Factors Influencing Snow Crystal Riming at Storm Peak, Steamboat Springs, Colorado

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Abstract: Drawing on past research and research techniques, the author of this paper along with a co-researcher collected and analyzed rime ice and snow at Storm Peak Laboratory in Steamboat Springs, Colorado. The collection times are paired with air trajectories from the same period to examine the possible effects of anthropogenic emissions on cloud condensation nuclei concentrations, which are a large factor in determining riming levels on snow crystals. A model derived for Lohmann et al. (2004) shows the cloud condensation nuclei concentration is affected by anthropogenic emissions. This paper will evaluate research done by direct observation and not on a model run to support or disprove the Lohmann et al. model (2004). Research techniques are adapted from these papers and are fully described.

Introduction

Often in winter storm clouds, liquid cloud droplets exist in addition to ice crystals. Rime is defined as "a white or milky granular deposit of ice formed by the rapid freezing of supercooled water droplets as they come in contact with an object in below freezing air" (*Meteorology Today*, 2000). The objects on which rime accumulates may be in the form of ice crystals suspended within the cloud or large surface objects such as vegetation and buildings. The riming effects and efficiencies are dependant on cloud condensation nuclei (CCN) of which the concentrations within the cloud determine the size of the cloud droplets and thus the ability for ice crystals to collect the rime within the cloud through the Bergeron process, which describes how a crystal grows at the expense of the liquid cloud droplets surrounding it. Borys et al. (2003) states that within a polluted cloud, the riming is essentially shut down when droplet sizes are small enough that the collision-coalescence process is stopped, which occurs when cloud droplets fall through the cloud to collide and merge with other droplets combining to form larger droplets. (*Meteorology Today*, 2000). The CCN concentrations are important for determining the size of the cloud droplets. This is shown in a model produced for Lohmann et al. (2004) and also examined in a Berg et al. study (1990) that agreed with the later developed model findings.

The importance of the study of the riming process is presented by Hindman et al. (1983) as he presents the frequency of riming events is high and therefore important to the overall hydrological cycle and can lead to differences in snow chemistry, density and fall amounts. The study also discusses the efficiency and collection processes of riming events. The findings, also supported by Hindman and Grant (1981) show that rime ice deposition occurred during most snowfall events in high elevations during a study period of February to April 1981 at Vail and Steamboat Springs, Colorado. These results as presented in Hindman et al (1983) show a rime ice occurrence of 75% in high elevation winter storms at Steamboat Springs as well as other research locations not dicussed here.

Also presented in the Hindman et al (1983) study is the spatial situation of rime ice collection. It is observed that on average the uppermost 400 meters of Storm Peak are enveloped in a cloud. As winds move the cloud and the droplets suspended within it over an area rime ice is deposited onto all collection surfaces present at the time. Through a series of calculations involving the rate of liquid water passage across Storm Peak, temperature, wind speed and cloud droplet radius, it is determined by Hindman et al. (1983) that rime is deposited on the order of 10^4 g/hr.

Also through observation it is documented that the riming rates are up to seven times greater than the precipitation rates (Hindman et al., 1983). In comparing precipitation and riming rates as well as the frequency of rime ice events it is concluded by Hindman et al. (1983) that the riming process contributes as much as 60% of the annual snowpack water content, showing that the study of rime ice events is important to furthering understanding the hydrological cycle as well as storm processes. As water is an important issue in the western United States and very regulated by the government, the study of rime can contribute to the rationing of water and prediction of liquid equivalent precipitation amounts available for public use. Rime ice on high elevation trees is said to account for 10% while 50% is attributed to the riming of ice crystals within the cloud.

As previously mentioned, the riming effects and efficiencies are affected by pollution as CCN in the cloud. Borys et al (2003) states that the riming rate as well as the snowfall rate is initially increased with the increase of pollutants. If the pollutant concentrations and therefore CCN concentrations increase to a level at which the cloud droplet sizes become too small for the collision-coalescence process to work properly (diameter equal to or less than 10 µm) the riming process is shut off. The pure snowfall rate then is eventually increased due to the accretion of snow crystals with drizzle-size drops within the polluted cloud.

With this idea in mind that an increase in CCN concentrations directly affects the riming process, Lohmann et al. (2004) studies the effects on increased CCN concentration due to anthropogenic emissions. A model known as the ECHAM4 GCM was created for the study to show the riming effects of pollution introduced into the atmosphere. When sulfate, black carbon and organic carbon emission rates were set to zero in the model run, only natural emissions from forests were left to influence the riming rates of a cloud. The model concluded a decrease in riming rates with the decrease in CCN diameter was due to increased anthropogenic aerosols from pollution. It should be noted that in this study all observations were taken from a model runs and natural occurrences of riming may not be accurately portrayed and should be further investigated in the natural environment. The study performed by Betker and Eagan at Storm Peak Laboratory will attempt to create a less model-dependant database for the comparison of pollution levels to riming levels through CCN concentrations.

Model air trajectory runs using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) were ran for the purpose of this paper's research to estimate pollution levels as high or low depending on origin and will be discussed later.

Prior to the development of the ECHAM4 GCM, a Berg et al. study (1990) took observations of rime deposits also to determine the effects of pollution on rime. Berg et al. (1990) looked at ion concentrations within the rime deposits to determine the effects of pollution. Betker and Eagan will also look at sample conductivity as well as pH levels for similar comparisons and attempt to connect this data with that of the HYSPLIT and other observations. The cloud acidity and chemistry of rime ice and snow can and will be addressed by Betker and Eagan to analyze the extent to which the pollution has affected the cloud processes. Berg et al. (1988) and Berg et al. (1991) studies mention that pollutant concentrations are significantly higher in rime deposits than in snow. Higher conductivity and lower pH indicate more riming on the snow crystals. The melted rime samples at each of five studied sites were found have larger ion concentrations than the melted snow samples at each site. For winter storms the ion concentration differences were found to be significantly greater than 0. This difference of conductivity and pH of rimed and unrimed snow shows that high pollution levels act to decrease riming due to decreasing the size of the cloud droplets within a polluted cloud. It is noted that small sample sizes could alter the impact of this data. It may be possible in that larger samples could produce less dramatic results but also that the differences that may occur with sample size differences are inescapable due to the differing chemistry of individual rime events at each location (Berg et al., 1998). The repetition of sampling sought to reduce the errors that may have occurred.

Many factors can affect the analysis of the influence of rime, as presented in Berg et al, (1990). The rime collection efficiency increases as the size of supercooled droplets and wind speed increase. The shapes of the collector, such as the varying shapes of ice crystals also affect the efficiency. The mere fact that riming occurs on snow crystals may somewhat alter the chemistry of the snow by mixing with the chemistry of the rime in some natural snow events. The chemistry of the rime may also be altered due to sublimation that may have occurred between the time of deposit and the time of collection. These factors that have the potential to alter the chemical and physical analysis of rime ice as well as snow were presented by the authors Berg et al in their 1990 study.

Each of the previous studies mentioned investigates different aspects of riming. The topics of pollution, frequency of events, rate of riming and chemistry were mainly developed throughout each of the papers. Betker and Eagan continue the study of rime in the Rocky Mountains at Storm Peak Laboratory in Steamboat Springs, Colorado, attempting to integrate all previous research into a single concise study. It has been determined that the effects of pollution due to anthropogenic sources impact the effects, efficiency and chemistry of riming due to the alteration of CCN concentrations and the introduction and alteration of ions into the atmosphere. The study of rime was shown to be valuable as its effects on the environment with respect to annual snowpack water content and pollution rates. All data and observations taken by Betker and Eagan are supportive of the previous data mentioned and will be further discussed throughout the following paper.

Methodology

All data was collected and processed over a weeklong period from 11-18 March 2006 at the Storm Peak Laboratory in Steamboat Springs, Colorado. Data was taken in collaboration with Bridgette Eagan, also an Undergraduate in the department of Atmospheric and Oceanic Sciences at the University of Wisconsin – Madison. Samples of pure rime were collected using a Cloud Sieve during snow events. The cloud sieve was mounted on the roof of the Storm Peak Laboratory perpendicular to the mean wind direction, determined by the main wind vane shown in figure 1a. This allowed for maximum collection of rime during each event. During the same events and in close proximity to the Cloud Sieve, snow was collected using clean plastic bags attached with rubber bands to de-iced wind-vane-equipped cylinders (shown in figure 1b). The wind vane allowed for the plastic bag openings to be continually directed into the wind for maximum collection volumes. Later samples were collected in a secondary collection device of plastic bags rubber-banded to a cardboard tube and the tube then was anchored to the roof hatch opening and faced into the wind (figure 1c) similar to the prior collection device. Eagan is shown in figure 1d attaching a plastic bag to the secondary collection device. Neoprene gloves were worn at all collection times so as not to contaminate the collected rime or snow. The cloud sieve and snow collection bags were mounted simultaneously and were allowed to collect samples for a period of approximately 18 minutes. Each time the sieve and snow collection bags were mounted and retrieved, three wind measurements were taken and averaged using a hand-held wind measurement gauge. By means of a DMT SPP-100 droplet-sizing probe, cloud condensation nuclei were also counted and sized continually throughout the collection period.

Figure 1a: Main Wind vane determining wind direction.

Figure 1b: Snow collection wind vane.

Figure 1c: Secondary Snow collection device.

Figure 1d: Eagan attaching plastic snow collection bag to secondary Snow collection device.

Samples were assessed during each sample collection time using a black felt-covered block and a microscope to determine levels of riming on the snow crystals. Snow was allowed to fall on the felt block and then was immediately placed under a microscope to analyze the crystals. Riming classification techniques followed the five-degree system proposed by Mitchell and Lamb in 1989. The degree of riming was "classified into five categories according to the fraction of the crystal surface covered by accreted drops: 'light' (less than about 1/5), 'light-to-moderate' (1/5 to 2/5), 'moderate' (2/5 to 3/5), 'moderate-to-heavy' (3/5 to 4/5), and 'heavy' (greater than 4/5, including graupel)" (Mitchell and Lamb, 1989). It must be noted that there is no universal classification for riming levels, and this is a qualitative analysis.

Samples of rime were scraped off the cloud sieve using a plastic scraping card onto a clean plastic sheet. The loose solid rime ice was then transferred to a clean plastic bag using a soft-bristled paint brush, here also neoprene gloves were used to avoid sample contamination. The plastic bags containing samples of rime and snow, respectively, were weighed using a sliding scale. The weight of a single empty bag was noted to be 4.6 grams. Samples were then transferred to dry, clean beakers, covered with plastic wrap to avoid evaporation and allowed to melt at room temperature. Conductivity and pH meters were next used to assess the conductivity and acidity of each sample. These meters were each calibrated separately to insure accuracy. Acidity of the pure rime will be compared to the acidity of the snow to evaluate how riming affects the acidity and conductivity of the snow later in this paper.

Finally, melted samples were transferred to a small cylinder held in a test tube clamp attached to a ring stand, rinsed with distilled water, to collect conductivity and pH measurements. The conductivity probe was first rinsed with distilled water to prevent sample contamination then inserted into the melted sample and the meter reading was recorded. The probe was then re-rinsed with the distilled water for the same reason. Next the rinsed pH probe was inserted into the cylinder containing the melted sample and the reading was recorded. The pH probe as well as the holding cylinder was then rinsed again with distilled water and the process was repeated with the next sample. This was repeated until all samples of melted rime ice and snow were analyzed

For increased accuracy in collection both researchers were involved in the collection process. This included collecting samples as well as properly storing and maintaining them. Betker specifically handled conductivity tests while Eagan conducted pH tests. Both researchers were responsible for snow crystal analysis to determine riming degrees. Dr. Randolph D. Borys aided the researchers in the education of operating equipment and general processes.

Also, for the times of each analyzed snow event and the 120 hours prior, air trajectories were created using the HYSPLIT model to assess and analyze the effects of anthropogenic forcings on the CCN and thus the riming levels.

Results

A total of eight sample periods were completed. Data from three of these periods is taken as representative and is analyzed to create results for this paper. Quantitative values of this data are presented in table 1. The data covers all high and low riming levels and thus a variety of values for all other variables.

As the riming level is shown to increase from level one to level five, the number of CCN decreases from 306.9 #/cc to 23.0 #/cc while the cloud droplet diameter increases from 21.6 µm to 10.0 µm. It is also noted that as more riming occurs on the snow crystals the mass of snow collected increases from 4.55 grams at the lowest riming level to 12.89 grams at the highest riming level. This is intuitive as more riming increases the volume of each snow crystal, leading to a larger mass. Conductivity measurements also increase with riming levels while snow pH measurements decrease indicating that more ions are present in more rimed snow leading to a more acidic chemical makeup of heavily rimed snow compared to lightly rimed snow.

Riming level	CCN conc. (#/cc)	Number mass diameter (µm)	Conductivity (amps/volt)	Snow pH	Collected Snow Mass (grams)
1	306.9	10.0	4.90	7.40	4.55
3	47.7	15.6	7.40	5.12	6.25
5	23.0	21.6	9.65	5.05	12.89

Table 1

The HYSPLIT data, later shown in figure 4, is from a model run taken for the period where the riming level was one. The trajectory, run for the 120 hours prior to the level one riming event, shows that air passing over southern California as well as northern Mexico. This indicates large levels of anthropogenic emissions present in the air leading to large CCN concentrations and small droplet diameters. This outcome is consistent with the data manually taken for the level one riming period at the Storm Peak Laboratory. HYSPLIT air trajectories run for the other two riming levels produced results that also supported the data taken manually at the Storm Peak Laboratory.

Discussion

The observations and data records showing that as conductivity increased, pH decreased and riming on snow crystals increased (figure 3) supports the conclusions of Berg et al. (1988) and Berg et al. (1991), presented above. The snow pH (blue line) decreases and the conductivity (green line) increases as riming level increases as outlined in the data in table 1.

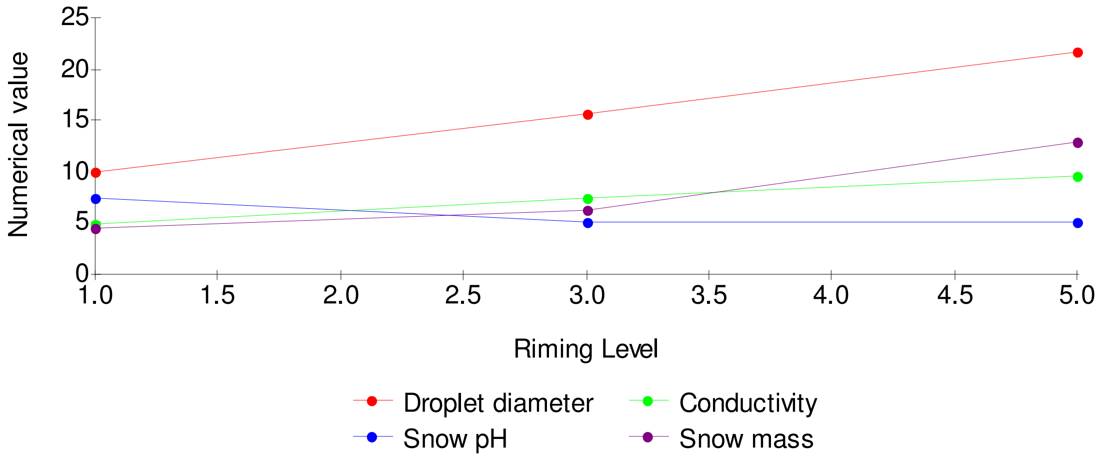

Figure 3: Data taken at Storm Peak Laboratory during the week of 11-18 March, 2006.

This increased riming also led to increased snow mass (figure 3, purple line). This is reasoned by noting that an increase in the riming from level one to five adds bulk to the snow crystal itself and therefore increased that mass from 4.55 grams to 12.89 grams by increasing the number of cloud droplets riming onto a single crystal. The sum of all cloud droplets combined onto a given crystal is positively correlated with the mass of the rimed crystal due to added volume.

The increased riming levels can be explained by an examination of the cloud droplet diameter. Also, shown in the red line of figure 3, is this positive correlation of increased cloud droplet diameter with increased riming levels. As the cloud droplet diameter increases from 10.0 μm to 21.6 μm the riming level increases from one to five. This is also in concurrence with the previously mentioned research of Borys et al. (2003). The cloud droplet diameter was ultimately affected by the CCN concentration within the cloud. As CCN concentrations decreased (figure 4) cloud droplet diameters increased (figure 3) as shown when figure 3 is compared with figure 4. Logically, as more CCN are present there is less liquid water available for each aerosol, thus each droplet is smaller than if there were less CCN and more liquid water for each aerosol.

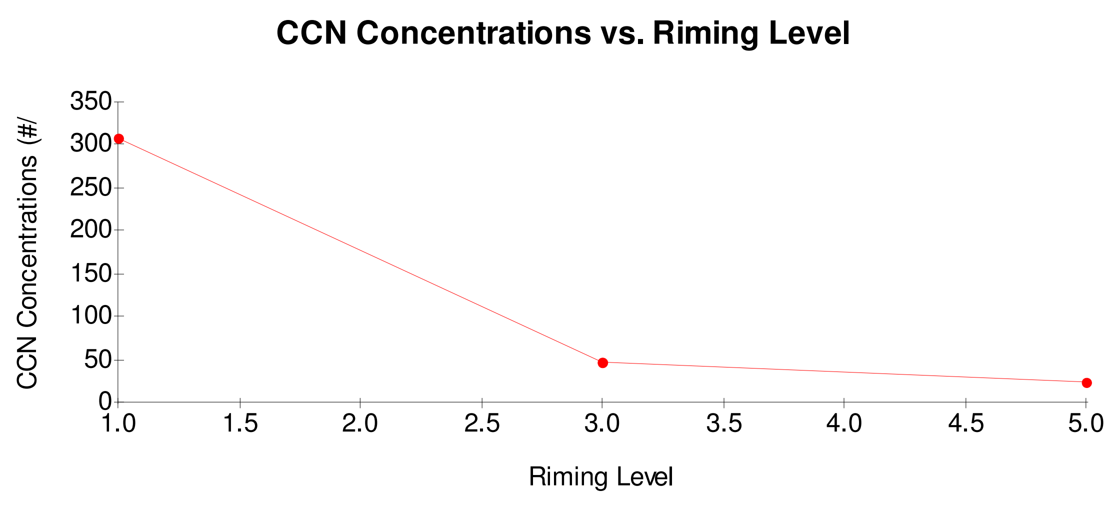

Figure 3: Data taken at Storm Peak Laboratory during the week of 11-18 March, 2006.

The changes in the CCN concentrations are explained by an examination of the pollution levels. This is achieved by using the HYSPLIT model showing air trajectories. The trajectory in figure 4 shows the air present during the level one riming period previously passed over southern California and then northern Mexico before reaching Storm Peak. Southern California is a highly populated area leading to high levels of pollution in that area in general. Northern Mexico is also highly polluted because there is an extreme lack of regulation of emissions. This trajectory explains the increased number of CCN (306.9 #/cc) during this level one riming period compared to a lower CCN concentration of 23.0 #/cc during a level five riming period. It is also noted that during this trajectory period there was no precipitation recorded although for a portion of the period high relative humidity values were recorded. Because there was no precipitation there was no opportunity to rid the air of the aerosols from the anthropogenic emissions collected in southern California and northern Mexico. This is supportive of the findings from Lohmann et al. (2004), which states that increased anthropogenic emissions leads to increased CCN concentrations and decreased riming levels. Combined with the Borys et al. (2003) study, this is explained by a shut down of the collision-coalescence process with decreased droplet diameters.

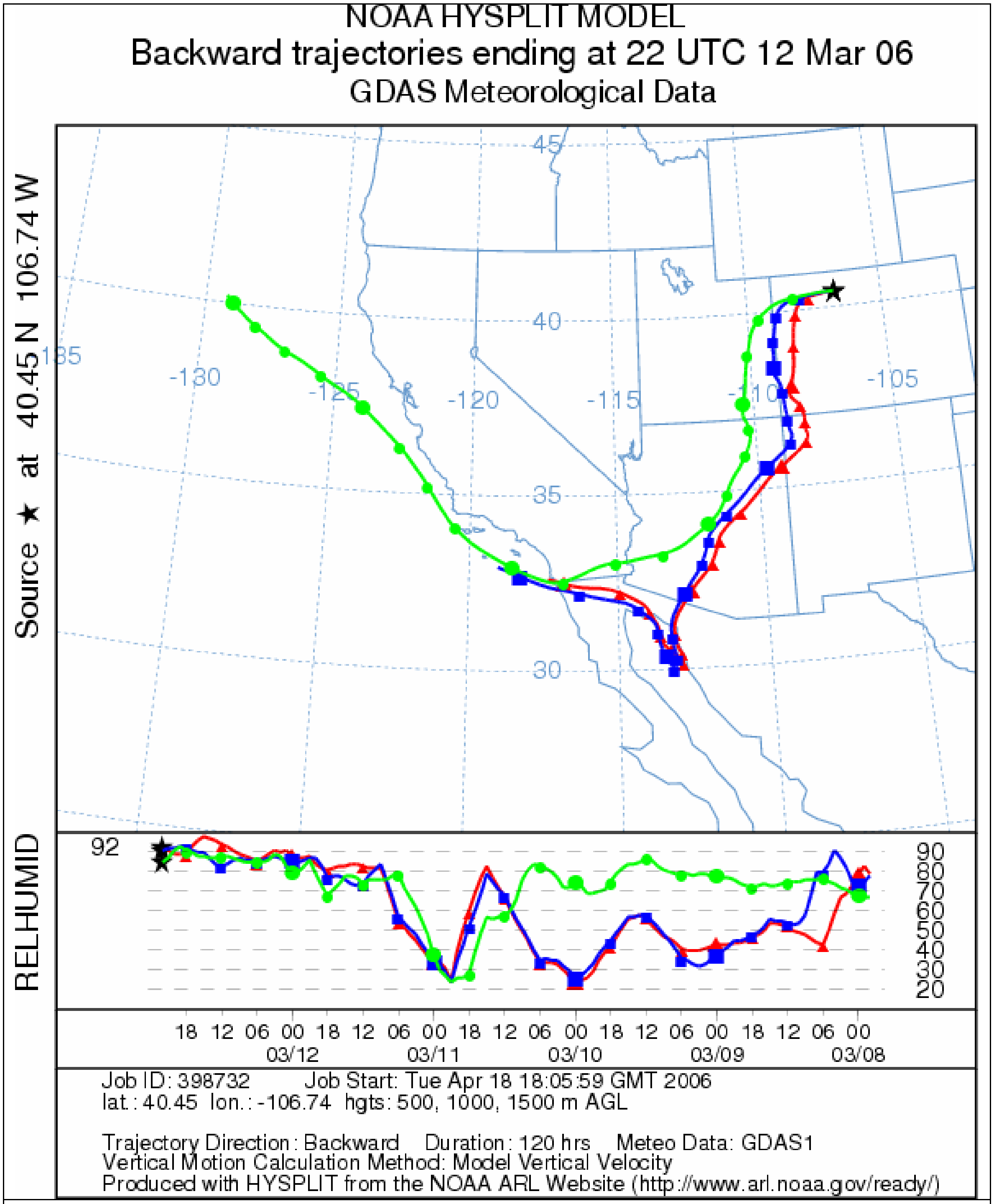

Figure 4: Air trajectory for 120 hours prior to the level one riming event using the HYSPLIT model.

Conclusion

The data taken by Betker and Eagan at Storm Peak Laboratory in Steamboat Springs, Colorado over the week of 11-18 March, 2006 has aided in the support of previous research done on the topic of rime ice deposition and named in the introduction section of this paper. The research of Betker and Eagan combines model data with observations to provide conclusions directly connecting previous research in one study instead of using individual data from separate papers that may provide varying information. The data suggests a negative correlation between anthropogenic emissions and riming levels. Possible complications may have occurred due to the differing techniques of snow collection that was necessary, however it is assumed for the purpose of this research that the effects were minimal. Further research is suggested on the effects of riming to the environment and precipitation rates. It is also suggested that direct observations of wind and emission concentrations be gathered and composed in a way to create an air trajectory that is not derived from model data. As anthropogenic emissions continue to influence and change the amounts and types of precipitation around the world, research that discovers relationships between these factors is important for understanding and determining the necessary actions to take to resolve newly developed problems as well and prepare for future changes in the precipitation cycle that may potentially occur. Further research will also help forecasters more accurately predict precipitation amounts by analyzing emission levels and the effects of riming on snow crystals. These changes will stem directly from changes in CCN concentrations with the increase in anthropogenic emissions and need to be addressed for the benefit and understanding of the environment we depend on.

References and Acknowledgements

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