tests should have similar results between the two of them if the data is consistent. If the tests have different results, then questions would arise about the data consistency (a bogus set of data). After the comparison was done, the data sets were combined for the final tally and the final chi-squared test was done.

To show the significance of the surface temperature to lightning generation, the raw surface observation data from AFCCC were categorized into temperature categories of 1 degree Fahrenheit bins. This study was done with the belief that different types of hydrometeors interact within the cloud (i.e., the cloud's particles are not all snow or ice crystals) to produce the charge separation necessary for lightning. This test could also show that the temperature is close to or at freezing symbolizing the close proximity of the rain-snow line and the presence of the melting layer, thus, different hydrometeors.

3.3) Other Work Done

To check some other physical mechanisms in the cloud that may correlate to lightning, the significance of the -10° C level was examined. In typical air mass thunderstorms, that level marks the average temperature where cloud charge reverses and where graupel's charge reverses. For a winter thunderstorm, this may not be the case since some storms' cloud tops are near or below that level. A small sample of vertical temperature soundings taken from the webite <www-das.uwyo.edu/upperair/sounding.html> were recorded and examined to find the pressure level at -10° C. The idea was then dropped since only a few cases would be able to be examined at or near the 00 UTC and 12 UTC times to show any correlation of the -10° C level. Also, Curran and Pearson's (1971) average sounding had the -10° C temperature at the 635 mb level, and since they had the average of 76 cases of thundersnow (well more than the ten soundings used for this study), pursuing the -10° C level study would have wasted valuable time in this study.

The idea of available moisture was also studied as one of the possibilities for a thundersnow/ice mechanism. Since more moisture means more or larger particles, the idea had some relevance to this topic. The composite moisture/precipitable water maps in the compact discs were examined to see the difference in available moisture of lightning producing and non-lightning events. A chi-square test was done to check for dependency.

3.4) Summary

This thesis was mainly a qualitative thesis. Since no one has done a comprehensive thundersnow study over land, all of the data had to be found via surface observations from AFCCC reports or by searching for them on 27 compact discs full of 100's of charts each. Though a lengthy process, finding the cases was easy once the strategy was developed. After scanning over 1000 maps, patterns were noticed and recorded. The results found from the data analysis are found in the next chapter.

IV. Results and Analysis

In order to show a synoptic pattern, the data were examined and categorized into bins of low-level wind shear intensity, upper-level divergence intensity, and a combination of both. Other aspects examined in this section are the temperature correlation to lightning, the vertical soundings of some cases, and the examination of the precipitable water. The low-level shear study was done in two separate studies (Trial 1 and Trail 2). The data used in Trial 1 were based on the months of data used early in the study, while the data used for Trial 2 were based on the monthly data obtained later in the study (see Tables 4 and 9 for the months for each trial). The divergence study was included in the first Trial because it was done with the monthly data used in the Trial 1 low-level shear study.

4.1) Low-level Shear and Upper-level Divergence

4.1.1) Trial 1

The data from Trial 1 is classified into low-level shear and upper-level divergence categories. The frequency distribution is shown in Table 2.

From Table 2, there appears to be a difference in the shear categories between the lightning and no-lightning cases. The lightning producing cases for each fall into the strong categories more frequently than the weak categories, whereas, the non-lightning cases have more in the weak categories than the strong. With the divergence cases, there appears to be a difference in that the non-lightning producing cases have higher percentages of weak divergence with each precipitation type. Though, with many complications in calculating the divergence accurately have forced the author to discontinue the research in the divergence aspect of this thesis. In Table 3, the combination of the low-level wind shear and upper-level divergence for each case is categorized.

Table 2. Categorized low-level shear and upper-level divergence data from Trial 1.

	Wk div (0-20 kts)	Mod div 20-29 kts	Stg div (30+ kts)	Wk shear (0-25 kts)	Mod shear 25-39 kts	Stg shear (40+ kts)
Snow w/ lightning	**3**	**7**	**3**	**0**	**7**	**6**
Ice w/ lightning	**10**	**9**	**3**	**1**	**9**	**12**
Rain w/ lightning	**7**	**10**	**8**	**2**	**11**	**12**
Snow wo/ lightning	**21**	**6**	**6**	**23**	**8**	**2**
Ice wo/ lightning	**13**	**6**	**0**	**7**	**9**	**3**
Rain wo/ lightning	**8**	**4**	**4**	**6**	**3**	**7**

Table 3. Combined low-level shear and upper-level divergence for Trial 1.

	Wk div + Wk Shear	Wk Div + Mo Shear	Wk Div + St Shear	Mo Div + Wk Shear	Mo Div + Mo Shear	Mo Div + St Shear	St Div + Wk Shear	St Div + Mo Shear	St Div + St Shear
Snow w/ Lightning	**0**	**2**	**1**	**0**	**5**	**2**	**0**	**0**	**3**
Ice w/ Lightning	**1**	**4**	**5**	**0**	**5**	**4**	**0**	**0**	**3**
Rain w/ Lightning	**0**	**6**	**1**	**2**	**3**	**5**	**0**	**2**	**6**
Snow wo/ Lightning	**15**	**5**	**1**	**5**	**1**	**0**	**3**	**2**	**1**
Ice wo/ Lightning	**5**	**6**	**2**	**2**	**3**	**1**	**0**	**0**	**0**
Rain wo/ Lightning	**4**	**2**	**1**	**1**	**1**	**3**	**1**	**1**	**2**

The data do not appear to show a direct correlation between shear and divergence, but factors such as strong, mature storms having larger magnitude features (i.e., both shear and divergence will be strong) than clipper systems (which tend to have little upper-level support) may skew the data. The 14 cases in the weak-weak category for snow show that these storms may be small clipper systems, which would skew the results.

The following table (Table 4) represents the shear(weak <25 knots, moderate 25-40 knots, strong >40 knots), divergence (weak <20 knots difference over 250 km, moderate 20-30, strong >30) and storm type classifications for each event that had at least two cloud-to-ground flashes of lightning. Refer to Appendix B for state abbreviations.

Table 4. Categorized data for the lightning producing events for Trial 1.

Date	Location	Precip Type	Shear	Divergence	Storm Type
6 JAN 95	AR	Ice	Strong	Weak	2
17 JAN 95	MN	Snow	Strong	Moderate	3,5
19 JAN 95	MO	Snow	Moderate	Moderate	5
28 JAN 95	MO	Rain	Moderate	Strong	3
4 FEB 95	NJ	Snow	Strong	Strong	5
14 FEB 95	AR	Ice	Strong	Moderate	3
24 FEB 95	WV	Rain	Moderate	Weak	4
26 FEB 95	IA	Ice	Strong	Weak	3
10 APR 95	NE	Ice	Strong	Strong	3,5
10 APR 95	MI	Snow	Strong	Moderate	3
1-2 FEB 96	AR	Ice	Strong	Moderate	3,4
23 FEB 96	MI	Ice	Strong	Strong	3
26 FEB 96	MN-WI	Ice	Moderate	Weak	3
27 FEB 96	OK-KS	Ice	Moderate	Weak	4
3 MAR 96	WV	Snow	Moderate	Weak	4
5 MAR 96	IA	Rain	Strong	Strong	3
7 MAR 96	KY	Rain	Moderate	Weak	3,4
21 MAR 96	MN	Ice	Strong	Weak	3
25 MAR 96	IA	Rain	Strong	Strong	3

Table 4 (cont.)

Date	Location	Precip Type	Shear	Divergence	Storm Type
27 MAR 96	TX	Ice	Moderate	Moderate	None
8 DEC 96	ME	Rain	Strong	Moderate	2
11 DEC 96	IN	Rain	Strong	Moderate	3
14 DEC 96	SD	Snow	Moderate	Moderate	3
15 DEC 96	MN	Snow	Moderate	Moderate	1
27 JAN 97	MO	Ice	Strong	Weak	3
26 OCT 97	NE	Snow	Strong	Strong	1
9 DEC 97	KS	Rain	Moderate	Weak	1
9 DEC 97	TN	Ice	Weak	Moderate	3
10 DEC 97	MO	Rain	Moderate	Weak	1,2
24 DEC 97	MO	Rain	Moderate	Strong	5
25 DEC 97	ME	Ice	Strong	Weak	2
30 DEC 97	NJ	Rain	Moderate	Moderate	5
4 JAN 98	OK	Rain	Strong	Strong	4
5 JAN 98	OK	Ice	Moderate	Moderate	4
9 JAN 98	VT	Ice	Moderate	Moderate	2
15 JAN 98	MO	Rain	Moderate	Moderate	4
22 JAN 98	OK	Rain	Weak	Moderate	4
25 FEB 98	ND	Rain and GR	Strong	Strong	1
1 JAN 99	MO	Ice	Moderate	Moderate	3
2 JAN 99	AR	Rain	Strong	Strong	3,5
3 JAN 99	NY	Ice	Strong	Strong	1
3 JAN 99	NC	Ice	Strong	Moderate	2
8 JAN 99	AR	Ice	Strong	Weak	3,4
13 JAN 99	MO	Ice	Weak	Weak	3,4
22 JAN 99	IL	Rain	Moderate	Moderate	3
29 JAN 99	TX	Snow	Moderate	Moderate	3,5
31 JAN 99	MO	Rain	Strong	Strong	2
8 FEB 99	MN	Ice	Moderate	Moderate	2
11 FEB 99	NE	Rain + SN	Strong	Moderate	4
11 FEB 99	IA	Snow + ZR	Strong	Weak	5,4
26 FEB 99	IA	Rain	Moderate	Weak	2
27 FEB 99	OH	Rain	Moderate	Weak	2
6 MAR 99	MI	Snow	Moderate	Weak	3
7 MAR 99	KS	Ice	Moderate	Weak	3
8 MAR 99	NE	Snow	Strong	Strong	1,2
12 MAR 99	TX	Rain	Strong	Moderate	5
14 MAR 99	MO	Snow	Moderate	Moderate	1
15 MAR 99	VA	Rain	Moderate	Weak	2
22 MAR 99	VT	Rain	Strong	Moderate	2
23 MAR 99	MO	Rain	Strong	Weak	5

4.1.2) Storm Types Observed in Trial 1

After noticing a distinct pattern within the cases of thundersnow/ice of thunderstorm location relative to the storm system, the location of each thunderstorm was classified into one of the following categories seen in Figure 13.

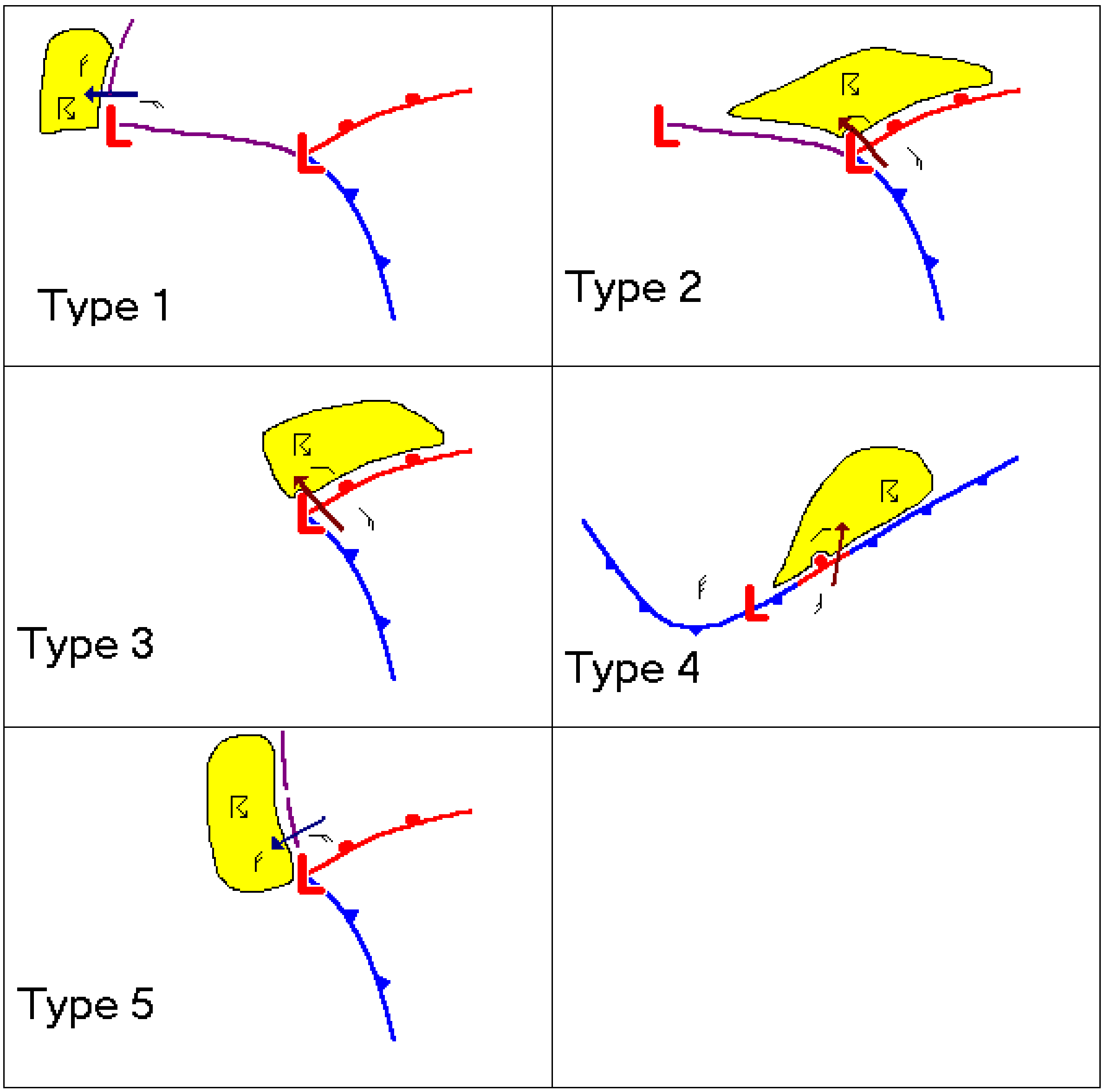

Figure 12. The five different storm structures observed for thundersnow or ice with thunder. The shaded zone denotes the area where the thunderstorm(s) occurred. The thick arrow represents the 850 mb wind, while the wind barbs indicate surface wind. The solid lines in Types One and Two denote a surface wind shift of some type.

Almost every occurrence of thundersnow or ice occurred in one of these categories in Figure 12. The similarity between these five cases is that the occurrence happened just downwind (relative to the low-level flow) on the cold side of a surface windshift. Some cases' wind shift line was a surface trough (some labeled on the synoptic chart, some not labeled) instead of a warm/occluded front, but there was an anti-cyclonic wind shift. Most of the Type 4 events were cold fronts (anafronts) where the precipitation was behind the cold front (in the cold side of the front). Some were warm or stationary fronts embedded along the cold front (very close to a Type 3), but were still labeled as a Type 4 because they did not resemble the Type 3 enough to count them as a Type 3.

Table 5 represents all of the cases that had less than two lightning strikes in the specified location of the storm (storm type) with the similar conditions found with Table 4.

Table 5. Categorized data for the no-lightning cases for Trial 1.

Date	Location	Precip Type	Shear	Divergence	Storm Type
1 JAN 95	NH	Ice	Moderate	Weak	3
7 JAN 95	ME	Ice	Strong	Weak	3
13 JAN 95	MN	Snow	Weak	Weak	5
14 JAN 95	MO	Rain	Strong	Strong	3
16 JAN 95	OH	Rain	Weak	Weak	3
21 JAN 95	ME	Rain	Strong	Strong	3
23 JAN 95	MS	Rain	Weak	Weak	3
27 JAN 95	IA	Ice	Weak	Moderate	3
29 JAN 95	MD	Snow	Weak	Moderate	2
5 FEB 95	ME	Snow	Strong	Weak	5
15 FEB 95	SD	Snow	Moderate	Weak	3
28 FEB 95	AR	Ice	Weak	Weak	3
3 FEB 96	KY	Snow	Weak	Weak	5

Table 5 (cont.)

Date	Location	Precip Type	Shear	Divergence	Storm Type
10 FEB 96	MN	Ice	Moderate	Moderate	2
11 FEB 96	ME	Ice	Strong	Moderate	2
14 FEB 96	MI	Snow	Weak	Weak	3
15 FEB 96	ME	Snow	Weak	Weak	5
16 FEB 96	MO	Snow	Weak	Weak	4
16 FEB 96	NY	Snow	Moderate	Weak	3
28 FEB 96	ME	Ice	Weak	Weak	2
1 DEC 96	KS	Snow	Weak	Weak	4
1 DEC 96	KS	Snow	Weak	Weak	4
3 DEC 96	IA	Snow	Weak	Weak	5
5 DEC 96	IA	Ice	Weak	Weak	2
5 DEC 96	IL, IN	Snow	Moderate	Strong	2
16 DEC 96	ND	Snow	Moderate	Moderate	4
17 DEC 96	ND	Snow	Weak	Weak	1
19 DEC 96	NH	Rain	Moderate	Weak	4
24 DEC 96	WI	Snow	Weak	Weak	5
28 DEC 96	IA	Ice	Weak	Moderate	3
30 DEC 96	MI	Ice	Moderate	Weak	4
31 DEC 96	IN	Rain	Moderate	Moderate	4
3 DEC 97	IA	Snow	Weak	Strong	4
6 DEC 97	ME	Snow	Weak	Strong	1
21 DEC 97	KS, OK	Ice	Moderate	Moderate	1
26 DEC 97	ME	Snow	Weak	Moderate	1
28 DEC 97	MD	Snow	Weak	Moderate	5
29 DEC 97	KY, TN	Snow	Weak	Weak	2
5 JAN 98	WI	Ice	Weak	Weak	3
15 JAN 98	IL	Snow	Weak	Moderate	3
15 JAN 98	MD	Ice	Moderate	Weak	5
21 JAN 98	IA	Snow	Moderate	Strong	3
24 JAN 98	PA	Snow	Weak	Weak	3
25 JAN 98	ME	Ice	Weak	Weak	5
28 JAN 98	MD	Rain	Moderate	Weak	5
29 JAN 98	WI	Snow	Weak	Strong	5
1 FEB 98	IA	Rain	Weak	Strong	3
12 FEB 98	ME	Rain	Strong	Moderate	3
19 FEB 98	ME	Rain	Weak	Weak	1
23 FEB 98	ND	Rain	Weak	Weak	2
24 FEB 98	PA	Snow	Weak	Weak	5
25 FEB 98	ME	Ice	Moderate	Moderate	3
28 FEB 98	MN	Snow	Weak	Weak	5

Table 5 (cont.)

Date	Location	Precip Type	Shear	Divergence	Storm Type
2 JAN 99	IN	Ice	Moderate	Weak	3
4 JAN 99	ME	Ice	Strong	Weak	2
8 JAN 99	ME	Rain	Strong	Weak	3
10 JAN 99	ME	Snow	Moderate	Weak	5
10 JAN 99	MA	Rain	Strong	Weak	4
14 JAN 99	OH	Ice	Moderate	Weak	4
16 JAN 99	ME	Rain	Strong	Moderate	2
18 JAN 99	ND	Snow	Weak	Weak	1
27 JAN 99	MN	Snow	Weak	Moderate	3
28 JAN 99	NC	Rain	Strong	Moderate	5
12 FEB 99	MN	Snow	Moderate	Weak	5
23 FEB 99	MO, NE	Snow	Moderate	Weak	3
1 MAR 99	ME	Rain	Weak	Weak	1
4 MAR 99	PA	Snow	Weak	Strong	1
9 MAR 99	OH	Snow	Strong	Strong	1

Low-level wind shear appears to be a factor for thundersnow and thunder during ice events. The chi-squared test done in Table 6 solidifies the hypothesis that low-level wind shear is a factor (in each bin, the top number is the frequency, the bottom left number is the expected value, and the bottom right number is the chi-square).

Table 6. Chi-Squared distribution for the snow cases for Trial 1. The top number is the frequency, the bottom left number is the expected value, and the bottom right number is the chi-square.

	Weak Shear	Moderate Shear	Strong Shear	Total Cases
Snow with Lightning	0 5.74, 5.74	7 4.49, 1.27	6 2.68, 4.13	13
Snow without Lightning	23 9.26, 3.55	8 7.41, 0.78	2 4.32, 2.55	33
Total Cases	23	15	8	46

Overall Chi-Square for Table 6: 20.19
P-Value: 0.0000
Degrees of Freedom: 2

The p-value of 0.0000 for Table 6 shows a strong dependency (according to a chi-square test) between wind shear and lightning in snow events. The only concern at this point is the small number of cases. If an additional case examined was a weak-shear, lightning occurring event, the p-value would then be 0.0002. If the next two cases were in that category, then the p-value would be 0.0005. To be within the confidence level of 99% (α=0.01), the next 5 cases could be weak-shear, lightning occurring events (p-value of 0.0064. Even if the next 5 cases examined are in that category, low-level wind shear appears to be a dependent factor for lightning in snow events. When examining what would happen if the next several cases were in the strong shear, no lightning category, it would be extremely unlikely to achieve a p-value of 0.01 or greater.

In order to determine if there is a difference with the conditions for thundersnow with the conditions for thunder with ice, a dependency test of low-level shear to ice events with lightning was done in Table 7.

Table 7. Chi-squared distribution for the ice cases for trial 1. The top number is the frequency, the bottom left number is the expected value, and the bottom right number is the chi-square.

	Weak Shear	Moderate Shear	Strong Shear	Total
Ice with Lightning	1 4.29, 2.53	9 9.66, 0.04	12 8.05, 1.94	22
Ice without Lightning	7 3.71, 2.92	9 8.34, 0.05	3 6.95, 2.25	19
Total	8	18	15	41

Overall Chi-Square for Table 7: 9.73
P-Value: 0.0077
Degrees of Freedom: 2

Like the snow cases, thunder with freezing rain or sleet appears to be associated with low-level wind shear (p-value of 0.0077). If the next case were a weak-shear, lightning occurring case, then the p-value would be 0.0196. If the next two were in that category, then the p-value would be 0.0386. The only concern for this result is the low number of cases in Table 7 in the ice without lightning row (19). However, the alignment of this sample is encouraging in that it follows the hypothesis of low-level shear as a factor. Finally, a dependency test of low-level shear to rain with lightning to determine how shear relates to thunder with rain was done in Table 8.

Table 8. Chi-Squared distribution for the rain cases for trial 1. The top number is the frequency, the bottom left number is the expected value, and the bottom right number is the chi-square.

	Weak Shear	Moderate Shear	Strong Shear	Total
Rain with Lightning	2 4.29, 1.22	11 10.00, 0.10	12 11.59, 0.01	25
Rain without Lightning	6 1.71, 3.05	3 4.00, 0.25	7 7.41, 0.02	16
Total	8	14	19	41

Overall Chi-Square for Table 8: 6.21
P-value: 0.0448
Degrees of Freedom: 2

With a p-value of 0.0448 for Table 8, low-level wind shear is not as associated with thunder with rain as thunder with snow. When using the 0.01 and 0.05 level of significance (99% and 95% confidence respectively), this test would reject the null hypothesis at a 0.01 level of significance, but would pass the 0.05 level of significance. Also, two events in the weak-shear with lightning category show that lightning can occur without moderate or stronger low-level wind shear. The high number of strong shear, no lightning cases show that either something else inhibits lightning when shear is present or lightning is not as dependent on shear for rain events as for snow and ice events. Overall, this still shows that low-level shear is associated with lightning in rain events, it's just not the sole or dependent factor.

4.1.3) Trail 2 Low-Level Shear Study

Since the results from the first trial for low-level shear were very successful for a small sample of cases, a second study for shear was done to verify the first study's results. The storm types are the same as the ones used in Trial 1. Table 9 shows the classifications for the lightning producing cases.

Table 9. Categorized data for the lightning producing cases for trial 2. Storm type can be seen in Figure 13.

Date	Location	Precip Type	Shear	Storm Type
2 Mar 95	TX	Ice	Weak	3
4 Mar 95	SD	Snow	Weak	3
5 Mar 95	NE	Ice	Moderate	3
7 Mar 95	MO	Rain	Moderate	4
7 Mar 95	ONT	Snow	Moderate	3
9 Mar 95	VA	Rain	Weak	5
25 Mar 95	IA	Rain	Moderate	2
27 Mar 95	WI	Snow	Moderate	3
10 Nov 95	VA	Rain	Strong	4
11 Nov 95	OK	Ice	Moderate	4
27 Nov 95	WI	Snow	Strong	3
6 Dec 95	VT	Snow	Moderate	2
19 Dec 95	MO	Snow	Moderate	5
3 Jan 96	IN, OH	Snow	Strong	1
8 Jan 96	PA	Snow	Strong	1
12 Jan 96	NC	Snow	Strong	2
12 Jan 96	PA	Snow	Moderate	5

Table 9 (cont.)

Date	Location	Precip Type	Shear	Storm Type
18 Jan 96	MN	Ice	Strong	3
23 Jan 96	MO	Ice	Weak	3
26 Jan 96	IA	Snow	Strong	3
27 Jan 96	WI	Snow	Moderate	2
16 Nov 96	MN	Rain	Strong	3
16 Nov 96	NE	Rain	Strong	4
23 Nov 96	NE	Snow	Weak	4
29 Nov 96	KS	Rain	Moderate	3
4 Jan 97	MN	Snow	Strong	1
7 Jan 97	AR	Rain	Weak	3
9 Jan 97	GA	Rain	Moderate	3
11 Jan 97	NC	Snow	Strong	4
13 Jan 97	TX	Ice	Moderate	3
15 Jan 97	LA	Rain	Strong	4
24 Jan 97	MO	Rain	Moderate	3
27 Jan 97	MO	Ice	Moderate	4
28 Jan 97	MO	Snow	Weak	4
4 Feb 97	IL	Rain	Weak	2
12 Feb 97	PA	Snow	Moderate	4
21 Feb 97	KS	Snow	Moderate	5
22 Feb 97	ME	Snow	Strong	3
5 Mar 97	OK	Rain	Moderate	4
6 Mar 97	OH	Rain	Moderate	3
9 Mar 97	IA	Rain	Strong	2
13 Mar 97	SD	Ice	Moderate	4
13 Mar 97	WI	Snow	Moderate	3
25 Mar 97	IA	Snow	Strong	3

For Table 10, the storm types are the same as the ones used in Trial 1. Table 10 represents the non-lightning producing cases.

Table 10. Categorized data for the no-lightning cases for trial 2. Storm type can be seen in Figure 13.

Date	Location	Precip Type	Shear	Storm Type
9 Mar 95	ME	Snow	Weak	3
17 Mar 95	NH	Rain	Weak	5
20 Mar 95	WI	Rain	Moderate	3
9 Nov 95	ND	Ice	Weak	3
14 Nov 95	PA	Rain	Weak	5
15 Nov 95	ME	Rain	Strong	2
18 Nov 95	MI	Rain	Weak	3
19 Nov 95	ME	Rain	Strong	2
29 Nov 95	MA	Snow	Weak	3
30 Nov 95	WI	Ice	Strong	3
2 Dec 95	ND	Ice	Moderate	1
8 Dec 95	SD	Snow	Weak	5
9 Dec 95	MD	Ice	Strong	5
10 Dec 95	ME	Snow	Moderate	2
14 Dec 95	IA	Ice	Moderate	3
14 Dec 95	MI	Rain	Strong	3
16 Dec 95	PA	Snow	Weak	3
18 Dec 95	KY	Rain	Moderate	3
20 Dec 95	ME	Snow	Weak	5
30 Dec 95	OK	Ice	Moderate	3
2 Jan 96	OK	Snow	Moderate	5
4 Jan 96	IA	Snow	Weak	3
7 Jan 96	TN	Snow	Weak	5
7 Jan 96	VA	Snow	Moderate	3
9 Jan 96	ME	Snow	Weak	1
10 Jan 96	ME	Snow	Moderate	1
13 Jan 96	MA	Ice	Moderate	3
19 Jan 96	IA	Snow	Weak	5
25 Jan 96	MN	Snow	Weak	3
28 Jan 96	SD	Snow	Moderate	3
29 Jan 96	NE	Snow	Weak	3
30 Jan 96	ME	Ice	Weak	3
31 Jan 96	SC	Snow	Moderate	4
31 Jan 96	ME	Rain	Weak	5
13 Nov 96	KS	Ice	Weak	3
17 Nov 96	ND	Snow	Moderate	5
21 Nov 96	IA	Snow	Weak	3
26 Nov 96	NY	Ice	Moderate	3
5 Feb 97	ME	Ice	Strong	2
9 Feb 97	MD	Snow	Weak	5

Table 10 (cont.)

Date	Location	Precip Type	Shear	Storm Type
14 Feb 97	VA	Ice	Strong	5
16 Feb 97	IA	Snow	Moderate	3
8 Dec 95	SD	Snow	Weak	5
9 Dec 95	MD	Ice	Strong	5
10 Dec 95	ME	Snow	Moderate	2
14 Dec 95	IA	Ice	Moderate	3
14 Dec 95	MI	Rain	Strong	3
16 Dec 95	PA	Snow	Weak	3
18 Dec 95	KY	Rain	Moderate	3
20 Dec 95	ME	Snow	Weak	5
30 Dec 95	OK	Ice	Moderate	3
2 Jan 96	OK	Snow	Moderate	5
4 Jan 96	IA	Snow	Weak	3
7 Jan 96	TN	Snow	Weak	5
7 Jan 96	VA	Snow	Moderate	3
9 Jan 96	ME	Snow	Weak	1
10 Jan 96	ME	Snow	Moderate	1
13 Jan 96	MA	Ice	Moderate	3
19 Jan 96	IA	Snow	Weak	5
25 Jan 96	MN	Snow	Weak	3
28 Jan 96	SD	Snow	Moderate	3
29 Jan 96	NE	Snow	Weak	3
30 Jan 96	ME	Ice	Weak	3
31 Jan 96	SC	Snow	Moderate	4
31 Jan 96	ME	Rain	Weak	5
13 Nov 96	KS	Ice	Weak	3
17 Nov 96	ND	Snow	Moderate	5
21 Nov 96	IA	Snow	Weak	3
26 Nov 96	NY	Ice	Moderate	3
5 Feb 97	ME	Ice	Strong	2
9 Feb 97	MD	Snow	Weak	5
14 Feb 97	VA	Ice	Strong	5
16 Feb 97	IA	Snow	Moderate	3
26 Feb 97	TX	Ice	Weak	4
7 Mar 97	ME	Snow	Moderate	1
8 Mar 97	NY	Snow	Moderate	3
10 Mar 97	MA	Snow	Moderate	2
14 Mar 97	MI	Ice	Weak	3
22 Mar 97	ME	Snow	Moderate	3
31 Mar 97	PA	Rain	Weak	5

As with the first trial, chi-squared dependency tests were done to find the dependency of low-level shear with the precipitation types. Tables 11, 12, and 13 represent the tests for dependency using a chi-squared distribution (where the bold number represents the number of cases, the second number represents the expected value, and the last number represents the chi-square).

Table 11. Chi-squared distribution for the snow cases for Trial 2 where the bold number represents the number of cases, the second number represents the expected value, and the last number represents the chi-square.

Snow	Weak Shear	Moderate Shear	Strong Shear	Total
Lightning	**3**, 7.76, 2.92	**9**, 9.13, 0	**9**, 4.11, 5.82	21
No Lightning	**14**, 9.24, 2.45	**11**, 10.87, 0	**0**, 4.89, 4.89	25
Total	17	20	9	46

Overall Chi-Square for Table 11: 16.09
P-Value: 0.0003
Degrees of Freedom: 2

This test (Table 11) once again shows a strong association with low-level wind shear with a p-value of 0.0003. With both Trials for snow passing with impressive results, low-level shear appears to be strongly associated for lightning development.

Table 12. Chi-squared distribution for the ice cases for Trial 2 where the bold number represents the number of cases, the second number represents the expected value, and the last number represents the chi-square.

Ice	Weak Shear	Moderate Shear	Strong Shear	Total
Lightning	**2**, 2.18, 0.02	**5**, 4.00, 0.25	**1**, 1.82, 0.37	8
No Lightning	**4**, 3.82, 0.01	**6**, 7.00, 0.14	**4**, 3.18, 0.21	14
Total	6	11	5	22

Overall Chi-Square for Table 12: 1.00
P-Value: 0.6080
Degrees of Freedom: 2

This test fails due to a high value of p and because there are too few cases rendering it invalid (Table 12). Even with the few cases categorized as they are, many doubts about low-level shear being a dependent factor for thunder with ice arise, especially when the small sample works against the previous trial and the hypothesis. A suggestion for why there is a difference for ice as for snow will be discussed later on.

Table 13. Chi-Squared distribution for the rain cases for Trial 2 where the bold number represents the number of cases, the second number represents the expected value, and the last number represents the chi-square.

Rain	Weak Shear	Moderate Shear	Strong Shear	Total
Lightning	**3**, 4.80, 0.67	**7**, 5.40, 0.47	**5**, 4.80, 0.01	15
No Lightning	**5**, 3.20, 1.01	**2**, 3.60, 0.71	**3**, 3.20, 0.01	10
Total	8	9	8	25

Overall Chi-Square for Table 13: 2.89
P-value: 0.2353
Degrees of Freedom: 2

Like the ice's second trial, this test (Table 13) lacks a sufficient number of cases to show anything. With this one, the results did follow the first trial, but just not as closely as the snow events' results.

4.1.4) Combined Analysis

Since the biggest problem during the two trials was having an insufficient number of cases, the trials were combined into one set for each precipitation type. The chi-squared test for each are done in the Tables 14, 15, and 16.

Table 14. Chi-squared distribution for the snow cases for both trials where the bold number represents the number of cases, the second number represents the expected value, and the last number represents the chi-square.

Snow	Weak Shear	Moderate Shear	Strong Shear	Total
Lightning	**3**, 14.78, 9.39	**16**, 12.93, 0.73	**15**, 6.28, 12.10	34
No Lightning	**37**, 25.22, 5.51	**19**, 22.07, 0.43	**2**, 10.72, 7.09	58
Total	40	35	17	92

Overall Chi-Square for Table 14: 35.24
P-Value: 0.0000
Degrees of Freedom: 2

Overall, low-level wind shear appears to be a mechanism for thundersnow. So far, no evidence suggests otherwise and a p-value of 0.0000 from Table 14 is rather convincing. Final conclusion: Low-level shear is strongly associated with thundersnow.

Table 15. Chi-squared distribution for the ice cases for both trials where the bold number represents the number of cases, the second number represents the expected value, and the last number represents the chi-square.

Ice	Weak Shear	Moderate Shear	Strong Shear	Total
Lightning	**3**, 6.67, 2.02	**14**, 13.81, 0	**13**, 9.52, 1.27	30
No Lightning	**11**, 7.33, 1.83	**15**, 15.19, 0	**7**, 10.48, 1.15	33
Total	14	29	20	63

Overall Chi-Square for Table 15: 6.28
P-Value: 0.0433
Degrees of Freedom: 2

Overall, low-level wind shear appears to be a strong factor, but something else also appears to play a role in inhibiting or producing lightning in the clouds that spawn freezing rain or sleet. The only explanation is that the freezing level must extend above the zone of maximum vertical shear and vertical velocity resulting in mostly liquid droplets as the colliding particles, which would reduce lightning generation. Figure 13 shows a visual idea of what may be happening. Final conclusion: Low-level shear is associated with thunder during ice events.

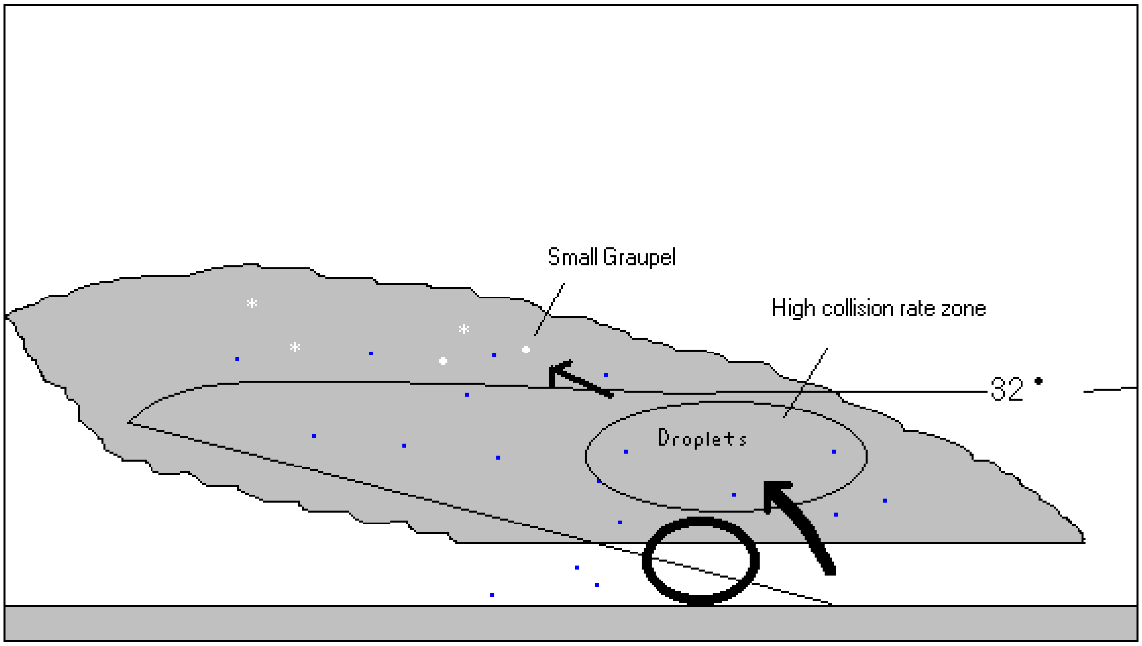

Figure 13. Schematic view of a cloud with a higher altitude level of freezing. The thick circle represents a vorticity tube formed by shear. The freezing line is drawn in to show the temperature profile of the stratiform cloud over the warm front. The thick arrows represent flow around the vortex tube.

Table 16. Chi-squared distribution for the rain cases for both trials where the bold number represents the number of cases, the second number represents the expected value, and the last number represents the chi-square.

Rain	Weak Shear	Moderate Shear	Strong Shear	Total
Lightning	**5**, 9.70, 2.28	**18**, 13.94, 1.18	**17**, 16.36, 0.02	40
No Lightning	**11**, 6.30, 3.50	**5**, 9.06, 1.82	**10**, 10.64, 0.04	26
Total	16	23	27	66

Overall Chi-Square for Table 16: 8.84
P-Value: 0.0120
Degrees of Freedom: 2

Overall, like the ice cases, shear appears to be a factor for lightning production in rain with temperatures between 33 and 37 degrees. In Table 16, the number of strong shear cases that do not produce lightning is too high to suggest that shear plays the dominant role. Again, the height of the freezing level may be a strong inhibiting factor for this precipitation type as well as seen in Figure 13. The shear between 700 mb and 850 mb may be something to examine during future work. Final conclusion: Low-level shear is slightly associated with lightning production during rain events with a surface temperature 37° F or colder.

4.2) Temperature Correlation

The following histograms (Figure 14) show the temperatures for the precipitation types while thunder occurred. The snow histogram is for all snow events (showery, intermittent, or continuous) and the ice histogram is for all ice and hail events (freezing rain/drizzle, sleet, snow pellets, graupel, or mixed). The freezing rain is less on the above freezing side of the 32° F because freezing rain needs either subfreezing air or a subfreezing ground temperature.

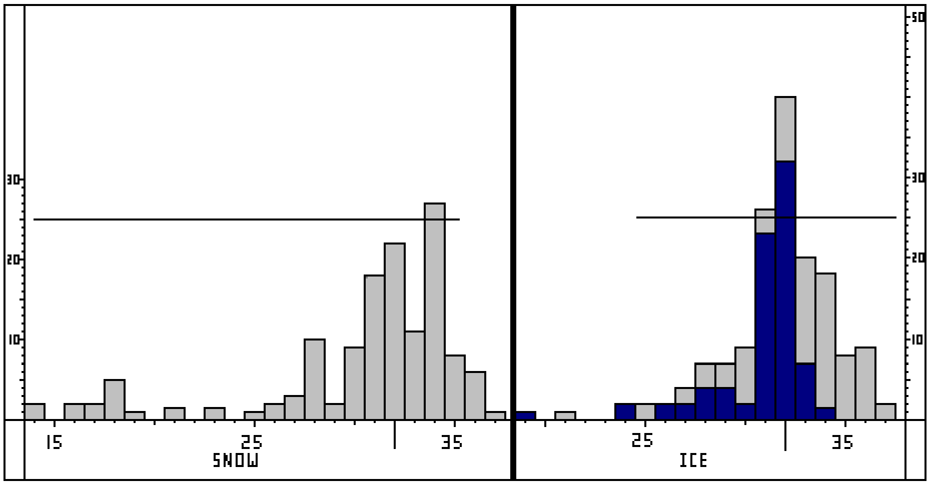

Figure 14. Temperature histograms for snow (left) and ice (right) with thunder occurrences. For ice, the dark shade denotes freezing rain, while the light shade denotes sleet. The 25 occurrences line is superimposed on the charts.

The overall synopsis is that lightning tends to be more frequent with increased temperature regardless of precipitation type. The frequency with temperatures above freezing drops because frozen precipitation normally does not occur in temperatures too warm to support it. All histograms seem to support such a notion (Figure 14). This helps to show that the melting layer is present for almost every case and that moisture levels are higher in magnitude.

Observing the snow cases finds a maximum of occurrences near the freezing point at the surface (Table 17). This is helpful in showing that wet snow is present. Also, this sample has the statistical mode at 34° F at the surface for snow, which indicates a wet snow is falling. For this sample, 78 of the 137 cases (57%) occurred when the temperature was between 30° and 34° F. Most cases occurred when the temperature was at or above 30° (93 of 137 or 68%). Table 17 shows the frequency of thundersnow temperatures.

Table 17. Frequency distribution of the thunder-temperature data for snow. The highest frequency is in bold.

Temperature °(F)	Frequency	Cumulative Percentage
37	1	0.7
36	6	5.1
35	8	10.9
34	**27**	30.7
33	11	38.7
32	22	54.7
31	18	67.9
30	9	74.5
29	3	76.6
28	10	83.9
27	3	86.1
26	2	87.6
25	1	88.3
24	0	88.3
23	2	89.8
22	0	89.8
21	2	91.2
20	0	91.2
<20	12	100

For ice with thunder, the same temperature regime took shape. Table 18 shows the statistical mode occurring at 32° F with 40 occurrences (over 25% alone). The numbers above 32° F are lower simply because freezing rain (the most frequent of the icy precipitation) is not a precipitation typically observed with a surface temperature above freezing. There are a couple freezing rain observations that are observed above freezing, but for freezing rain to occur at these temperatures, the ground must be below freezing. For the ice though, 98.7% occurred above 23° F which is not as significant considering that freezing rain and sleet rarely occur below that temperature, however, that number is most likely a higher percentage than the percentage of freezing rain/sleet occurrence without lightning below 24° F.

Table 18. Frequency distribution of the thunder-temperature data for ice. The highest frequency is the bold number, and the temperatures of the two <24º F cases are in parentheses.

Temperature °(F)	Frequency	Cumulative Percentage
37	2	1.3
36	9	7.0
35	8	12.0
34	18	23.4
33	20	36.1
32	**40**	61.4
31	26	77.8
30	9	83.5
29	7	88.0
28	7	92.4
27	4	94.9
26	2	96.2
25	2	97.5
24	2	98.7
<24	2 (21°, 19°)	100

Overall, for all thunder occurrences at or below 37° F, the frequency distribution in Table 19 looked the same as seen in Table 18, which is for all occurrences of thunder regardless of precipitation falling or precipitation type. Once again, the mode is above freezing at 34° F (224 cases or 20.3% of all occurrences). An interesting thing to note is the relative minima that occur in the data (Table 19) at 35º F and 33º F. This is probably due to some temperature readings being recorded in Celsius then converted over to Fahrenheit. This would mean that the all 0° C would convert to 32° F, all 1° C would convert to 34° F, all 2° C would convert to 36° F, and all 3° C would convert to 37° F. Notice that 33° F and 35° F are not represented. When examining the frequency distributions, all three have a relative minimum at these temperatures. That may explain the maxima and minima that occur within the data.

Table 19. Frequency distribution for the thunder-temperature data for all events. The highest frequency is in bold.

Temperature °(F)	Frequency	Cumulative Percentage
37	39	3.5
36	212	22.8
35	177	38.8
34	**224**	59.1
33	116	69.6
32	114	80.0
31	65	85.9
30	37	89.2
29	24	91.4
28	24	93.6
27	16	95.0
26	9	95.8
25	4	96.2
24	5	96.6
23	5	97.1
22	1	97.2
21	4	97.6
20	2	97.7
<20	25	100

4.3) Upper Air Soundings

In order to find the -10° C level, which is considered to be a significant level, a small sample of upper air soundings were observed. The temperature profiles for the cases are in Table 20 where bold numbers represent 0°C or warmer temperatures and the numbers in italics represent the level of the -10° C temperature.

Table 20. Vertical sounding data for ten cases with the -10° C level in italics, and the freezing or warmer temperatures (in Celsius) highlighted in bold script. The pressure levels are along the top row (from 950 mb-500 mb), and the precipitation type is in the fifth column (RA for rain, SN for snow).

	dd	m	yy	Pcp	950	900	850	800	750	700	650	600	550	500	*-10*
KS	11	4	97	RA	**0**	**7**	**4**	**1**	**1**	-2	-4	-7	-13	-17	*575*
KS	4	1	98	Ice	-7	**5**	**8**	**6**	**3**	-2	-5	-10	-13	-18	*580*
KS	8	3	99	RA	-2	-3	-1	**4**	**3**	**0**	-3	-7	-12	-18	*575*
KS	12	3	99	SN	X	-3	**0**	-1	**1**	-2	-6	-12	-16	-22	*620*
WI	27	2	96	Ice	-7	**3**	**5**	**5**	-2	-4	-7	-12	-16	-22	*625*
AR	6	1	95	Ice	-1	**8**	**8**	**6**	**3**	-1	-5	-9	-13	-19	*590*
OH	27	2	99	RA	**5**	**10**	**8**	**5**	**0**	-2	-4	-8	-13	-17	*580*
NE	10	4	95	RA	-2	-3	**8**	**6**	**3**	-1	-3	-7	-12	-16	*570*
OK	4	1	98	RA	**0**	**11**	**8**	**6**	**3**	**1**	-3	-7	-12	-16	*565*
NE	8	3	99	SN	-4	-5	-5	**0**	-2	-3	-6	-9	-13	-17	*580*
GA	9	1	97	RA	-2	**0**	**11**	**8**	**6**	**3**	-1	-4	-8	-13	*530*

To find the vertical soundings used in Table 20, the raw surface observation data was scanned to find any occurrence of thunder within an hour of the vertical sounding times (00Z and 12 Z). Only confirmed reports were used for this. For all ten cases, the inversion reached the freezing mark at some level. This helps to support the claim that snow is not the only hydrometeor found in the cloud and that wet snow is most likely falling.

4.4) Precipitable Water

In an effort to examine the precipitable water, a small sample of cases were compared to find a dependency of precipitable water to lightning. Table 21 shows the cases used (35 lightning, 35 non-lightning) for the comparison.

Table 21. Precipitable water (in inches) for 35 cases in each category.

Date	Lightning		Date	Non-Lightning
6-Jan-95	0.86		1-Jan-95	0.55
17-Jan-95	0.57		7-Jan-95	0.8
19-Jan-95	0.59		13-Jan-95	0.46
23-Jan-95	0.6		14-Jan-95	0.67
1-Feb-96	0.55		16-Jan-95	0.8
23-Feb-96	0.77		21-Jan-95	0.75
26-Feb-96	0.61		23-Jan-95	0.5
27-Feb-96	0.72		27-Jan-95	0.4
4-Jan-98	0.93		29-Jan-95	0.49
5-Jan-98	0.74		3-Feb-96	0.4
9-Jan-98	0.75		3-Feb-96	0.77
15-Jan-98	0.63		10-Feb-96	0.66
22-Jan-98	0.63		11-Feb-96	0.6
25-Feb-98	0.8		14-Feb-96	0.29
1-Jan-99	0.58		15-Feb-96	0.24
2-Jan-99	1.1		16-Feb-96	0.29
3-Jan-99	1.2		16-Feb-96	0.17
3-Jan-99	0.62		28-Feb-96	0.7
8-Jan-99	0.83		5-Jan-98	0.7
22-Jan-99	1.08		15-Jan-98	0.6
29-Jan-99	0.67		15-Jan-98	0.61
31-Jan-99	0.98		21-Jan-98	0.47
8-Feb-99	0.53		24-Jan-98	0.88
11-Feb-99	0.78		25-Jan-98	0.94
11-Feb-99	0.59		28-Jan-98	0.81
26-Feb-99	0.8		29-Jan-98	0.33
27-Feb-99	0.89		1-Feb-98	0.64
6-Mar-99	0.42		12-Feb-98	0.78
7-Mar-99	0.63		19-Feb-98	0.64
8-Mar-99	0.63		23-Feb-98	0.5
12-Mar-99	0.8		24-Feb-98	0.58

Table 21 (cont.)

Date	Lightning		Date	No-Lightning
14-Mar-99	0.6		25-Feb-98	0.77
15-Mar-99	0.93		28-Feb-98	0.52
22-Mar-99	0.58		8-Jan-99	0.08
23-Mar-99	0.57		28-Jan-99	0.41

The average precipitable water values were 0.57 inches for non-lightning and 0.73 inches for lightning producing events. Table 22 shows the results of the Chi-squared dependency test to this study where bold represents the frequency, the second number represents the chi-square, and the expected value is half the total in each bin.

Table 22. Chi-squared distribution for the precipitable water cases. Bold represents the frequency and the second number represents the chi-square; the expected value is half the total in each bin.

	0-0.2	0.21-0.4	0.41-0.6	0.61-0.8	0.81-1.0	1.01-1.2	Total
Lightning	**0** 1.00	**0** 3.00	**11** 0	**15** 0.17	**6** 0.2	**3** 1.50	35
No-Lightning	**2** 1.00	**6** 3.00	**11** 0	**12** 0.17	**4** 0.2	**0** 1.5	35
Total	2	6	22	27	10	3	70

(note: Precipitable wter categories are in inches)

Overall Chi-Square for Table 22: 11.73
P-Value: 0.0386
Degrees of Freedom: 5

According to the chi-squared test in Table 22, precipitable water would be a dependent factor for a level of significance of 0.05 (95 % confidence). From this data, a threshold value of 0.41 inches is necessary to produce lightning. With a small number of cases, this statement holds little significance.

4.5) Summary

Overall, the tests to find some of the mechanisms associated with producing lightning during snow and ice events were successful. The chi-square dependency tests for low-level shear to lightning showed a strong association with snow, an association with ice, and a slight association with rain. Examining the temperatures at the surface showed surface temperature to be related in that lightning occurred most frequently within 2º F of freezing. No apparent correlation stemmed from the –10° C level study or the vertical temperature profiles (except for the possible influence of wet snow). Precipitable water also showed no significant association to lightning. Chapter 5 will go into the detailed description of the results and the synthesis of them.

V. Conclusions

The results found from this study of the mechanisms associated with lightning in snow or icestorms show a strong association to low-level wind shear. The divergence study showed no conclusive evidence due to the subjectivity and uncertainty of its calculation rendering the results invalid. Precipitable water appears to have a slight correlation with lightning, but its effects were not thoroughly studied in this work. The surface temperature study showed a strong relationship of lightning to surface temperature in that most events occur with 2º F of freezing for thundersnow, and 80% of all thunder events for snow, ice, and rain occurred when the temperature was at or above freezing (up to 37° F). When examining the -10° C level, no apparent association was found from this level in this work. The temperature profiles from the vertical soundings and surface temperatures did help to show the likelihood of wet snow and other types of hydrometeors, which have different fall speeds and drag coefficients. Also, most thundersnow observations from the first set of data (the only set with the remarks section) reported wet snow or other forms of precipitation mixed with the snow.

With the general knowledge of graupel and graupel charging, graupel does seem very important in the electrification process. Overall, when considering that some thunderclouds are only as high as 5000 meters (Takeuchi et al. 1978), low level shear and above freezing temperatures in the low levels combine for the mixing of the different types of hydrometeors which should enhance cloud charge separation thus explaining how lightning develops in these mostly stratiform clouds, particularly in the convective regions (embedded thunderstorms) (Appendix C).

5.1) Synthesis

Reverting back to the frontal circulation (Emanuel 1985), a circulation below 500 mb is present along fronts. The wind velocity difference between the 850 mb level and the ground, creates turbulent eddies along or near the frontal boundary. These eddies, especially the ones within the cloud, are important in that they help to mix the different types of hydrometeors, thus increasing the charge separation. The precipitation downdraft formed by the falling precipitation (especially wet snow) may help to enhance the frontal circulation (basically a large turbulent eddy) on the cold side while forming a bubble of high pressure at the surface similar to that of a thunderstorm. This high helps to create a gust front (smaller magnitude compared to a summertime thunderstorm) that would force the warm moist air from the warm sector up and over the circulation. Based on the vertical velocity that Sanders and Bosart (1985) found to be on the order of 12 m/s for the low-level circulation, this idea is feasible. Since most thundersnow events are embedded convection within stratiform precipitation (Appendix C), the gust front interaction with the low-level jet may help to force the moisture upward. This is important because the storm now has an updraft source and is able to generate many hydrometeors, including graupel.

Another important influence of this upward forcing, providing that the vertical velocity is strong enough, is that graupel and snow pellets can be formed. Graupel interaction in the cloud has been thought to be a major factor in cloud charging (Fukao 1991) and has been observed in many cases of thundersnow. Simpson (1909) observed graupel during thundersnow almost every time while observing it rarely during no-lightning events. Graupel and snow pellets may be the reason that thundersnow is possible.

A portion of this thesis shows a correlation of the surface temperatures to thundersnow. These results help to show that lightning during snow and ice events occurred very close (within 100 km most of the time) to the rain-snow line or the melting layer. This supports the idea of cloud charging via different hydrometeors with different shapes, sizes, and drag coefficients, thus different fall speeds allowing a higher rate of particle collision in the cloud. When adding the turbulent eddies created by the low-level wind shear, these particles are thrown around and mixed to enhance the collision rate, which increases the charge separation. Though the air at the surface is less likely to influence processes within the cloud, the turbulent eddies may mix the surface air with the lower part of the cloud.

The precipitable water study showed a difference between lightning and no-lightning cases. These results may have been skewed by statistical outliers, but theoretically, stronger, lightning producing systems should have more moisture. When applying the velocity increase due to the tunneling effect (or vertical convergence), the moisture is squeezed into a small area, which may account for the necessary moisture convergence. When applying the frontal circulation effects, the increased vertical velocity on the warm side of the front provides a strong updraft on the order of 12 m/s (Sandera and Bosart 1985). The combined effects of the increased velocity (increased updraft speed) and the moisture convergence should produce convection capable of producing lightning.

Curran and Pearson's work in 1971 helps to support the hypothesis as well. They found the average vertical sounding for thundersnow occurrence among 76 events and found that the inversion around 800 mb was above 32° F. The small number of cases study in this work found temperatures above freezing at 800 mb as well. This is significant in that it shows that different types of hydrometeors exist in the typical case of thundersnow (the above freezing layer indicates that the melting layer is over the station that reports the thundersnow).

In conclusion, the vertical shear created by the strong low-level flow (typically on the order of 40+ knots) creates turbulent eddies that throw the cloud's hydrometeors into one another, thus enhancing charge separation. Another possible effect that low-level shear has is that it may help to enhance the frontal circulation, which is essentially one large turbulent eddy, along or near the front. This circulation has an updraft that flows into the subfreezing air above 800 mb forming graupel. As long as the freezing level is low enough heightwise to be in the strong part of the updraft, the graupel should be allowed to travel farther, thus growing larger through riming and aggregation. This large graupel interacts as it falls with the other particles to add to the charge separation in the cloud. Once the space charge density becomes large enough, lightning can occur.

5.2) The Uncooperative Cases

<u>*5.2.1) Discussion of the Snow Cases*</u>

In the thundersnow low-level shear study, two cases were observed with strong shear without producing lightning (two cases of no lightning verses 15 cases of lightning in strong shear). These cases were the Ohio and Indiana snowstorm on 9 March 1999 and the Maine snowstorm on 5 Feb 95. The March storm possibly produced one cloud-to-ground flash according to the lightning data, but did not qualify for a thundersnow case because it was the only flash. The Maine snowstorm did produce lightning in the snowfall from Virginia to Connecticut, but did not produce any lightning in Maine where snow with strong shear was recorded. An interesting point to note is that Maine produced only one case of thundersnow (22 Feb 97, strong shear) compared to five non-lightning cases in moderate shear and one non-lightning case in strong shear in Maine. When observing the minimal lightning activity in the Holle et al. (1998) thunder frequency plot, the knowledge that graupel over the sea has very little charge on it (Isono et al. 1966), and looking at Maine's thundersnow frequency helps to support the effects of graupel to thundersnow.

When examining the three weak shear cases of thundersnow, all were in the Midwest (28 January 1997- MO, 23 November 1996-Nebraska, 4 March 1995- South Dakota (SD)). The SD case had graupel reported on the radar summary while the other two are unknown as to whether they had graupel nearby. So, based on the trend that has unfolded throughout this research, graupel and/or snow pellets appear to have a major role in thundersnow. Another interesting point to note is that they had strong shear between the 700 mb level and the surface. So, overall, the statistical oddities are not too damaging to the final results for shear.

5.2.2) The Ice and Rain Cases

The effects of low-level wind shear are not as pronounced for these precipitation types as for snow. For freezing rain and sleet, 7 of 20 total strong shear cases did not produce lightning, while 3 of 14 weak cases did produce lightning. For rain with surface temperatures between 33 and 37 degrees Fahrenheit, 10 of 27 strong shear cases failed to produce lightning, while 5 of 16 weak shear cases did produce lightning. No apparent reasons are known as to why so many strong shear cases failed to produce lightning, other than maybe their inversion's upper freezing level extended above the strongest vertical velocity zone (collision zone) to where most of the colliding particles where liquid water droplets colliding with other droplets. When examining the vertical soundings for some cases, the freezing level was between 700 mb and 750 mb. As for the weak cases, the strong low-level flow may have been above or below the 850 mb surface, so the shear between 850 mb and the surface will be lower despite having a strong low-level flow.

5.3) Recommended Future Work

Throughout this thesis, many small patterns appeared in terms of possible mechanisms that enhance the production of lightning. These patterns were not examined thoroughly due to time constraints, however, other factors may also be involved. They are as follows:

1) Search for evidence of different precipitation types occurring with thundersnow and examine the distances of the thundersnow occurrences from the melting layer.

2) Find the numerical values of upper-level divergence and examine the values of potential vorticity at all levels for the cases.

3) Examine the 700 mb and 500 mb surfaces for shear. A pattern is noticeable in the 500 mb surface with a drop off in the wind speed. With the 700 mb surface, look for shear between it and the 850 mb surface.

4) Examine the vertical temperature profiles within the clouds to find the levels of the super freezing air and see where they are with respect to the low-level circulation.

5) Examine the vertical velocity with height to see where the maximum vertical velocity values occur.

6) Examine the effects of instability (conditional symmetric instability) in the upper-levels (300 mb cold pockets).

Appendix A.

Listed below is the IDL computer program used to plot the lightning data used for this thesis (italics denote interchangeable features, bold denotes computer programs stored in the AFIT weather lab computer data base). Any other modifications to the program (i.e., changing plotting symbols from a plus sign to a circle) can be referenced in *IDL Programming* manuel (Fanning, 1999).

isolate_data

```
openr, lun, '/home/fujita12/flash/lgh1999/mar99.lgh',/get_lun
a=fstat (lun)
f=bytarr (11, a.size/11)
n=a.size/11
readu, lun, f
close, lun

f=exp_lgh(f)

map_set, 0, -100, 0, limit=[25.0, -125.0, 50.0, -67.0], /hires, /usa, color=100,$
title='mar99'
pos=where(f.peak GT 10.0, pcount)
neg=where(f.peak LT 10.0, ncount)
plots, f[pos].lon, f[pos].lat, psym=1, color=250
plots, f[neg].lon, f[neg].lat, psym=2, color=250

image=tvrd()
write_gif, 'mar99.gif', image, r, g, b

num=strcompress(sindgen(40), /remove_all)

for I=0,30 do begin

map_set, 0, -100, 0, limit=[25.0, -125.0, 50.0, -67.0], /hires, /usa, color=100,$
title=num(i)+1
one=where(f.day EQ I+1, count)

if (count GT 0) then begin
pos=where (f.[one].peak GT 10.0, pcount)
```

```
neg= where (f.[one].peak LT 10.0, ncount)

if (pcount GT 0)then $
plots, f[one[pos]].lon, f[one[pos]].lat, psym=1, color=150

if (ncount GT 0)then $
plots, f[one[neg]].lon, f[one[neg]].lat, psym=2, color=150

image=tvrd()
write_gif, num(i)+'day.gif', image, r, g, b

end if

end for
```

Appendix B

Listed below are the state abbreviations used in the thesis.

AR Arkansas
DE Delaware
GA Georgia
IL Illinois
IN Indiana
IA Iowa
KS Kansas
KY Kentucky
LA Louisiana
ME Maine
MD Maryland
MA Massachusetts
MI Michigan
MN Minnesota
MS Mississippi
MO Missouri
NE Nebraska
NH New Hampshire
NJ New Jersey
NY New York
NC North Carolina
ND North Dakota
OH Ohio
OK Oklahoma
ONT Ontario (Canada)
PA Pennsylvania
SD South Dakota
SC South Carolina
TN Tennessee
TX Texas
VT Vermont
VA Virginia
WV West Virginia
WI Wisconsin

Appendix C

The 26 October 1997 radar mosaic is shown in Figure 15. The thunderstorms are embedded within the stratiform precipitation in eastern Nebraska and western Iowa.

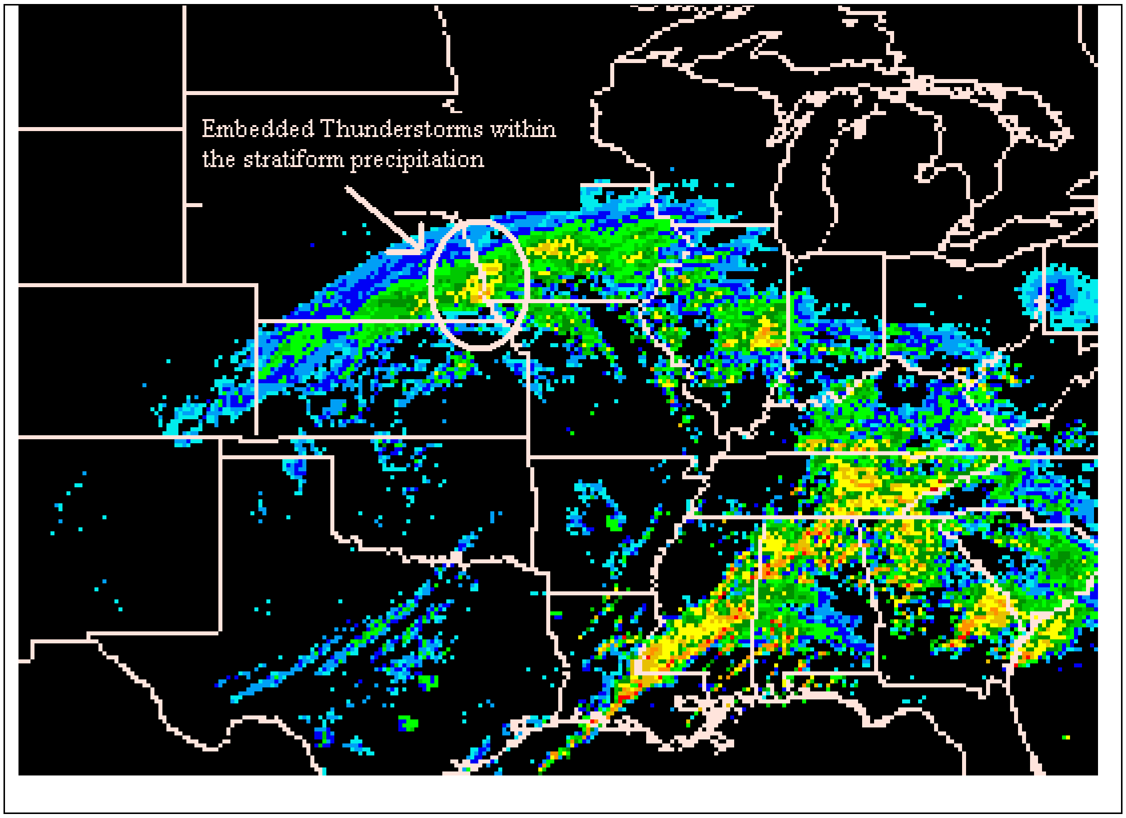

Figure 15. Radar mosaic for 26 October 1997 at 0800. The embedded thunderstorms are circled and labeled around Lincoln Nebraska.

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Vita

Second Lieutenant Randall J. Haeberle was born in Washington D.C. He graduated seventh in his class from Daniel Boone High School in Gray, Tennessee in May 1995. He entered undergraduate studies at Parks College of Saint Louis University where he graduated with a Bachelor of Science degree in Meteorology in May 1999. He was commissioned through the AFROTC Detachment 207 at Saint Louis University in May 1999.

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