OBSERVATIONS OF SNOW PARTICLE CHARACTERISTICS DURING THE 9-10 DECEMBER 2018 MAJOR SNOWSTORM IN THE SOUTHERN APPALACHIAN MOUNTAINS

by

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Abstract

Although major snowstorms result in substantial societal and economic impact across the southern Appalachian Mountains, numerous critical parameters (e.g., lower tropospheric thermal structure, snow crystal type and degree of riming, quantitative precipitation forecast) are frequently not well characterized in numerical weather prediction models. This study analyzes the meteorological characteristics of the 9-10 December 2018 major winter storm using data from a Multi-Angle Snowflake Camera (MASC), a vertically pointing Micro Rain Radar (MRR), the ERA-Interim dataset, NOAA's Rapid Update Cycle (RUC) soundings, and other in-situ measurements. In particular, the MASC data allowed for classification of snow crystal types, complexities, and degree of riming throughout the entire storm. There is a clear correlation in the complexity and roughness of the ice crystals as the storm progressed in time. This correlation aligns with different weather variables that were collected on the surface as well as aloft. This study enhances an understanding of the process and components of the winter storm along with an improved understanding of the differences among snowfall events.

Acknowledgements

I would like to specifically thank my thesis advisor, Dr. Rene Salinas. Without his assistance and involvement throughout the entire process, my research and paper would not have been accomplished.

I also would like to thank my research supervisor, Dr. Lester B. Perry. Thank you for allowing me the opportunity to be involved with research in the Geography department. I have learned more throughout this research than I could have ever imagined.

I would like to thank everyone who played a role in my academic accomplishments. My parents, who have supported me throughout my entire college career and challenged me to do my absolute best. As well as my professors, who have provided knowledge, help and support throughout my time at Appalachian State.

Contents

1 Introduction

Temperature, humidity and other upper level atmospheric conditions are all factors that contribute to the formation of ice crystals. The intricate shape of a single arm of the snowflake is determined by the atmospheric conditions on the entire ice crystal as it falls. As a crystal is moving throughout various conditions, it could grow arms in one manner and then slight changes could occur causing the ice crystal to grow another way because of the surrounding temperature and dew point temperature. While the arms of the crystal experience the same atmospheric conditions, the arms will always look identical [3]. Through this, the result is a production of diverse, complex patterns throughout all formations of the crystals.

On 8 December 2018, a strong high pressure was centered at the Great Lakes to the Mid-Atlantic. Simultaneously, an area of low pressure was strengthening across the southeast. The area of low pressure was over Louisiana and the cold air regime set up across Virginia and parts of the Carolinas with strong winds out of the north east. This low pressure pulled significant moisture from the Gulf and Atlantic into the Southern Appalachian region. The cold layer was deep enough for mainly snow, with brief periods of sleet and very light freezing rain towards the beginning of the storm. This winter storm crippled parts of the southeastern United States. The resulting snowfall was significant throughout the entire forecast area. The swath of heavy snow had enough weight in some places that it resulted in power outages, and created extremely hazardous conditions. This was the second or third largest December snowfall on record for many of the locations affected [10] [12]. There was a staggering 34 inches recorded on the top of Mount Mitchell in North Carolina and 16.5 inches recorded in Boone (Fig. 1) [12].

The progression of the storm is shown through a surface analysis, Infrared (IR) satellite image, and a weather radar analysis [5]. The surface analysis shows locations of synoptic scale high and low pressure centers with associated surface fronts and troughs for the specific analysis time (Fig. 2). The IR satellite image acts as a temperature map, showing any detection of heat energy in the infrared spectrum. It displays clouds, water, or land surfaces based on the temperature of the object. Warm temperatures appear in the cooler shades, while the colder temperatures display in the warmer shades (Fig. 3). The weather radar analysis is used to locate precipitation, calculate its motion, and estimate the type of precipitation (Fig. 4). Lastly, the 250 mb height wind analysis shows the wind speed and direction at the 250 mb height (Fig. 5) [6].

At 0000 UTC on 9 December 2018, the WPC Surface Weather Analysis placed a 1010 mb center of low pressure over the Gulf of Mexico on the coast of Mississippi (Fig. 2). The cold front extended south from the low pressure along with a warm front stretching across the panhandle of Florida. The was a high pressure of 1036 mb placed over Ohio and Lake Erie. The winds were pushing North East, with the strongest winds displayed as the darkest colors (Fig. 5). The infrared satellite imagery shows a cloud pattern typical of those associated with developing low pressure systems (Fig. 3). By 1200 UTC, the low pressure of 1010 mb had moved into Georgia, and the high pressure had moved down into eastern Pennsylvania. The warm front progressed out into the Atlantic, and a stationary front had developed in South Georgia and the winds shifted to NNE direction. Precipitation started moving up the east coast and the common cloud pattern seen in satellite imagery developed. By this time, Boone was receiving some of the heaviest precipitation seen throughout the entire storm. While the low is still located on the Mississippi coast, precipitation covers the majority of the South Eastern United States. As the low pressure moves up the Atlantic coast line, we see the weather being pushed by the low pressure into the majority of the Carolinas, Virginia, Kentucky and Tennessee. With this push, there is a squall line that moves along in front of the cold font, that brought a line of rain storms through the entire state of Florida. As this stormed moved up the coast, there was also a change in surface wind directions. Early on 9 December, the winds were recorded as an easterly flow, which transitioned to more of a north easterly flow by 0800 UTC. The winds stayed north easterly, until about 0100 UTC on 10 December, and then we saw a shift to Northerly and North Westerly winds. The remainder of the storm finished with strong Northerly winds. This effect is typically seen when big storms move north through the Appalachian Mountains. As the storm is being pushed north, there is a circulation of the snow that pushes one last band of weather back over the Appalachian Mountains. This is typically known as a Northwest Flow Snow (NWFS) event. NWFS are known for nearly 50% of average snowfall totals along the Southern Appalachian Mountains [8]. The winds at the 250 mb level from 0000 UTC on 9 December to 0000 UTC on 11 December were also reviewed. The winds started almost easterly, and as the storm progressed, a trough developed in the central United States. This then shifted the winds north easterly and they continued this way as the trough moved over the eastern states (Fig. 5).

2 Methods

A multi-angle snowflake camera (MASC) is placed on top of Garwood Hall in Boone, North Carolina. This device has three different cameras that take images of a flake when the top-mounted motion sensor is triggered. The cameras are triggered by a vertically stacked bank sensitive infrared motion sensors that are designed to filter out slow variations in ambient light. Once the camera photographs whatever passes in front of it, the MASC provides a more accurate overview of what forms snowflakes typically take. The MASC also measures the speed at which the flakes fall [7]. Surprisingly, the physical forms of the snowflakes taken from these cameras turns out to not depict what a typical snowflake looks like. A six-sided snowflake, is very rare to capture. Falling snowflakes will accumulate water droplets and they will freeze onto them and combine with other snowflakes which will typically been displayed in a variety of shapes and sizes. The MASC device incorporates two 1.2-megapixel cameras and one 5-megapixel camera. Tens of thousands of images can be captured in a day, and everything is recorded into a large dataset. The MASC withstands all types of cold weather and runs unattended [7].

After the images are captured, they are sent to students and staff at North Carolina State University. All of the images are run through a program which defines a variety of variables for each of the individual flakes. All of these variables are then placed into an application called The Client App. This application can be downloaded, and users have access to a large dataset filled with years of snow flake data. On the client app, you can query many different databases. I filtered out data for MASC table and used the site name 'asu.' This allowed me to select any date from the Appalachian State database of snowflake images. By selected the 9-10 December 2018 winter storm, I had access to over 10,000 images and variables for snowflake data in Boone. On the Client application you are able to filter through different variables. The program that the images of the flakes are ran through creates a list of variables to be able to filter through. The dataset created contains the flakes fall speed, max diameter, equivalent radius, perimeter, cross section, aspect ratio, complexity, focus, total pores, symmetry, fractal, mean intensity, solidity, radial variance, roughness, corners, and more. I primarily used the diameter, complexity, radial variance and roughness. The max diameter is defined as the length of the axis that is the maximum diameter of the flake cross-section and is measured in millimeters. The complexity is measured as the product of two different values. Complexity is measured as the product of the ratio of the perimeter to the computed circumference and 1 plus the average inter-pixel brightness of the flake. Complexity is measured with values close to 1. If the values are less than 1.35, the flake tends to be lump or conical graupel. If the value is greater than 1.75, the flake tends to be more aggregated. I also used radial variance and roughness which are two values that also have success in delineating between graupel and aggregates as well as between degrees of riming. Radial variance is measured from the calculated center of the flake to the area of the convex hull that encloses the flake and is measured as value from 0 to 1. The roughness is measured as the difference between the max diameter and the max diameter as calculated by the measured area of the flake. Roughness is measured in millimeters.

The vertically pointing Micro Rain Radar (MRR) located in Boone, provided another outlook on the event. Data was provided through the METEK MRR dataset from North Carolina State University on an online OPL MRR Java Viewer. A time vs. height display of the radar reflectivity showed the passage of the initial storm between 0100 UTC and 1800 UTC on 9 December (Fig. 6). Moderate to heavy snow throughout the storm was observed from 0700 UTC to 1300 UTC. Then on 10 December, from 0700 UTC to 1400 UTC, another band of the winter storm came through Boone. The radar derived Doppler velocity product from the MRR gave additional information about precipitation type in the column above the radar (Fig. 7). The darker blue shades, and green indicated faster fall speeds. The near-surface dark blue shades were the time during which moderate to heavy snow was observed.

Two other datasets were used in comparison to the MASC data. I retrieved data from ERA-Interim dataset. ERA-Interim is a global atmospheric reanalysis from 1979 that is continuously updated. The data assimilation system used to produce the ERA-Interim is based on a 2006 release of the IFS (Cy31r2). The system includes a 4-dimensional vibrational analysis (4D-Var) with a 12-hour analysis window. The spatial resolution of the data set is approximately 80 km on 60 vertical levels from the surface [1]. Through the ERA-Interim, I was able to specify a custom area to 36.316°N, 81.979°W. The custom area needed to encompass a 0.125x0.125-

degree box around the point of interest. So, I subtracted half of 0.125 from the latitude and longitude of the point to derive the West and South coordinates and add the same amount to derive the East and North components. I then was able to extract 500, 700, 850, and 1000 mb level data with a variety of different variables over the span of the winter storm. This extracted data every six hours throughout each day. The ERA-Interim extracted divergence, fraction of cloud cover, geopotential, ozone mass mixing ratio, potential vorticity, relative humidity, specific cloud ice water content, specific cloud liquid water content, specific humidity, temperature, U component of wind, V component of wind, vertical velocity, and relative vorticity. The relative humidity, temperature and U and V components of the wind were the most beneficial variables for this study from this dataset.

NOAA's Rapid Update Cycle (RUC) soundings were also used in the study. I was able to access sounding analysis for the 9-10 December snow storm. These soundings provided a visual for the surface and upper atmosphere conditions (Fig. 8). I was able to extract soundings from each hour. With these soundings came a text file that included the altitude in feet, the pressure level, temperature, dew point temperature, wind speed, wind direction, and time [2]. All of these parameters were beneficial to this study and were all used. I extracted the data from each hour at specific pressure heights. I stayed consistent with the ERA-Interim data and extracted 500, 700, 850, and 1000 mb data. This allowed me to look at the hourly conditions at different levels in our atmosphere.

After extracting all the data necessary, I was able to average hourly data from the MASC dataset. The original dataset had over 4,000 entries of flakes, which made it difficult to see any trends. I took an average of all the flake data within the same hours. This created a smaller dataset that allowed me to look at correlations clearly. I was then able to see some trends in the flakes over time, specifically in the complexity and roughness variables. Then with the MASC dataset being hourly, the RUC soundings were easy to compare. This is where I found the majority of my results.

3 Results

Flakes continue to change as they fall through different atmospheric conditions. As I was looking at the flakes as they approached the surface, I saw the strongest correlations with the near surface atmospheric conditions. Focusing on the conditions at the 900 mb level, temperature, dew point, and relative humidity were all factors that I found to contribute to the formation of the ice crystals.

As I looked at the MRR data, there was a clear break in the storm (Fig. 6, 7). As I analyzed the complexity, radial variance, and roughness of the flakes I noticed that as the storm progressed, these variables increased. As the storm moved through Boone, the temperature and dew point temperature continued to increase as well. The roughness of the flakes generally increased with an increase in dew point temperature at the 900 mb level. The roughness of the flakes also increased with an increase in the air temperature at the 900 mb level (Fig. 9). There is also a positive correlation in the average roughness of the flakes over time, and it has a very similar trend to the correlation of dew point at 900 mb and the roughness of the flakes (Fig. 10).

As the storm progressed, the temperature and dew point temperature both significantly increased as well (Fig. 11). At the start of the storm, the temperature and dew point were higher, which is why we saw higher complexity flakes. The higher temperature and dew point create more aggregation in the flakes. Aggregates can be explained by a group of ice crystals lumping together. These ice crystals can be seen in any formation, but for this storm the majority were dendrites. As the storm became colder and dryer, we typically saw single dendrites or a single graupel. As the storm moved through Boone, the trailing end of the storm had significantly larger roughness values that correlated with a higher temperature and a higher dew point temperature. The aggregates seen during these conditions had much higher roughness values and were larger in diameter (Fig. 12).

The typical structure of a snowflake is six sided. As flakes fall through different atmospheric conditions, their overall formation can change. When individual dendrites or graupel fall through moist conditions they condensate. As this occurs the flakes are more likely to clump together. This is why some of the images from the MASC don't appear how one may assume a typical snowflake would appear [3] [4]. As the temperatures rose and were nearing freezing point, the atmospheric conditions were extremely moist. This is why the flakes depicted for the second part of the storm appeared to be larger and more aggregated (Fig.12). The temperature and dew point temperature had a strong correlation with the diameter of the flakes. The higher the temperature or dew point temperature, the larger the diameter (Fig. 13).

I was also able to extract images of the flakes from any of the MASC dataset entries throughout the storm. By doing this I was able to see exactly how the flakes appeared in relation to their complexity and roughness values (Fig. 14). The flakes at the beginning of the storm had on average a roughness value of 1.8. As the storm progressed, the roughness values decreased. The roughness continued to stay relatively low, especially from 1500 – 1700 UTC on 9 December. Looking at the Doppler velocity data (Fig. 7), we can see that during this time the dark blue shades were near the surface. As these dark blue shades indicate a faster fall speed, this indicates that this was a time where moderate to heavy snow was observed. Also, this shows that there was an increase in the degree of riming and the formation of graupel as there was an increase in the Doppler velocity in the lowest parts of the storm. The combined information from the MASC images and the MRR allows us to quantify the variability of the flakes throughout the entirety of the storm.

As the second part of the storm passed through on 10 December at 0700 – 1400, flake roughness was statistically significant from the initial part of the storm. Not only did the roughness look significantly different, but the diameter did as well. With a visually large difference, I decided to run a two- sample t-test to test the difference (d_0) between the mean values from the two parts of the storm. This will help to see if the average difference between the two groups is really significant or if it is due to random chance [9]. I first defined the hypothesis. The null hypothesis (H_o) was that the two means were equal: $\mu_1 = \mu_2$. The alternative hypothesis was H_a: $\mu_1 = \mu_2$. After running the two-sample t-test, the results showed a p-value < 0.1. The two-sample t-test calculated a p-value = 6.6×10^{-4}(Fig. 15). With this p-value I was able to reject the null, H_0, and accept the alternative, H_a. The alternative hypothesis states that the difference in means is not equal to zero, $d_o \neq 0$. This essentially states that there is a statistical difference between the two means.

As the storm progressed, not only did the flakes become more complex but they also appeared larger. As the warmer temperatures influenced the formation of the flakes, the larger the aggregates became. I then ran a two-sample t-test on the mean diameter values from both parts of the storm, using the same null and alternative hypothesis. The two-sample t-test calculated a p-value = 9.4×10^{-3} (Fig. 16). With this p-value I was able to reject the null, H_0, and accept the alternative, H_a. This also shows that there was a statistically significant difference between the two means.

4 Conclusion

With a statistically significant difference in the roughness value between the two parts of the storm, I was able to see that the temperature and dew point had an influential effect on the formation of the flakes near the surface. Snow flakes appear differently at different layers in the atmosphere, and continue to alter their formation as they fall. Looking at the near surface conditions helped to see what was causing the flakes to appear the way they were at the surface.

As the storm started, the snow was very dry and the consistency was similar to powder. When the air was dry near the surface, the flakes fell mostly as single dendrites or as a single graupel. As the storm progressed, we saw an increase in temperature and dew point on the surface which then lead to more of a heavy and wet snow. The surface at this time had more moisture with warmer temperatures and higher dew points. This influenced the snowflake formation by creating more aggregates. As the flakes fell through the warmer conditions, they had more condensation and stuck to each other. This created a more complex, larger formation of the flakes.

Through this study there were some complications. Extracting meteorological datasets were challenging, and not easily accessible. It took a lot of manipulation of code in MATLAB, along with finding and downloading the specific variables desired to extract. I also had to contact people working for NOAA, which took a lot of time to hear back from them. There were also some outliers found throughout the MASC data. There were four flakes that had extremely high complexity and roughness values in the middle of the storm around 2200 UTC on 9 December. Looking at the MRR data, there was no precipitation falling at the time. With only four flakes, we concluded that they weren't significant enough to keep in the data and were removed.

As I have studied the surface conditions along with flake formations, further research incorporating upper level conditions from the ERA-Interim and RUC Soundings datasets could have shown more correlations related to the dynamics of the atmosphere and the formation of the flakes. I would want to compare the upper level conditions to the type of flake that fell to the surface (e.g. dendrite, needle, or graupel). Throughout this storm there were a variety of formations seen at the surface. I think it would be interesting to look at the upper level conditions to see the relation to the form of the flake that lands at the surface. Additionally, analyses of other large snow events could also provide insight into the observations of snow particle characteristics.

5 References

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6 Figures and Tables

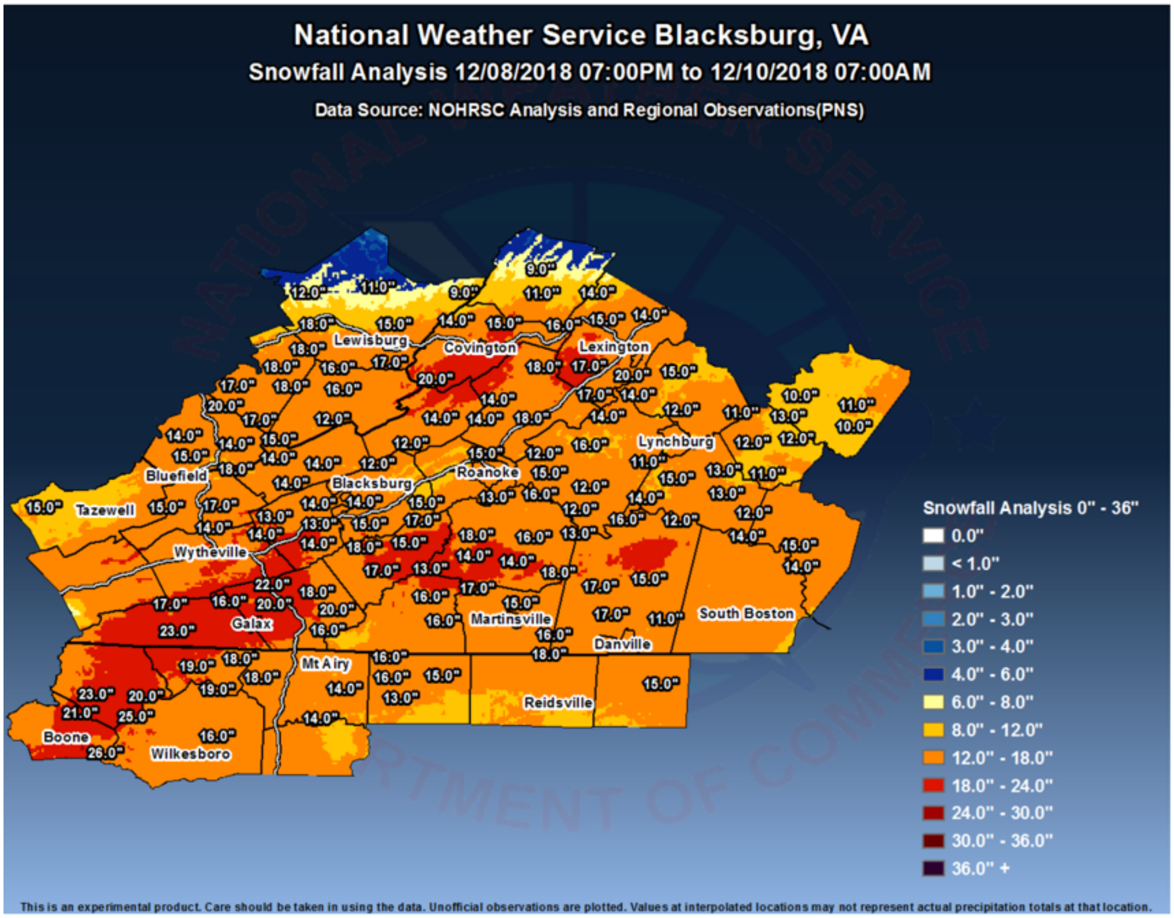

Figure 1. ***Image of Snowfall Report:*** *The total snow accumulation for the period 8-10 December 2018 across the Southern Appalachian Mountain area [11].*

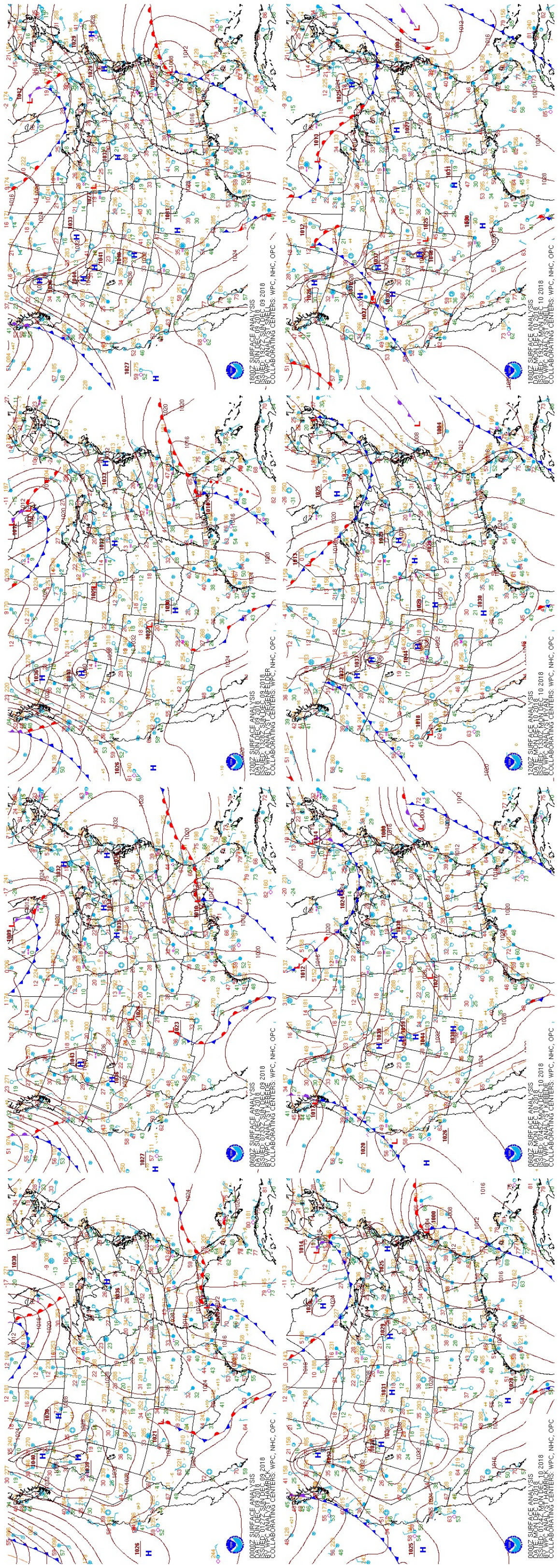

Figure 2. ***The surface analysis*** *-The top left image of each analysis is at 0000UTC on 9 December and is pictured every six hours. The images are read from left to right and continue to 1800 UTC on 10 December [5].*

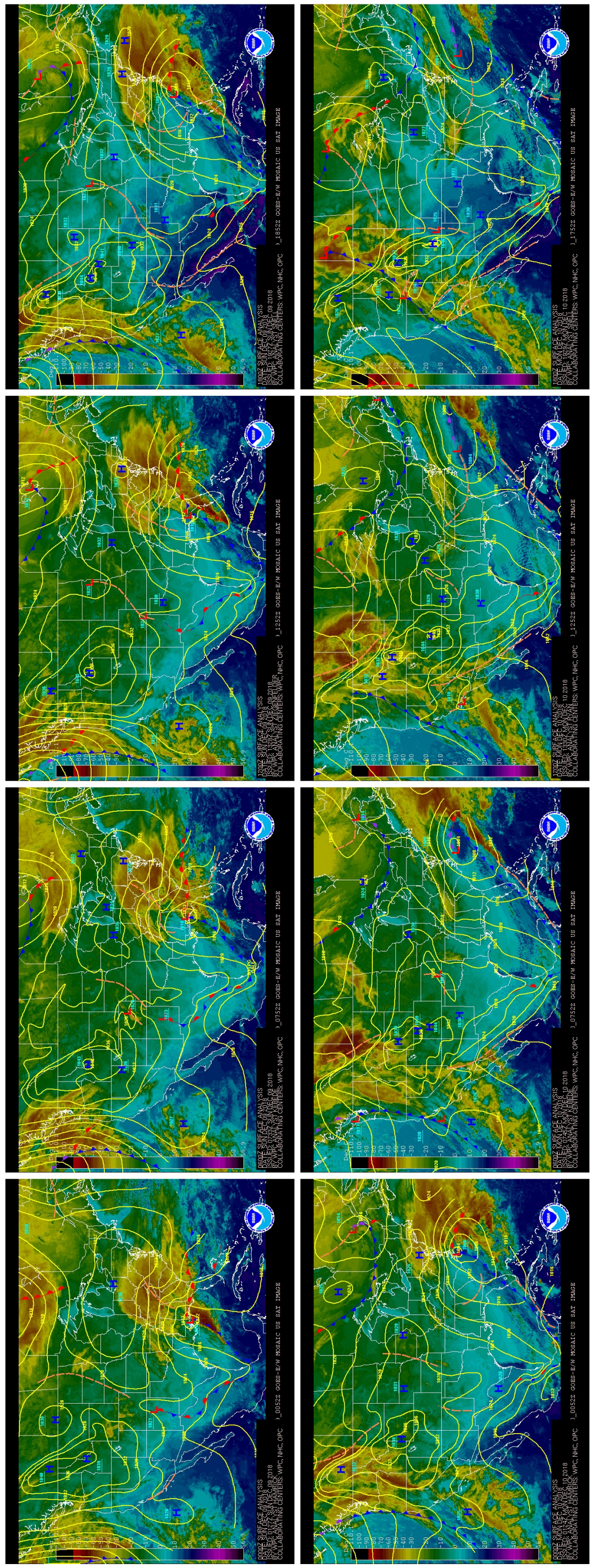

Figure 3. ***Infrared (IR) satellite image*** *-The top left image of each analysis is at 0000UTC on 9 December and is pictured every six hours. The images are read from left to right and continue to 1800 UTC on 10 December [5].*

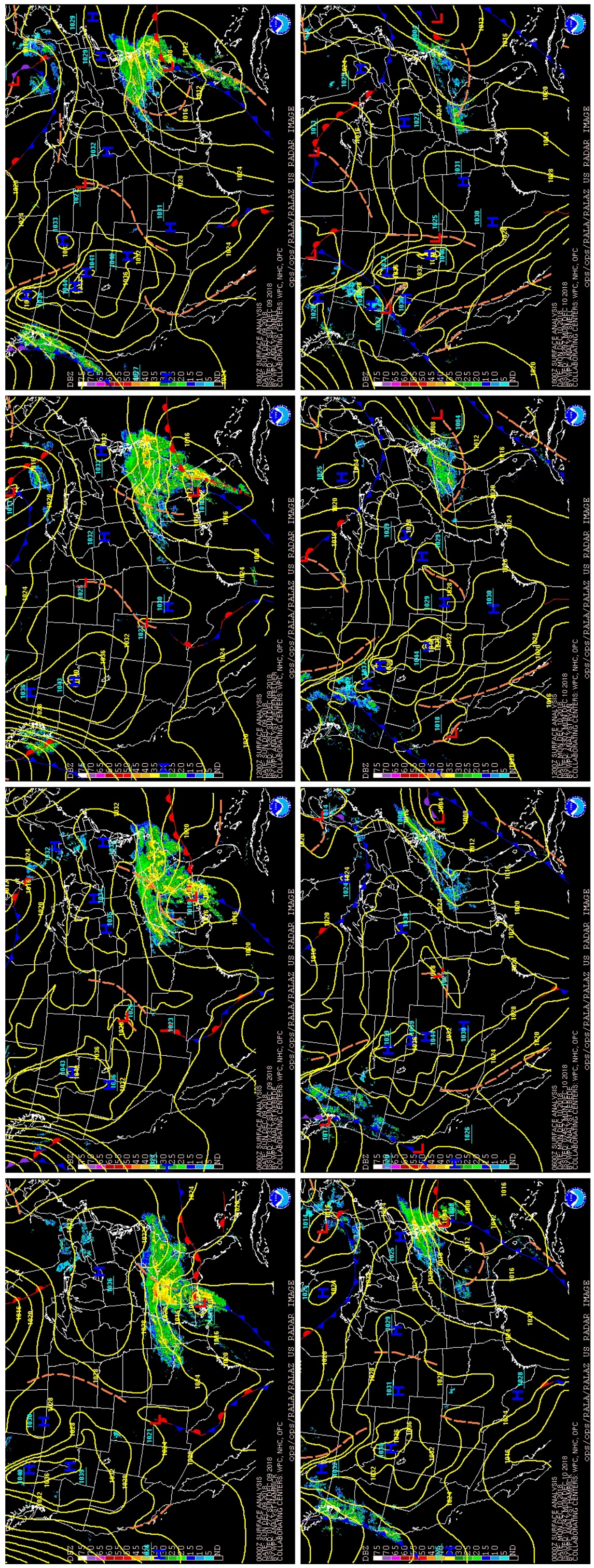

Figure 4. ***Weather Radar Analysis***-*The top left image of each analysis is at 0000UTC on 9 December and is pictured every six hours. The images are read from left to right and continue to 1800 UTC on 10 December [5].*

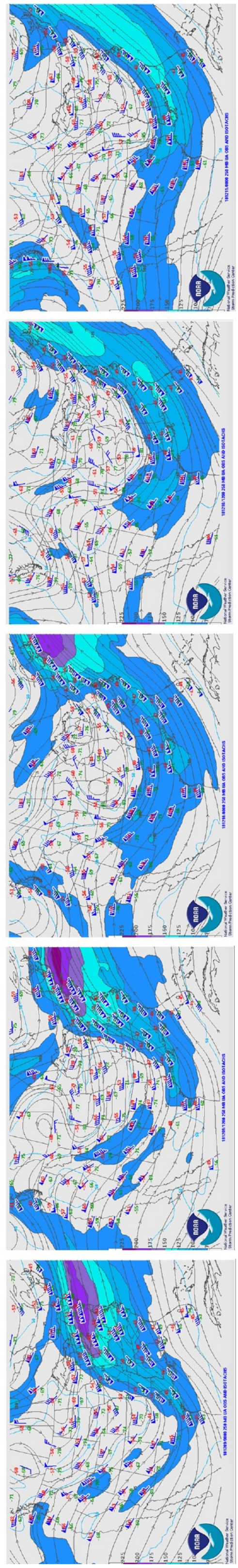

Figure 5. ***250 mb Level Winds:*** *The winds are shown from 0000 UTC on 9 December and imaged every 12 hours to 0000 UTC on 11 December. The images depict the wind direction and wind speed with the darker blue colors displaying the fastest wind speeds [6].*

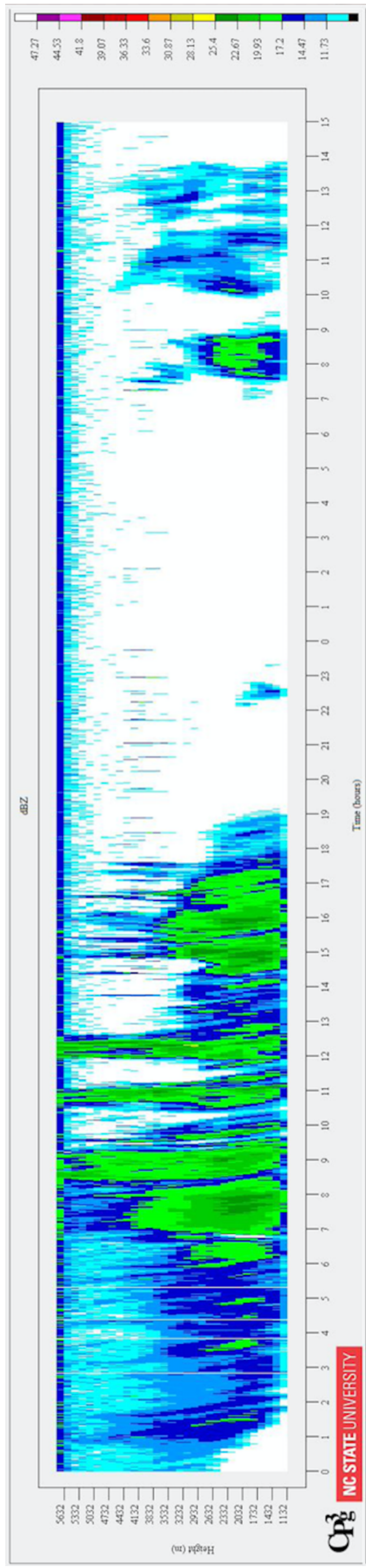

Figure 6. *Vertical profile of radar reflectivity from the MRR in Boone, North Carolina, from 0000 UTC on 9 December to 1500 UTC on 10 December. Horizontal axis is time (UTC). Vertical axis is height above ground level (m).*

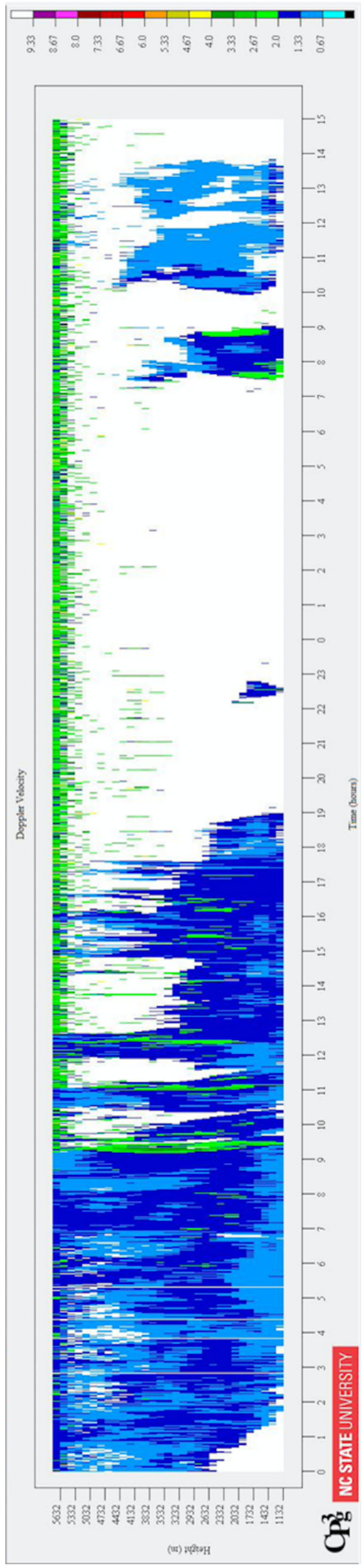

Figure 7. *Vertical profile of particle fall Doppler velocity from the MRR in Boone, North Carolina, from 0000 UTC on 9 December to 1500 UTC on 10 December. Horizontal axis is time (UTC). Vertical axis is height above ground level (m).*

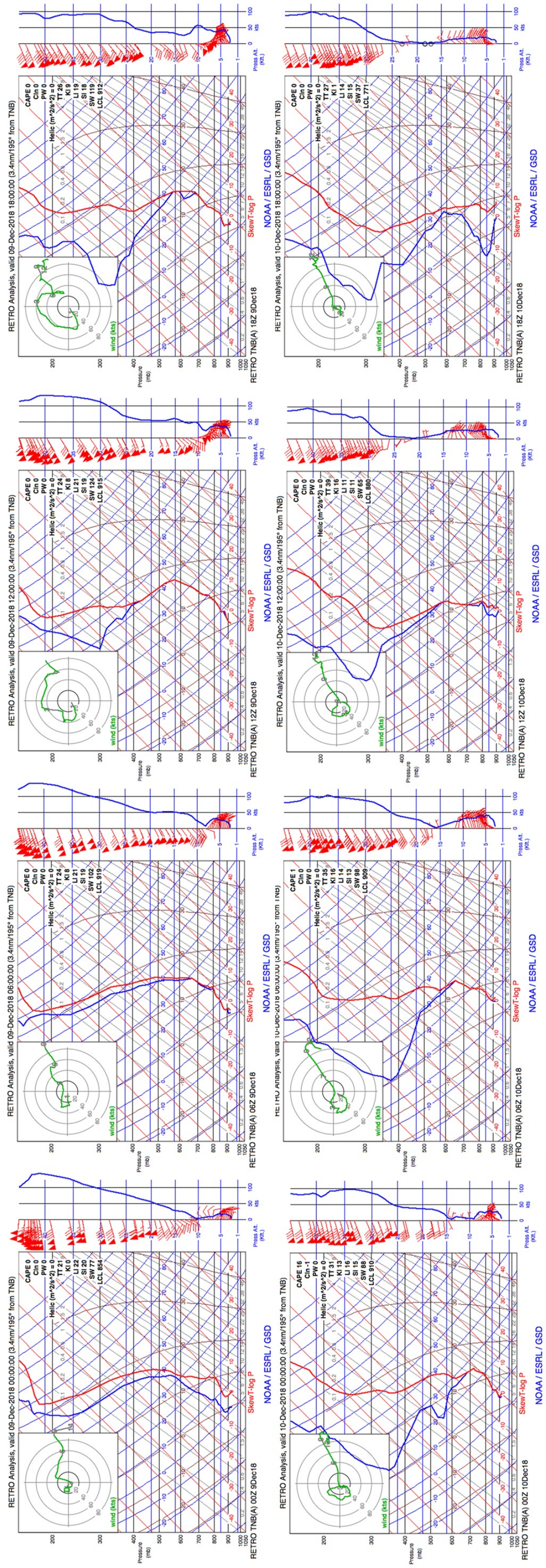

Figure 8. ***RUC Soundings*** *- Top left image is at 0000 UTC on 9 December. Images are every six hours and goes through 1800 UTC 10 December. The soundings include the dew point temperature, actual temperature, wind speed, and wind direction [2].*

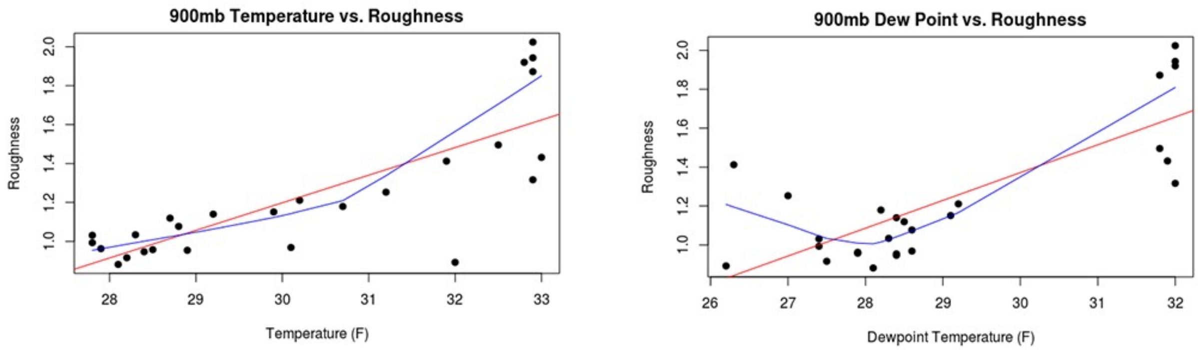

Figure 9. *The left image shows Temperature at 900 mb vs. roughness of the flakes. The right image shows the dew point temperature at 900 mb vs. roughness of the flakes.*

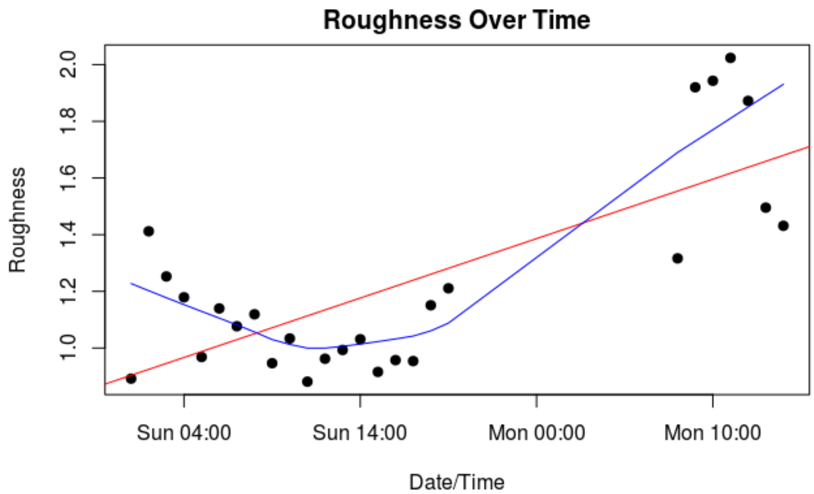

Figure 10. *Average roughness of flakes over time*

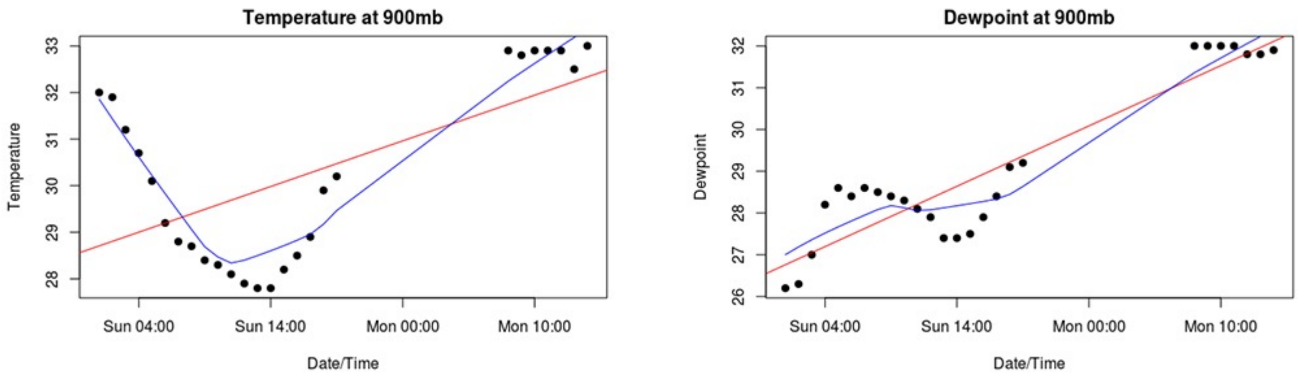

Figure 11. *The Image on the left shows the temperature at the 900mb level over the time of the storm. The Image on the right shows the dew point temperature at the 900 mb level over the time of the storm.*

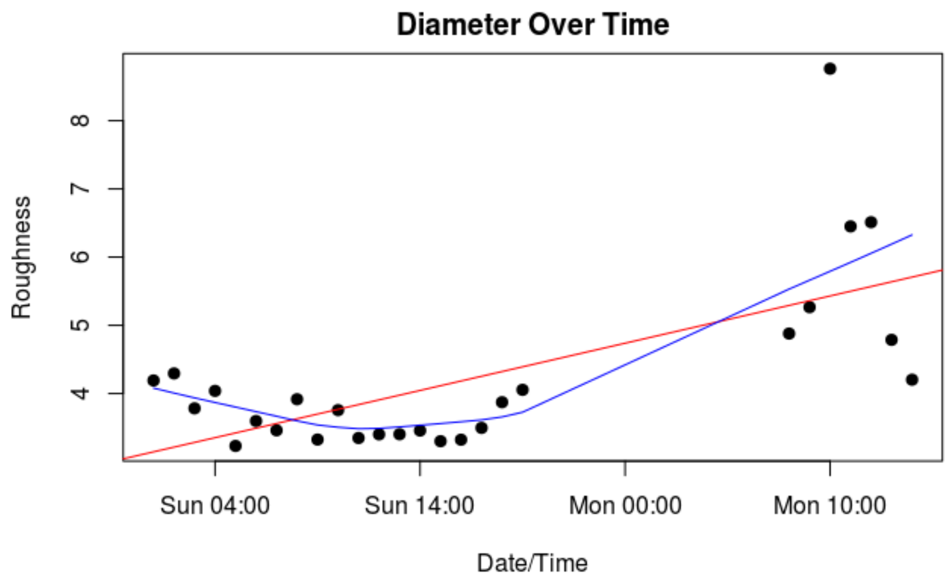

Figure 12. *Average diameter of the flakes over time*

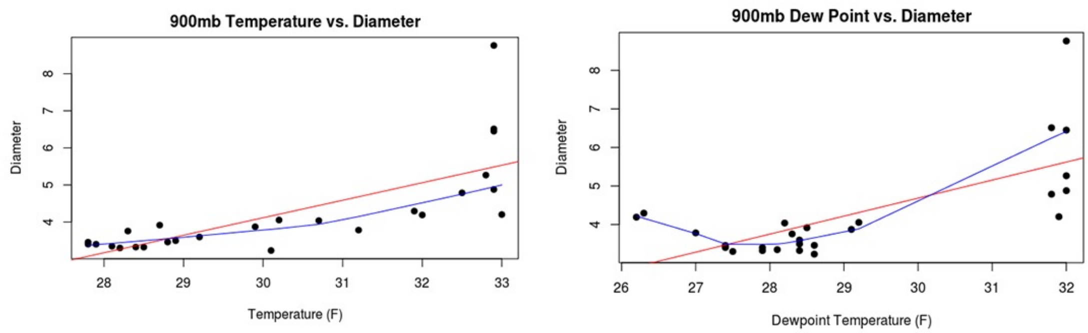

Figure 13. *The left image shows Temperature at 900 mb vs. the diameter of the flakes. The right image shows the dew point temperature at 900 mb vs. the diameter of the flakes.*

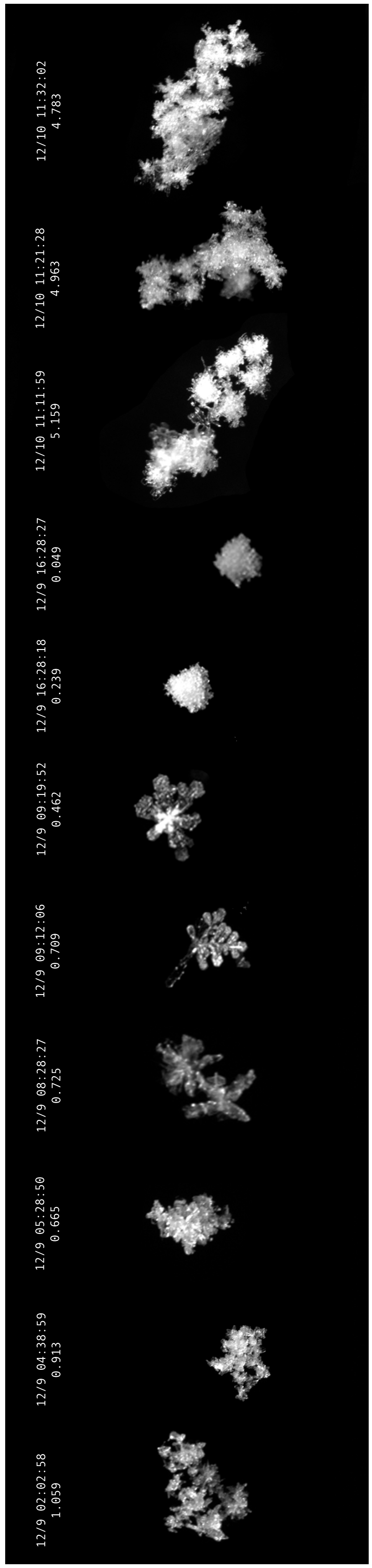

Figure 12. *Images from the MASC. Images are in order of the progression of the storm. Listed above each of the flakes is the date and time, along with the roughness value of the specific flake shown.*

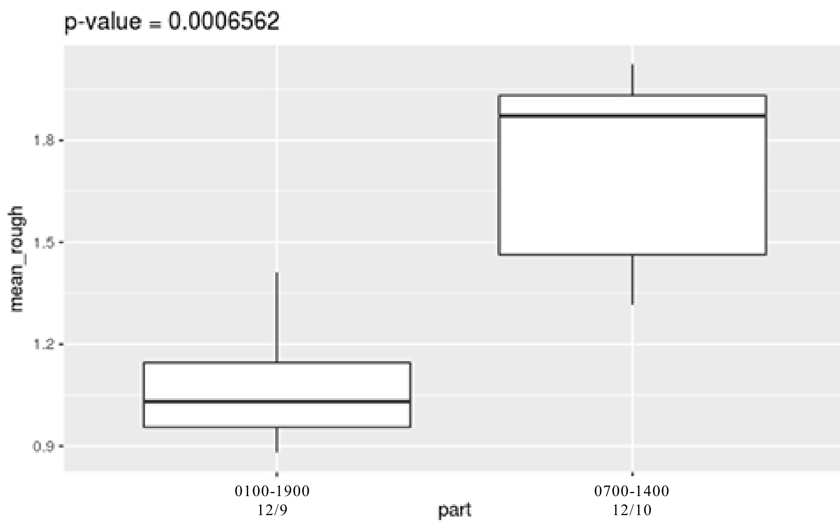

Figure 13. *A box plot of the mean roughness values for the first and second part of the storm.*

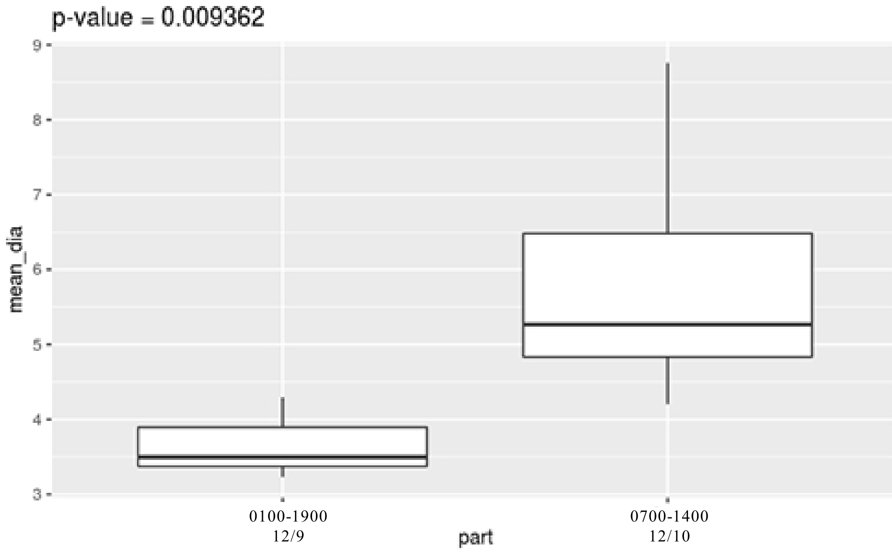

Figure 14. A box plot of the mean diameter values for the first and second part of the storm.

Table 1. *Statistical variables for the roughness value for the two parts of the storm.*

	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum	StDev
12/9 0100 - 1900	0.8813	0.9556	1.0310	1.0566	1.1453	1.4120	0.1406
12/10 0700 - 1400	1.316	1.463	1.872	1.715	1.931	2.024	0.2891

Table 2. *Statistical variables for the diameter value for the two parts of the storm.*

	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum	StDev
12/9 0100 - 1900	3.232	3.375	3.497	3.645	3.895	4.295	0.333
12/10 0700 - 1400	4.203	4.833	5.266	5.837	6.481	8.762	1.549