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A Composite Study of Mean Atmospheric Conditions Associated with Large Hail Events in South-Central North Dakota

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1. Introduction

Of the notable types of severe weather which occur in the Bismarck, North Dakota National Weather Service (NWS) County Warning Area (CWA), severe hailstones garner much more attention by the general public and media than several other types of significant weather experienced in the area. This can be attributed in part to the agricultural use of much of the land in the Bismarck CWA, which is composed of thirty-six counties in western and central North Dakota.

Determining the potential for large hail in western and central North Dakota can be a significant challenge to forecasters. As a result, it is prudent to identify those conditions which are most apt to result in large hail events and thus improve both short- and long-term assessments of high-impact convective events. Compositing historical atmospheric data fields related to a forecast problem, in this case, events which produced large hail, allows for the creation of a data set of those conditions which are most likely to result in the particular weather event. This is not a new idea; it has been applied to several different forecast problems ranging from heavy rain and freezing rain (Fors and Leblang 1993) to persistent low overcast events over the upper Midwest (Roebber et al. 1998). Once a composite study has been completed, the information gained from it can be useful to both new and experienced forecasters. When studies of different atmospheric phenomena encountered in a particular area are undertaken, a library of the information can be developed for use by local forecasters. This was one of the original intents of the paper by Fors and Leblang (1993), and this study follows suit with the intent of contributing to a library of composited historical weather events for use by northern Plains severe weather forecasters.

2. Methodology

A vast amount of historical meteorological observations is available through a variety of sources today. The most notable of these is the National Climatic Data Center (NCDC). Through this center, a number of data fields are available, including historic upper air data and a storm events database, both of which were utilized in this study. Additionally, a software application developed locally at NWS Bismarck, DeCep, uses historic data from the National Centers for Environmental Prediction (NCEP) Grid Point

Data Set prepared by the University of Washington (Mass 1987) to create composite data fields with ease. The DeCep program was used extensively in this project.

For a composite study of those conditions which yielded a particular event to have any significance, the event being studied must be anomalous enough that a significant and not climatic signal develops in the composite analyses. It has been suggested that the type of phenomenon being studied should have been observed on roughly 10 to 40 historical dates in order for a significant meteorological pattern to be revealed by a composite study (Fors and Leblang 1993). Accordingly, it is necessary in most cases to make use of a small study area. As a result, it was decided that for the purpose of this study, those hail events which occurred locally would be researched. The original intent of this research was to study cases that impacted metropolitan Bismarck and Mandan, North Dakota, but because the storm events database available through NCDC is limited to county areas and the Storm Data from the era being assessed does not specify exact event locations in many cases, the study was expanded to include all of Burleigh and Morton Counties. The time period from which events were selected was from 1950 to 1994, a range dictated by the availability of data in the NCDC storm events database and the DeCep program.

The Storm Prediction Center defines a *significant* severe thunderstorm event as one containing hail greater than or equal to two inches in diameter and/or winds greater than or equal to 65 knots (Craven et al. 2002). In accordance with these criteria, an interrogation of NCDC storm data was conducted for reports of two inch or greater diameter hail which had fallen in Burleigh and Morton Counties. This resulted in a relatively small sample of events; a number below that suggested by Fors and Leblang (1993) as a baseline for such studies. When the criterion for the diameter of hail to be utilized in this study was lowered to one and three-quarter inches, or golf ball size, a larger sample of events was attained.

Once the initial database of hail reports greater than or equal to 1.75" in diameter was established, an assessment was made to determine whether a specific report was an isolated event or if it was concomitant with a larger severe weather episode across the state. Isolated events were not included in the composite study. To ensure that the event was not isolated, at least four separate reports of weather meeting minimum severe criteria from a several-county area, in addition to the 1.75" or greater hail report from Burleigh and Morton Counties, were required for the event to be included in the composited fields. In addition, the synoptic conditions which resulted in the event must be similar enough for a relevant pattern to develop from the dates composited. That is, those dates exhibiting similar synoptic patterns were grouped together, such as similar southwesterly upper- level flow events (Fors and Leblang 1993). Utilizing these requirements resulted in a total of nineteen separate dates to composite for the purposes of establishing key patterns which have historically produced large hail in Burleigh and Morton Counties.

The DeCep program was used to analyze both the 1200 and 0000 UTC surface and upper-air data for each of the nineteen dates chosen for the study. These data were then used to develop several charts portraying the mean synoptic patterns for each event. All charts displayed herein represent the composite 1200 UTC fields in order to portray the environment in the time leading up to the severe weather event. Additionally, the individual sounding data from several of the upper-air sites in the northern Plains, including Bismarck, Glasgow, Huron, and Rapid City were assessed, with several mean thermodynamic and kinematic quantities typically used in the thunderstorm forecast process defined.

3. Results

When the synoptic composites were completed, three primary patterns became apparent in the data, all of which coincided with those that Hirt (1985) found to be associated with severe weather in the state. The two patterns that contained the most events in the study featured large-scale southwesterly flow aloft downstream of a trough of varying amplitude which had an axis west of the state. Moreover, it was apparent that a mid-level shortwave ridge existed across much of the northern Plains, especially early in the period, and pronounced warm air advection was implied across the region. This suggests a mean pattern similar to that which Hirt (1985) and Fors and Leblang (1993) previously found to be associated with convective episodes across the state. A third pattern found was dominated by a large upper-level ridge of high pressure anchored across the southern Rockies that allowed the southern edge of the jet axis to reside across the northern Plains.

With eighty percent of the individual events and in all three mean patterns, it was noted that a mean 500-hPa height of 5820 meters was located in the state of North Dakota. The mean 500-hPa height over the state during the May-August 1950-1994 period was 5760 meters. The above-average heights often associated with severe episodes signifies the importance of warm air advection in local convective events.

A. Composite Pattern A

Composite Pattern A (Fig. 1) accounted for six of the nineteen dates utilized in the study. It consisted of a positively tilted trough axis between 120 and 124 degrees west longitude, often with an upper low located somewhere from southern British Columbia to just off the coast of Oregon. The 700-hPa layer (Fig. 2) also showed shortwave ridging across the region at 1200 UTC. This ridging translated eastward by 0000 UTC (not shown). Composition of mean sea level surface pressures showed that a trough moved from eastern Montana at 1200 UTC (Fig. 3), into the western Dakotas by 0000 UTC (not shown). At 850 hPa, a long fetch of southerly flow existed across the region as a result of the trough at that level having its axis to the west of the state. Mean thermal profiles at 850 hPa (Fig. 4) yielded temperatures of 20° to 25° C. In addition, the 700–hPa 10° C isotherm (not shown) was nudging into the southern tier of North Dakota. Significant warm air advection, as evident in Figure 4, acts to destabilize the atmosphere and is an important precursor to deep convective development in this pattern.

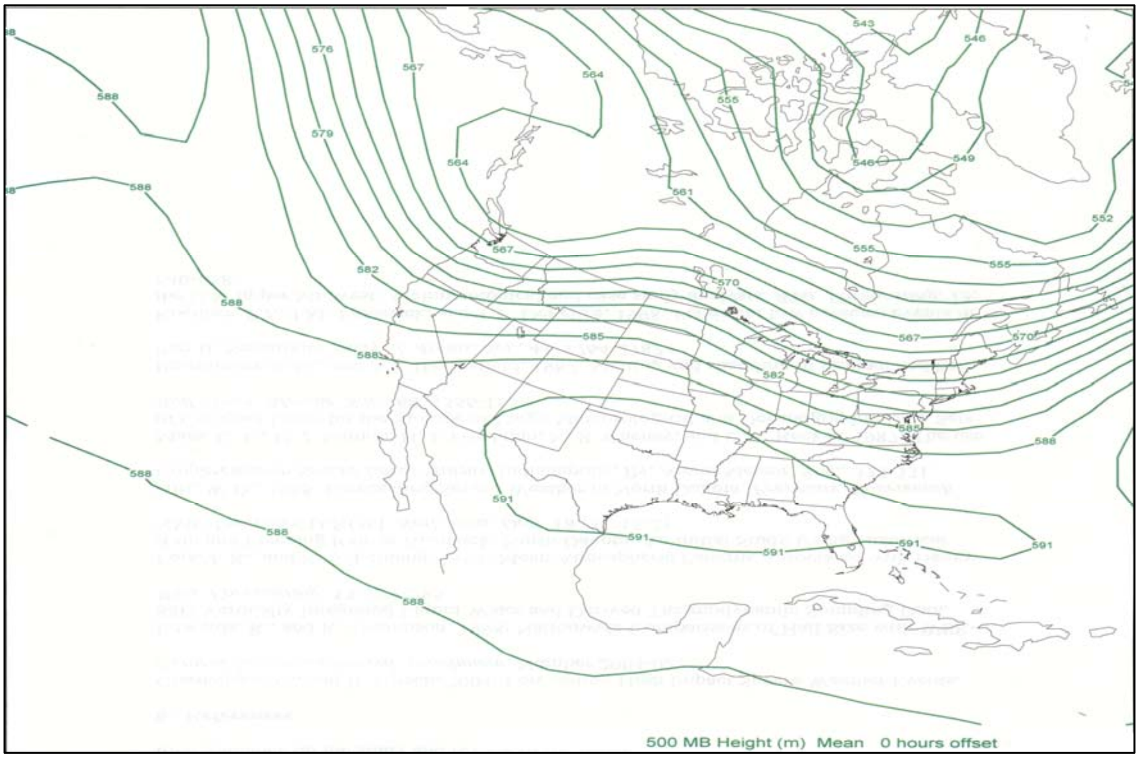

Figure 1. Composite 500-hPa heights (interval 6 dam) at 1200 UTC.

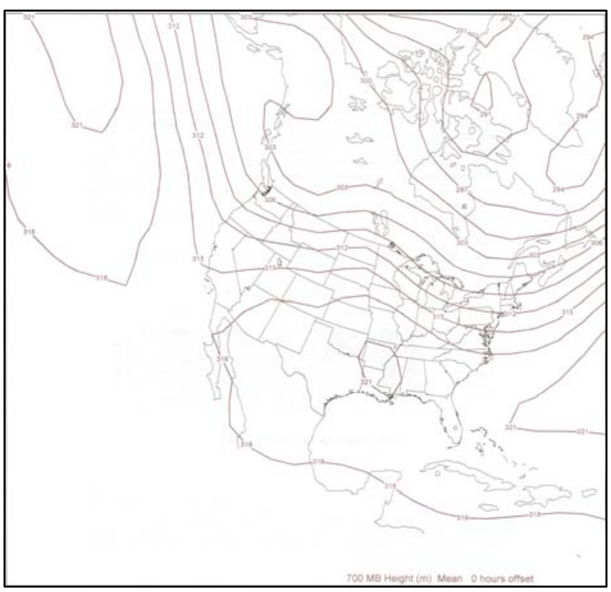

Figure 2. Composite 700-hPa heights (interval 3 dam) at 1200 UTC.

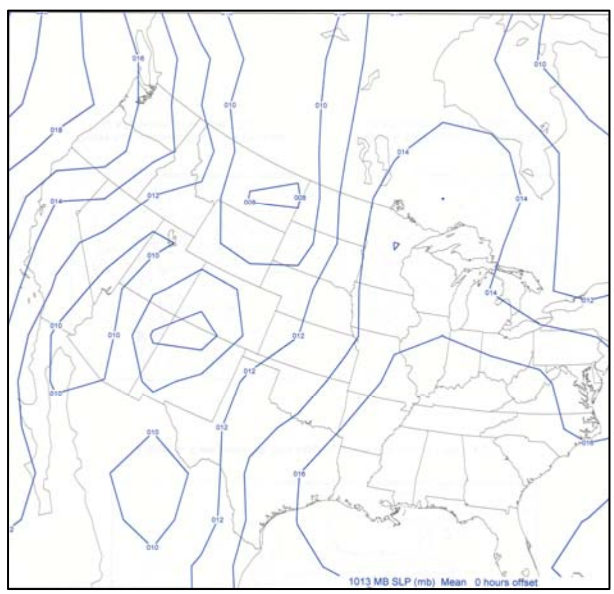

Figure 3. Composite Seal Level Pressure (interval 2 hPa) at 1200 UTC.

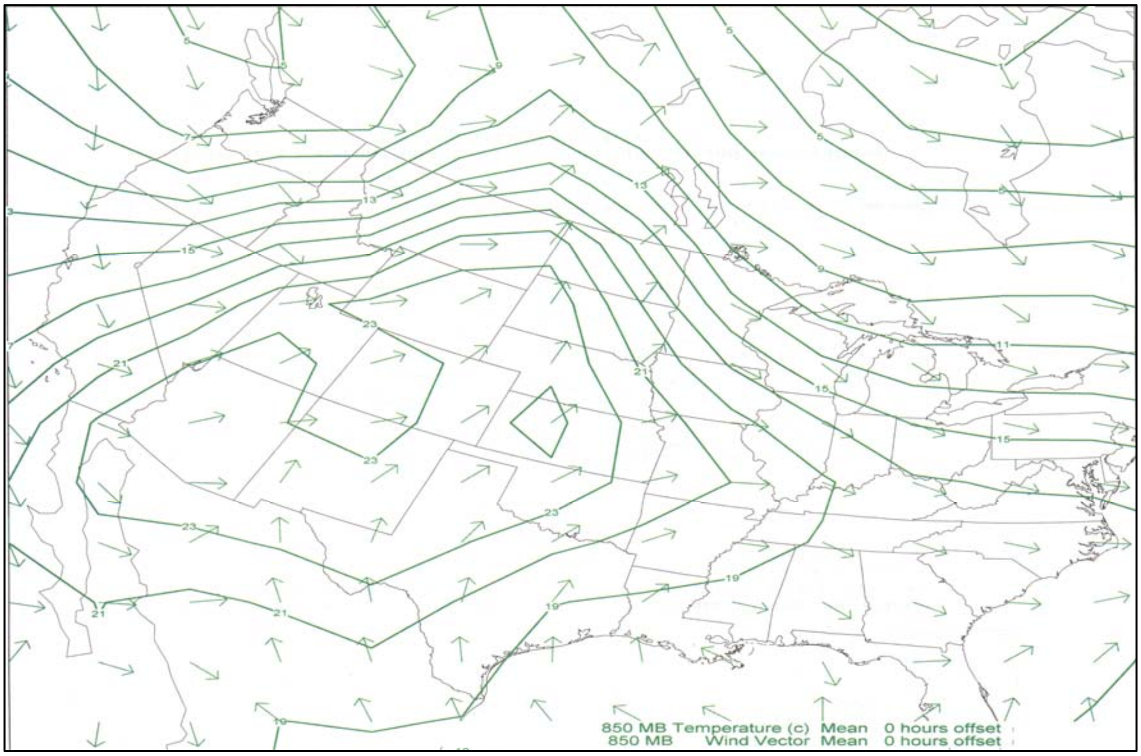

Figure 4. Composite 850-hPa isotherms (°C, 2° C interval) and wind vectors at 1200 UTC.

B. Composite Pattern B

This composite accounted for nine of the nineteen dates utilized in the study. It was represented by a positively tilted trough axis between 114 and 120 degrees west longitude with an upper low located in southern Alberta (Fig. 5). The 700-hPa analysis also showed a trough axis west of the area at 1200 UTC (Fig. 6). An area of surface low pressure was noted across western South Dakota at both 1200 UTC (Fig. 7) and 0000 UTC (not shown).

At 850 hPa (Fig. 8), a thermal ridge axis was located over the region. The mean low- and mid-level temperatures are cooler in this pattern than that of Composite Pattern A, but the nose of the thermal ridges being just of south of the area is indicative of the warm-air advection regime being focused in south-central North Dakota – likely in association with a low- level warm frontal boundary.

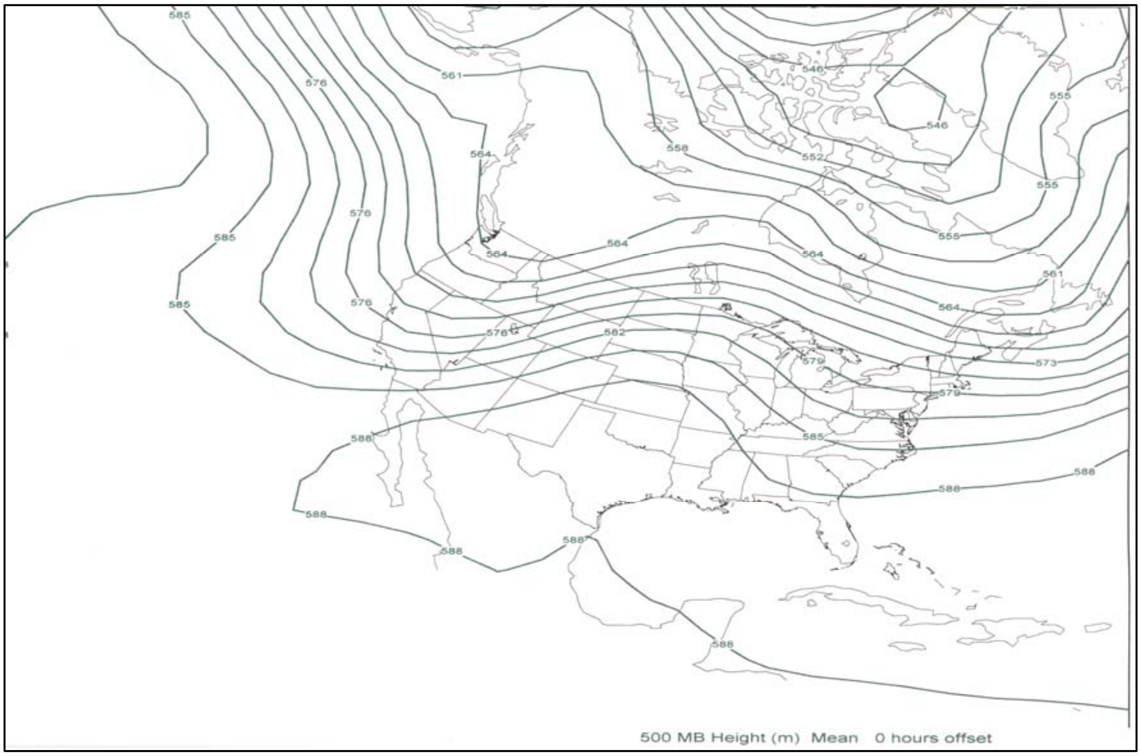

Figure 5. Same as Figure 1 but for Composite Pattern B.

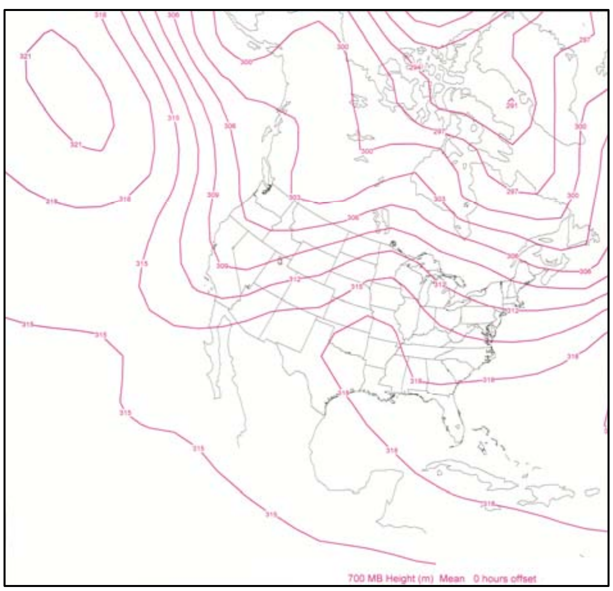

Figure 6. Same as Figure 2 but for Composite Pattern B.

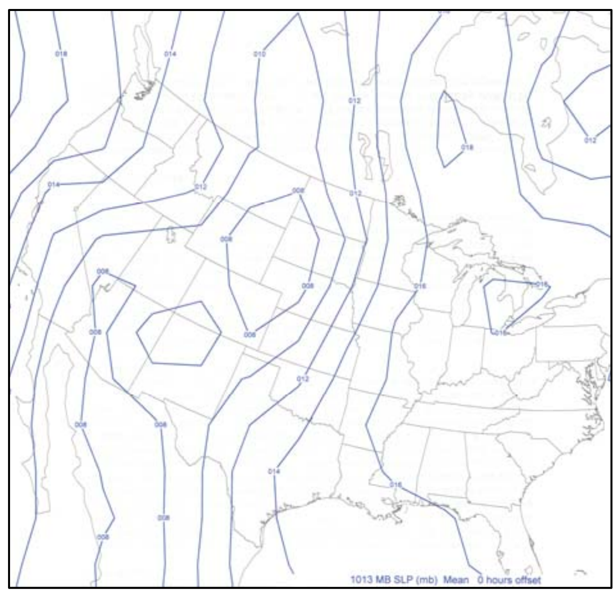

Figure 7. Same as Figure 3 but for Composite Pattern B.

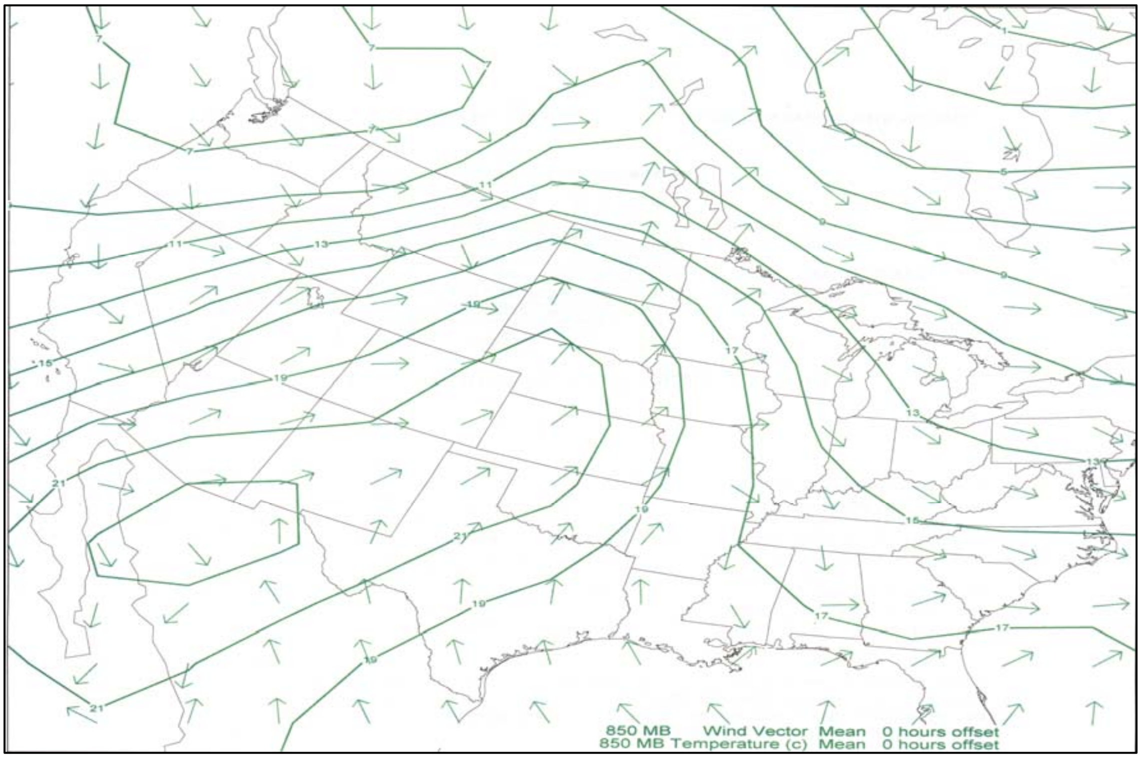

Figure 8. Same as Figure 4 but for Composite Pattern B.

C. Composite Pattern C

Composite pattern C, identified by a 500-hPa upper-level ridge axis located to the west of the area, and centered over the southern Rocky Mountains, accounted for four dates in the study (Fig. 9). The 700-hPa plot (Fig. 10) showed westerly flow aloft, a scenario that allows for steep mid-level lapse rates to overspread the low-level moist axis while contributing to a deep-layer shear profile suitable for severe local storms. There is little of significance on the surface pressure composite (Fig. 11) for this particular pattern, possibly as a result of the averaging associated with the compositing process. At 850 hPa (Fig. 12), a trough axis was located in the western part of North Dakota, with southerly flow shifting to a more westerly direction over the state.

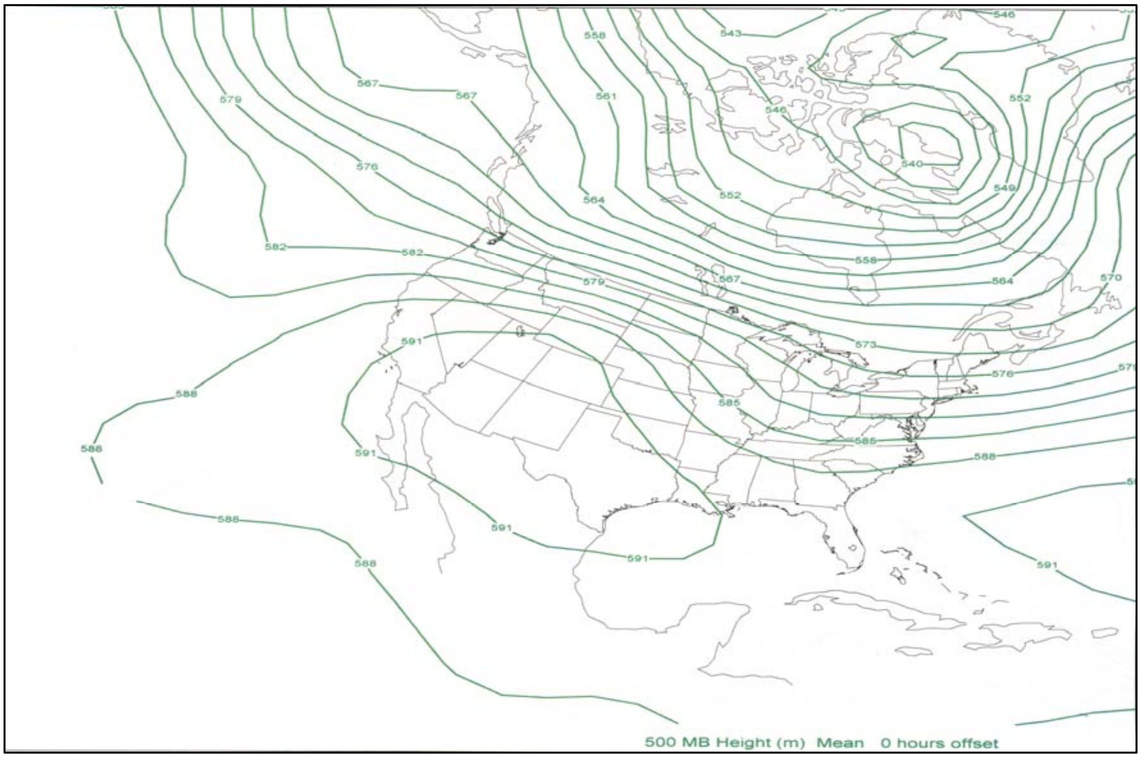

Figure 9. Same as Figure 1 but for Composite Pattern C.

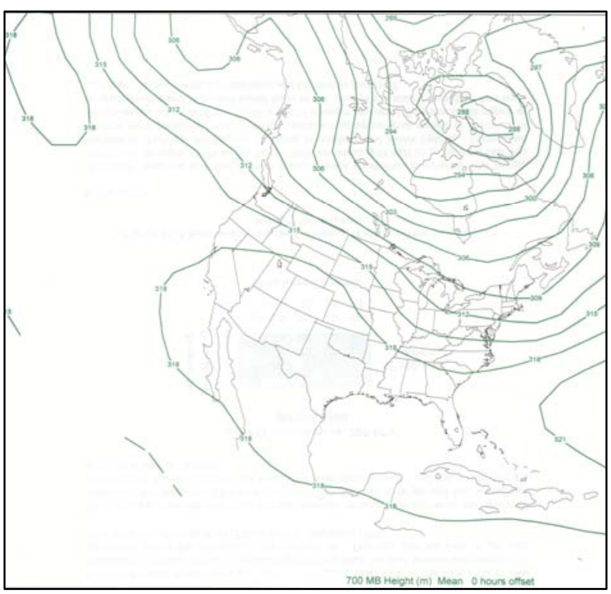

Figure 10. Same as Figure 2 but for Composite Pattern C.

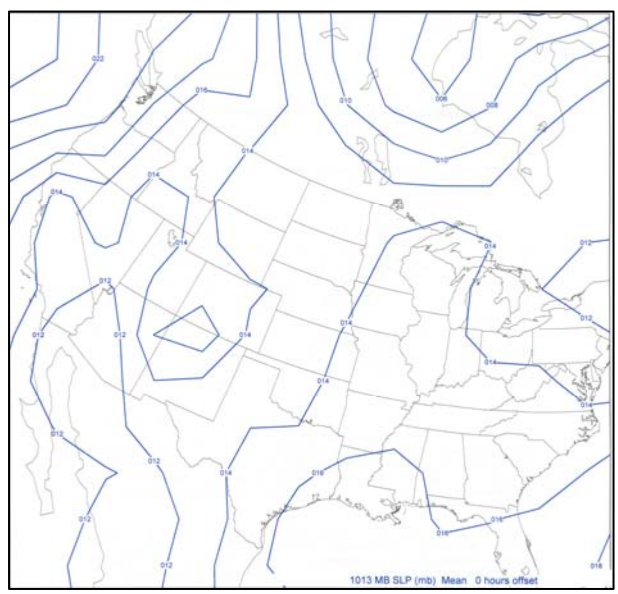

Figure 11. Same as Figure 3 but for Composite Pattern C.

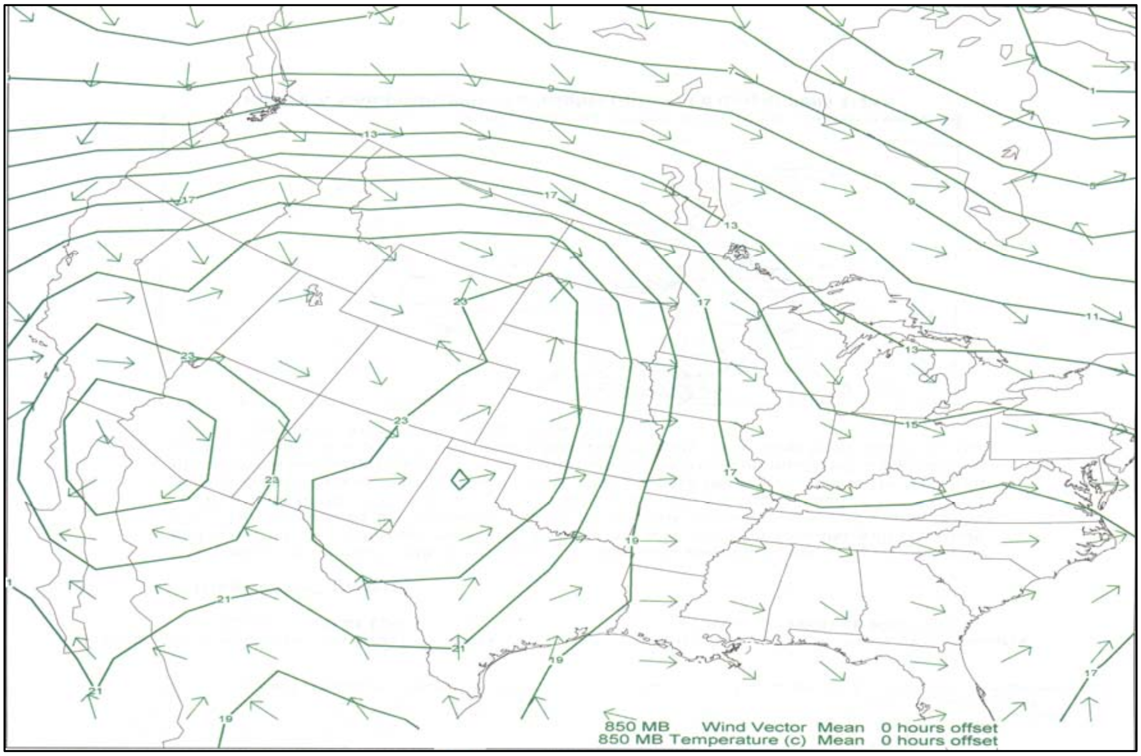

Figure 12. Same as Figure 4 but for Composite Pattern C.

4. Sounding Assessment

Regional atmospheric sounding data were obtained from NCDC and analyzed for the dates comprising the study. Several keys to significant hail episodes became apparent, many of which have previously been recognized as factors in the development of severe weather events (Hirt 1985; Fors and Leblang 1993). In addition to Bismarck's sounding data, radiosonde observations from Glasgow, Montana, and Rapid City and Huron, South Dakota were also interrogated.

Often, forecasters utilize the height of the environmental 0° C level when assessing severe weather potential. It was found that the majority of hail events in the study occurred with 0° C levels between 14,000 and 15,999 feet (above ground level) as shown in figure 13. The average 0° C level for all hail events on the 1200 UTC sounding was 14,422 feet, and 14,917 feet on the 0000 UTC sounding. This is not surprising as other studies have shown that very large hailstones undergo less melting on their descent to the ground than their smaller counterparts (Rasmussen and Heymsfield 1987).

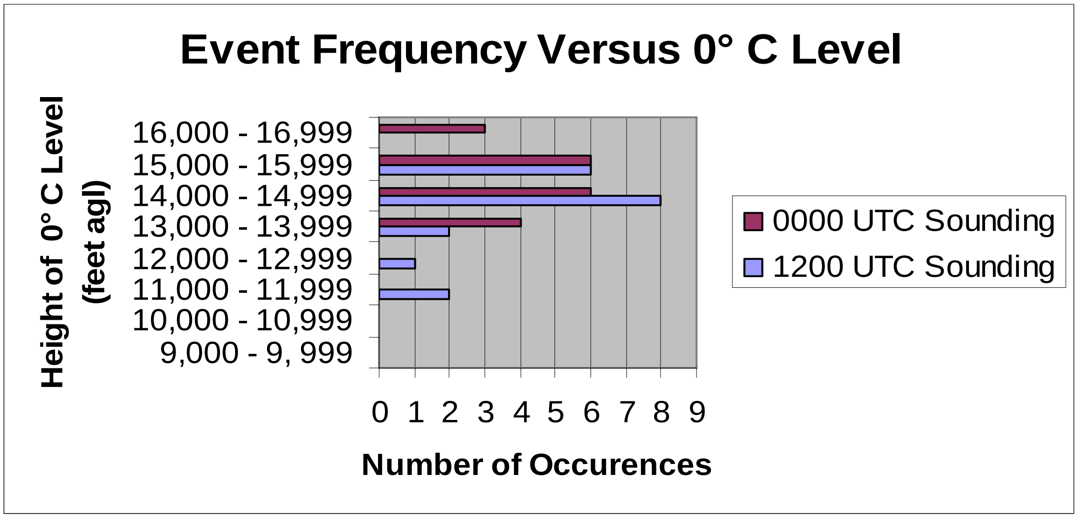

Figure 13. Histogram comparing the event frequency of very large hail events with the environmental 0° C level.

The warming of the airmass was not only demonstrated by rises in the 0° C levels between 1200 UTC and 0000 UTC, but also by increases in the average temperatures at 850, 700, and 500 hPa, the 1000 – 500 hPa thickness values, and the height of the -10° and -30° C levels that bound the hail growth layer. While partially a result of solar heating, this is also indicative of the role of warm-air advection in setting the stage for northern Plains convection. The average height of the -10° C isotherm was 18,507 feet on the 1200 UTC sounding and 18,898 feet on the 0000 UTC sounding, while the mean -30° C height was found to be 27,910 feet at 1200 UTC and 28,045 feet at 0000 UTC. This establishes a mean depth of the -10° C to -30° C hail growth layer of 9,403 feet at 1200 UTC and 9,147 feet at 0000 UTC.

Lapse rates between 700 and 500 hPa were assessed to better determine the amount of instability present in the middle atmosphere and whether any correlation existed between them and the study events. It was found that approximately 75% of the cases had mid-level lapse rates steeper than 7.0° C km^{-1}. In fact, 50% of the dates in the study had 700 to 500–hPa lapse rates steeper than 7.5° C km^{-1} (Fig. 14).

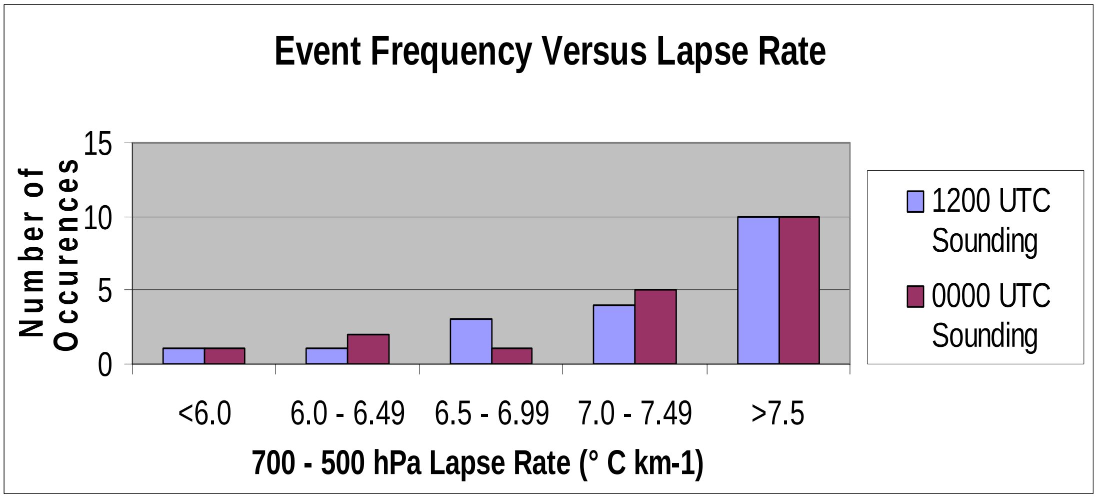

Figure 14. Histogram comparing the event frequency with mid-level lapse rates.

In all of the events, strong mid-level flow was present, with jet segments of 30 to 60 knots present across the northern Plains at the 500-hPa level. However, even though the hail events were located near the Bismarck sounding site, these speeds were not necessarily present there. In fact, several of the 0000 UTC soundings from Bismarck that were representative of the hail-producing environment had 500-hPa winds between only 20 and 29 knots. No events had observed 500-hPa winds less than 20 knots, however, which suggests that this may be a cutoff for speeds necessary to produce a deep-layer shear profile suitable for significant hail in a typical synoptic environment in south-central North Dakota (Fig. 15).

It was found that while significant low-level moisture is necessary to form deep potential energy in the form of instability, this moisture does not have to be present in the region for an extended period before the event. In fact, analysis of sounding data showed that in most cases a strong, but short-term (24 hours or less) advection pattern was sufficient to support deep convection.

Several additional convective indices were also calculated for the soundings. The observed value of any given index varied greatly from event to event, likely in part due to low-level mesoscale influences on the severe storm environment that are not discernable in a historical context such as this one. For example, surface-based convective available potential energy (CAPE) values for the Bismarck sounding site near the time of the hail event ranged from around 100 to over 4000 J kg^{-1}. Rasmussen and Blanchard (1998) note that CAPE alone may have some value as a predictor of supercells. However, it is clear that most of the time a single index does not provide an exclusive means from which a significant hail event can be forecast, particularly when the index is used in an averaged state. Rather, a combination of favorable parameters more strongly discriminated hail-producing thunderstorms from those not producing hail. This agrees with previous work done at a national level (Edwards and Thompson 1998).

The soundings from the four dates that had baseball or larger size hail were also analyzed separately, but only subtle differences from the golf ball or larger size hail soundings were observed. Most notable was the fact that the soundings were slightly cooler and contained stronger winds aloft, especially at 250 hPa.

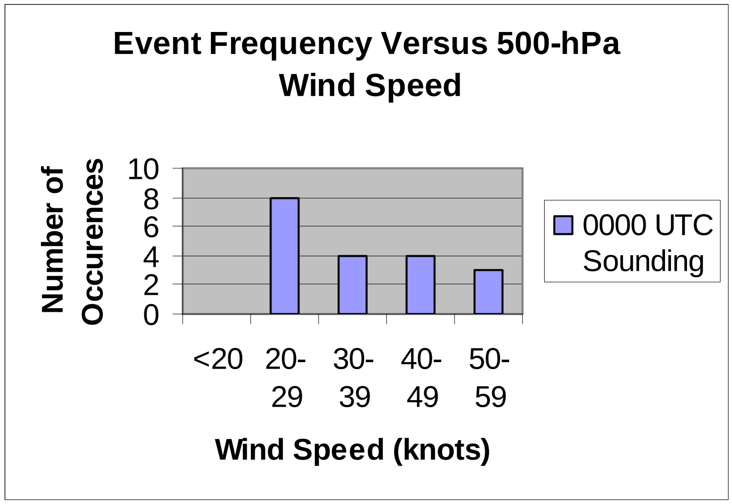

Figure 15. Bar chart comparing the event frequency with 500-hPa wind speed categories.

4. Summary and Conclusions

This study assessed and found mean synoptic-scale conditions associated with nineteen dates from the early 1950s to the early 1990s on which golf ball or larger size hail was reported in Burleigh and Morton Counties in south-central North Dakota. Three main patterns were identified, two of which contained an upper-level trough to the west of North Dakota, and a third that found a belt of stronger mid-level flow across the region as an upper-level ridge axis established itself to the west of the state. Warm advection is an important contributor to the convective environment in all three patterns.

Due to the significant low-level warming that takes place in these events, mean environmental 0° C levels are almost 15,000 feet above ground level on the 0000 UTC soundings, near the time of most of the hail events. Forecasters are thus cautioned against using the height of the 0° C level as a means of discriminating between episodes that produce significant hail and those that do not. Mid-level lapse rates, however, do show a significant correlation to the large hail events in the study. Seventy-five percent of all cases had 700 to 500-hPa lapse rates steeper than 7.0° C km^{-1}. Another discriminator of organized significant hail events may be mid level wind speeds. No case in the study had 500-hPa wind speeds less than 20 knots, though winds did not need to be excessive in order to support the events; several episodes took place with 500-hPa winds between 20 and 30 knots. In addition, most hail events in south-central North Dakota during the period of study took place when low-level moisture values were increasing rapidly, not when rich low-level moisture had been in place for an extended period. A combination of strong warm and moist advection and a favorable synoptic pattern should be an indicator of potential for large hail events in the area. However, no single parameter should be used to forecast a hail event. Several factors should be considered with careful attention paid to those outlined in the study such as mid-level lapse rates and wind speeds.

5. Acknowledgements

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