Environmental Controls on Banded Versus Cellular Organization of Mesoscale Snow Squalls in Western South Dakota

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1. Introduction

Snow squalls are fast-moving, intense mesoscale systems that can turn fair weather into whiteout conditions in a matter of minutes. They are characterized by low snowfall amounts, gusty winds, dropping temperatures, and low visibilities (Banacos et al. 2014). Even though these systems do not produce large snow accumulations, the snowfall rate can be upwards of two or three inches per hour. Paired with wind speeds potentially higher than 14.1 m s^{-1} (32 mph), this can cause visibility to decrease to under a quarter of a mile in the span of a few minutes. The quick onset of reduced visibility and snow-covered roadways can cause a rapid deterioration of driving conditions. These events have been known to cause fatal accidents and multicar pileups when they pass over high traffic areas (Banacos et al. 2014; Stevens et al. 2019). Considering this, the National Weather Service has recently implemented a snow squall warning project beginning in the winter of 2018-2019 (Hawkins 2019). This study seeks to help improve the forecast and warning of snow squalls by studying their storm-scale organization.

Previous studies have focused on the environments associated with snow squalls through both case studies. Milrad et al. (2011) and (2014) looked at two “snow burst” events in Canada, focusing on environmental parameters and triggers They concluded that these events occurred shortly after a passing cold front and that Environmental Canada should strongly consider implementing a warning for “wintertime convection”.

Banacos et al. (2014) conducted a study on snow squalls in the northeastern United States. They defined a snow squall as mesoscale in size; having visibilities of less than half a mile; falling temperatures; an increase in wind speeds before or as the system passed; and lasting for less than one hour. They also concluded that snow squalls generally formed with the 300-hPa height near climatological average values, cold air advection present at 850-hPa, a cold front present at the surface, and measurable CAPE which is uncommon for winter phenomena. Banacos et al. (2014) mentioned the presence of two main modes of snow squall, bands and cells, but did not research them further.

To build upon this past work, this study will focus on the radar characteristics of banded and cellular snow squalls, environmental conditions that may differentiate between these modes, and seek to determine which mode of snow squall is more impactful. This is done in a similar vein to numerous studies of warm-season convective storm that have related convective organization to the background environment and severe weather hazards (e.g. Bluestein and Jain 1985, Bluestein and Parker 1993, Smith et al. 2012). The guiding hypotheses for this work are that: 1) The different modes will be clearly distinguishable on radar-based on size, depth, and intensity, 2) These modes will occur in distinctly different environments characterized by unique profiles of buoyancy, vertical wind shear, moisture, and sources of lift, and 3) Banded snow squalls will be more impactful owing to their larger areal extent, and potential to align with major roadways.

These hypotheses will be tested by classifying and analyzing two modes of snow squalls using radar data, examining the environments for both modes of snow squalls using archived model analyses, and examining the human impacts of each case using motor vehicle crash data.

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2. Methodology

This study focused on snow squall cases in western South Dakota. The criteria for a snow squall within this study was a combination of snow being present and visibility less than half a mile for a period of three hours or less. Banacos et al. (2014) included a wind threshold and falling temperatures as additional identifiers for snow squalls. Due to missing wind gust data for some stations, and an interest in not limiting cases to those in the vicinity of cold fronts, the dropping temperature and wind threshold were neglected from the case selection. Any system impacting a single observing station for longer than three hours was removed as an initial filter to avoid synoptic-scale snowstorms.

Cases were selected using the Automated Surface Observation System (ASOS) due to the frequency of observations (every five minutes), and ease of accessing the data record. Three western South Dakota stations were chosen due to their proximity to Interstate 90, and the Black Hills: Rapid City Regional Airport (KRAP), Custer (KCUT) and Philip (KPHP). Six years of data spanning January 2012 through December 2017 were reviewed. The date range was chosen to coincide with the availability of dual-polarization radar data from the WSR-88D and to provide the option of using these data as part of our analysis. Seventy-eight potential snow squall cases were identified in the target area during this period.

Archived regional composite radar reflectivity data from the National Center for Atmospheric Research's Mesoscale and Microscale Meteorology Laboratory, were used to determine the size and overall system structure. To ensure a focus on mesoscale snow squalls, cases that encompassed an area larger than 200 km in length or that were part of a synoptic-scale winter storm were removed. This filtering reduced the original seventy-eight potential cases to forty viable snow squall cases. Of these, three cases were missing environmental data (RAP model analyses, accessed from National Centers for Environmental Information archives) and removed from the final list of potential snow squall cases. In total, there were thirty-seven total snow squall cases with viable environmental data to examine

Single-site WSR-88D data for the Rapid City radar (KUDX) were acquired through the Next Generation Weather Radar archive database, maintained by the National Oceanic and Atmospheric Administration. Data were analyzed for each case using GR2Analyst in order to identify patterns in reflectivity and velocity. To determine storm heights, vertical cross-sections were created for each system using GR2Analyst. Multiple cross-sections of the system were taken, and maximum storm tops were estimated. The storm tops identified by areas of reflectivity below 10 dBZ.

Fairman et al. (2016) determined a reflectivity threshold of 20 dBZ for adequately identifying wintertime banded precipitation and this was used as a threshold for classifying the modes of snow squalls. This helped identify the most intense region of the snow squall and allowed length-to-width ratios to be easily identified. Three modes of snow squalls were identified. Banded cases had a length-to-width ratio of ≥1:2 (Figure 1a), while cellular cases had a length-to-width ratio close to 1:1 (Figure 1b).

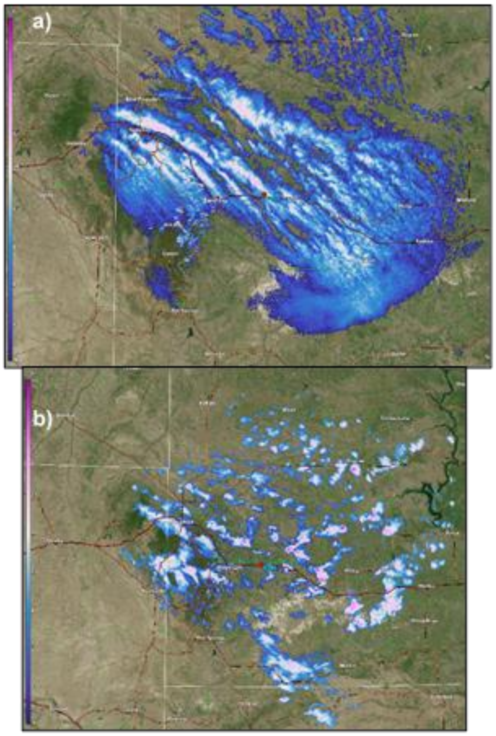

Figure 1: Radar reflectivity factor (dBZ, shaded as shown), for example, cases of banded (a) and cellular (b) classifications. Note that the maximum value of reflectivity plotted is 50 dBZ.

Cases that had both bands and cells present in one radar scan were classified as a mixed category. From a visual analysis using the reflectivity threshold defined above, twenty-one cases fit into the band category, ten cases into the cell category, and the remaining six cases were defined as mixed.

The environmental analysis was completed using the Grid Analysis and Display System (GrADS) and Rapid Refresh (RAP) model analysis data (Benjamin et al. 2016). Maps of geopotential height, temperature, wind vectors, bulk Richardson number, and moisture were created for standard pressure levels to discern the details of banded versus cellular environments.

Skew-T/log-P analysis used the Sounding/Hodograph Analysis and Research Program in Python (SHARPpy) (Blumberg et al. 2017). Sounding-derived fields included instability, wind shear, storm motion estimates, precipitable water, and dendritic growth zone depth.

Composite plots of instability and moisture for band and cell cases were used in the environmental analysis. Precipitation efficiency, as suggested by Wetzel and Martin (2001), was also examined to try to determine which mode of snow squall would have lower visibilities due to higher snow densities. Dewpoint depressions were used to trace relative amounts of moisture at the surface. The upper and lower bounds for the dendritic growth zone have varied in the literature: -10° C to -15° C (Wetzel and Martin 2001), -12° C to -18° C (e.g., Roebber et al. 2002, DeVoir et al. 2004), -10° C to -16° C (Bechini et al. 2013). For this paper, the dendritic growth zone was defined as the layer between -12° C and -16° C.

Finally, human impacts were inferred from county vehicle crash reports in western South Dakota. Crash data were provided by the South Dakota Department of Public Safety and retrieved from the online accident record database (https://dps.sd.gov/records/accident-records/sdcat). Crash records are only available from 2014 and some events had no crashes recorded. Due to these gaps in data, only twenty-two out of thirty-seven cases had crash reports on the days when snow squalls occurred. A crash was only counted as “likely” being from a snow squall if two criteria were met: 1) the crash happened at the same time as the passing snow squall; and 2) weather was reported as a cause of crash in the daily report.

3. Results and Discussion

Bands:

Bands were easily identified on radar based on size and shape due to their having a preferred long axis. Bands formed throughout the cool season (Nov-May) but were favored during the colder months with a seasonal peak during February (Figure 2).

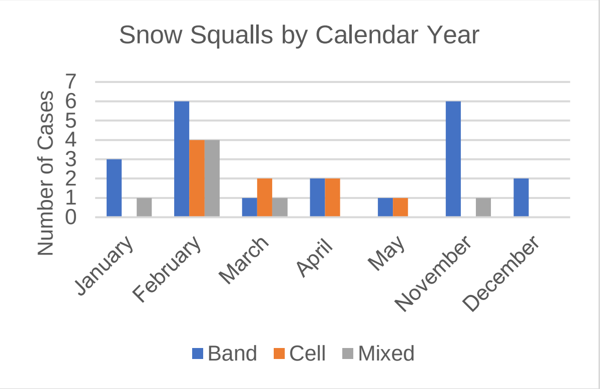

Figure 2: A graph showing the total number of snow squalls that occurred in each month by mode (colored bars, as indicated). The months of June through October are excluded due to a lack of recorded snow squalls.

Bands had a diurnal pattern, generally occurring in the late afternoon/early evening and formed in more stable (Figures 3a and 4), but higher sheared environments when compared with cells (Figure 5). Bulk Richardson number for these cases was generally below three, indicating that these were shear-dominated systems. Bands moved with the 500-hPa steering wind, oriented along the surface–500-hPa shear vector. Sub-band structures were observed to move along the band (and thus along the deep-layer shear vector), suggesting a possible propagation component to the system motion as well.

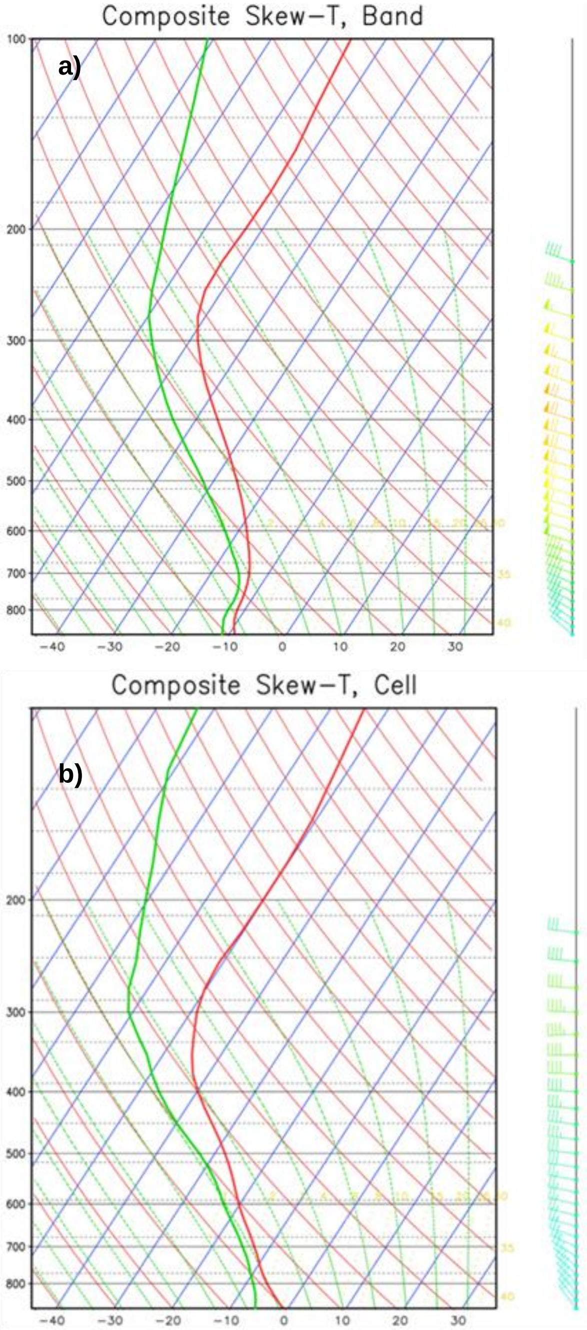

Figure 3: Composite skew-T ln-p diagrams of temperature (solid red) dew point temperature (solid green) and wind (barbs) for banded cases (a), and cellular cases (b).

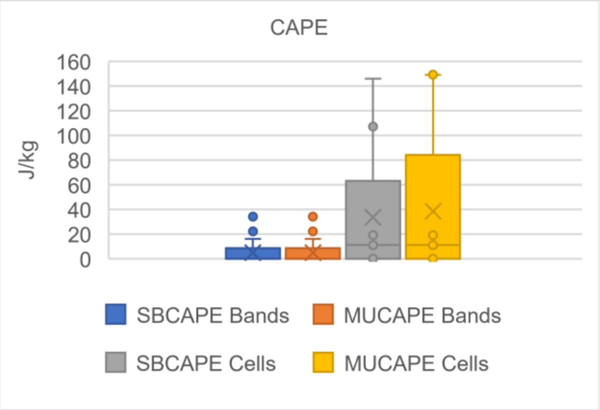

Figure 4: A box a whisker plot depicting CAPE calculated for surface-based and most unstable parcels for bands and cells.

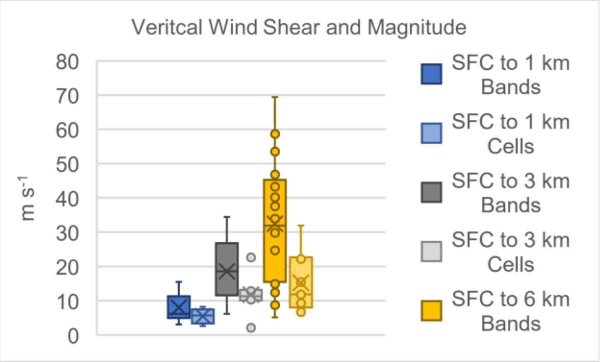

Figure 5: Box and whisker plot of bulk vertical wind shear vector magnitude over three layers of the atmosphere.

Cells:

Cells were identified on radar by having length-to-width ratios close to 1:1 and were found to have higher radar reflectivity values than bands. Cells were most common in February, extending into the spring months (Figure 2). They generally formed in weakly-forced synoptic patterns that included a cold pool aloft that aided in the development of lower tropospheric static instability. Cells formed in more unstable environments, relative to bands, but CAPE values were far below what is necessary for summertime convection (Figure 3b and Figure 4). The Bulk Richardson number was generally above twenty for cells, indicating that these are instability-dominated systems. Cells formed in lower wind shear environments (Figure 5) and their motion followed the 500-hPa steering wind.

Human Impacts:

To determine which mode of snow squall produced the most snow and lower visibilities moisture, dendritic growth zone and ASOS visibility observations were examined. Cells had higher relative humidity over a deeper layer than bands (Figure 3), implying more available water vapor to produce snow. However, bands had deeper dendritic growth zones (Figure 6).

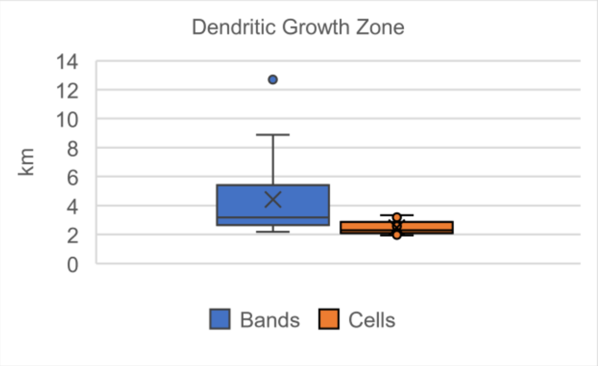

Figure 6: Box and whisker plot for dendritic growth zone depth. Banded cases are shaded blue, and, on the left, cellular are shaded orange and on the right.

This implies that banded cases may have benefitted from deeper layers of efficient snow production. When ASOS data were examined it was found that the average visibility for both bands and cells were the same.

For the twenty-two events with crash data there were a total of fifty-two crashes likely occurring with a passing snow squall. Of those fifty-two crashes, thirty-six were from the banded mode. This lends credence to the idea that bands may be higher impact, but the limited data preclude a definitive conclusion to this end.

4. Conclusions and Future Work

Returning to the three hypotheses posed in Section 1, the following conclusions are drawn based on the results presented:

1) The different modes were clearly distinguishable on radar-based on size, depth, and intensity.

Bands and cells were found to be easily discernable on radar based on length to width ratios. Cells had higher reflectivity values, implying they are more intense, while storm depths were virtually the same around 2 km for both bands and cells. Bands tended to align the long axis parallel to the surface to 500 hPa shear vector.

2) The modes occurred in distinctly different environments characterized by unique profiles of buoyancy, vertical wind shear, and moisture.

Bands formed in the colder months while cells formed in warmer. Bands were found to form more stable environments most commonly in a post-cold frontal environment. Cells had a colder temperature aloft (at the 500-hPa level), creating more instability at the surface which can be seen in the CAPE profiles (Figure 4). Bands formed in higher sheared environments, which could be the reason for their banded appearance. Cells had more moisture, but bands had deeper dendritic growth zones. Both bands and cells have similar average wind values across all layers, and both tended to form in environments with weak synoptic forcing

3) Banded snow squalls were associated with more traffic accidents, but data were limited.

While the crash data was limited it is implied that bands cause more crashes, but more work is needed to clarify this conclusion and determine why. Visibility data show that both bands and cells resulted in similar average visibilities implying similar potential to cause traffic accidents. It is still hypothesized that bands may be more impactful to this end given their larger areal extent, but more complete vehicle crash data are needed to more fully test this hypothesis.

To forecast for a banded or cellular snow squall, in western South Dakota, it is suggested to utilize a combination of instability, shear and moisture, in a similar sense to an ingredients-based forecast for summertime convection (e.g., Doswell 1987, Johns and Doswell 1992). To determine if there is going to be banded or cellular snow squalls vertical wind shear, CAPE and sounding (observed or model) profiles should be used. For bands, there may be minimal CAPE, but high vertical wind shear and an isothermal layer or temperature inversion in the temperature profile. For cells, higher values of CAPE are expected (though still small in comparison to summer convection), low vertical wind shear and more moisture should be evident in the sounding profile. These suggestions should work for *most* snow squall environments, however there are always outlier systems.

More work needs to be done expanding the number of snow squall cases across various areas. While this, and other studies (e.g., Bancos et al. 2014), have done regional studies, a more extensive climatology for snow squalls, over a larger geographic area is needed. Increasing the dataset of snow squalls would help solidify any environmental conclusions made in this work, and others. This would also help identify local scale, environmental differences for snow squalls across the nation giving forecasters a better understanding of their triggers and potential impacts.

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