Solid-to-Liquid Ratio Analysis for 2023

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Abstract:

The Mount Washington Observatory is known for its extreme weather conditions and harsh winters. Knowledge of the climatological mean and factors that influence a location's solid-to-liquid ratio (SLR) is important in order to accurately forecast snow accumulations, community impacts, and avalanche conditions. This research explores the relationship between the SLR and parameters such as temperature, wind speed, wind direction, seasonality, and solid and liquid precipitation accumulation. This analysis will provide insight into the complex atmospheric environment, forecasting, and atmospheric dynamics of Mount Washington.

Introduction:

Knowledge of the solid-to-liquid ratio (SLR) and how it varies by location, and in relation to different atmospheric variables is important for accurately forecasting total accumulations, societal impacts, and avalanche conditions. Prior research on SLR has been done around the continental US, and globally (Baxter et al. 2005). SLR is influenced by various factors, temperature being one of the most important (Baxter et al. 2005). Higher ratios are found in dry, 'fluffy' snow, which is liable to be blown around, while lower ratios characterize wet, heavy snow that is more likely to remain in place. Windy conditions have been found to play a small role in lowering snow ratios since turbulent winds can break snowflakes apart (Ware et al. 2005). However, another study determined that there were no correlation between wind speed and SLR (Baxter et al. 2005).

High elevation research on SLR was completed in Utah's Wasatch Mountains, examining SLR variability and predictability (Alcott et al. 2009). In that analysis, the temperature dependency of SLR was examined using the temperatures at 650 hPa. *Alcott et al. 2009* determined that SLR increased was positively correlated with temperature between -23°C to -17°C [-9.4°F to 1.4°F], and negatively correlated with temperature above -13°C [8.6°F].

The average SLR for the continental US is generally assumed to be 10:1, though *Baxter et al. 2005* determined that the actual value is closer to 13:1. As this is an average over a large spatial scale, there existed significant variation about this mean value (across the US), as well as over the course of the snow season.

The Mount Washington Observatory dataset is one of North America's longest continuous alpine climate records, dating back to the 1932. Observers continue to add to this dataset with hourly weather observations. The summit of Mount Washington is known as the 'home of the world's worst weather,' with especially harsh winter conditions. With decades of data accumulated from hourly observations, continuing research will provide the opportunity for a better understanding of the weather and climate on the northeastern United States' highest peak. Mount Washington Observatory's unique long-term dataset also provides the opportunity to analyze climatological trends. This research on Mount Washington's SLR will determine what the annual average is, and if and how it is related to temperature, wind, and seasonality.

Data and Methods:

Weather observers on Mount Washington have collected hourly weather data for over 90 years, but only data for 2023 was used for this particular study. Both B-16 hourly data which included the date, time, wind direction, wind speed, and the present weather and the 6-hourly B-15 synoptic data, which included the present temperature, both the 6 hour maximum and minimum temperatures, snowfall accumulation, and liquid precipitation equivalent were used in this study. 'Present weather' includes all the codable weather that occurred within the hour of observation, though the weather phenomena on the B-16 were not organized according to their preponderance within the hour. Hourly precipitation amounts on the B-16 were estimated by weather observers based how the measured 6-hourly synoptic precipitation appeared to be distributed over the previous 6 hours. The SLR is a ratio between solid accumulation and its liquid equivalent. This is calculated by measuring the amount of solid accumulation (in inches) and then melting it to measure the corresponding amount of water (in inches). With these quantities, SLR can be calculated in 6-hourly intervals, and climatological trends can be analyzed.

At MWObs, the SLR can be calculated every 6-hours during synoptic observations and the temperature was calculated by taking the average of the 6 hourly maximum and minimum temperatures.

The data from the Mount Washington Observatory was filtered prior to beginning the following analyses. In order to be selected, snow or snow showers (or both) had to have been reported in hourly present weather data in the B-16. It is important to note that filtering the data in this way did not exclude mixed frozen precipitation, therefore the remainder of this study refers to SLR as the 'solid' to liquid ratio, rather than the 'snow' to liquid ratio. To calculate the SLR, both the solid accumulations *and* its liquid equivalent had to have been measurable (present in quantities >= 0.01'' for liquid, and >=0.1'' for solid).

Daily SLR Average Observations
07:00 same day
13:00 same day
19:00 same day
01:00 next day

Table 1: Observations used for daily SLR analysis 2023

The next analysis involved calculating daily SLR averages. One day consisted of four consecutive 6-hourly intervals beginning with the 7:00EST observation of the same day and ending with the 1:00EST observation of the following day (Table 1). To do this, precipitation collections in which either no or a trace of solid precipitation was measured were removed along with liquid precipitation that fell within that period. Once filtered, the liquid and solid precipitation collections that were not removed in the above step were summed over the 24 hour period and then divided. This produced daily values for solid accumulation and its liquid equivalent. In the case that there was measureable solid precipitation but only a trace of liquid equivalent, a NaN was inserted as a placeholder for that day. Proceeding according to the above method, there was a total of 216 days of measurable snowfall in 2023 that were included in this analysis.

The climatology of SLR's for Mount Washington Observatory (MWObs) was analyzed with respect to mean temperature, wind direction and wind speed over 6-hourly and daily time periods, as well graphing the calculated SLRs over the entire year to examine its seasonality.

Analysis and Results:

First, SLR was plotted versus time between January and December (Fig 1). The average value of the 6-hourly SLR in 2023 was 9.9:1.This plot not only shows the range of the ratios, but also highlighted frequently measured ratios such as 10:1, 20:1, and 30:1. These ratios have distinct 'lines' throughout the year made from many data points. This may be due to frequent cases of low snow accumulation, which coincide with low liquid accumulations. To further examine this first plot, a running mean using 27 consecutive 6-hourly observations (approximately a 7-day window) data points was created (Fig. 2), with the running average displayed as a red line over data displayed in Fig.1.

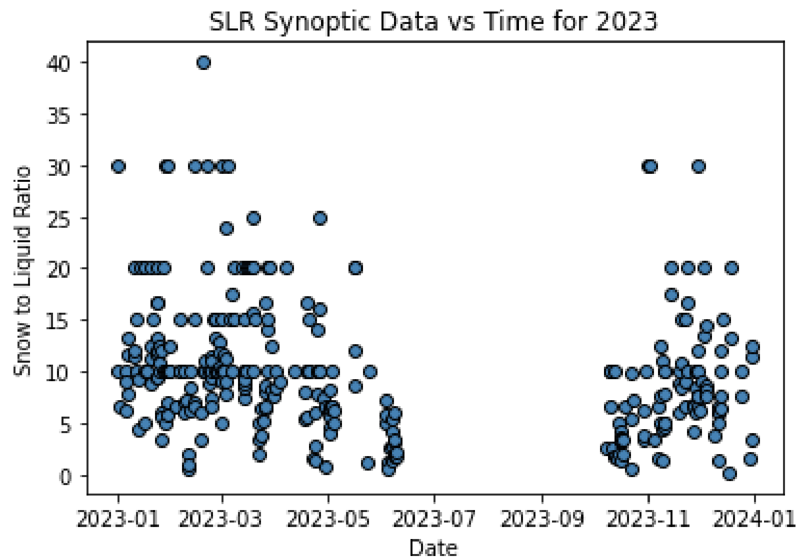

Figure 1: SLR versus time for 2023

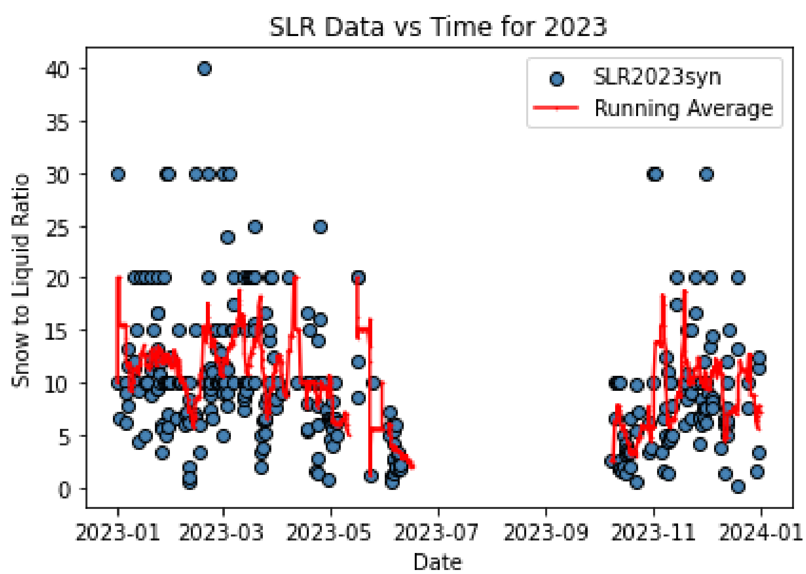

Figure 2: SLR versus time for 2023 with running average displayed

The scatter plot of daily averages of SLR versus time for 2023 was made to determine if the same distinct SLR is found (Fig. 3). In this plot, the 10:1 ratio is significantly less visible than in the previous figure. With this daily analysis, the shoulder season SLR values at the terminus and the commencement of the snow season, have an interesting small spread with most values below 5:1 with noticeable trends heading into and away from the snow-free season, though values within the remainder of the snow season are more highly variable.

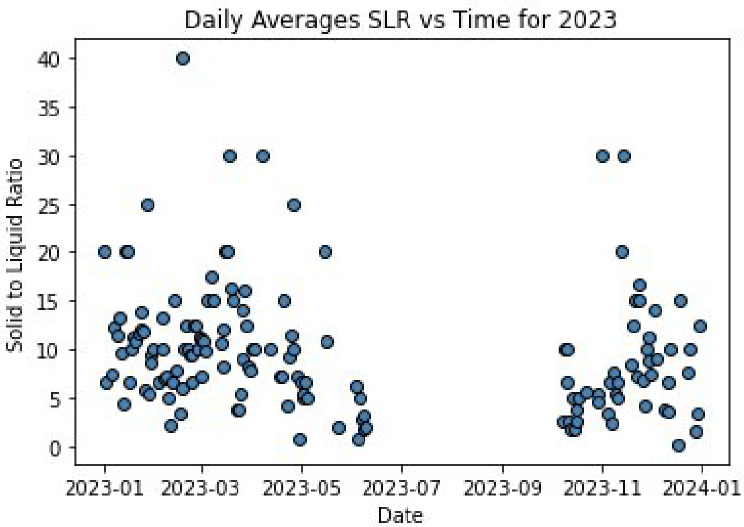

Figure 3: Daily averages of SLR versus time for 2023

Determining the most frequent SLR on Mount Washington in 2023 was the next step. Using a histogram with 20 bins, corresponding to SLR increments of 2, the 6-hourly synoptic data and the daily averages are displayed next to one another for easy comparison. For the 6-hourly SLR histogram (Fig. 4a), an SLR of 8-10 was the most commonly observed, having been measured 86 times, with an SLR of 6-8 the second most common with 49 observations.. The vertical, red-dashed line highlights the median for the data which was 9.3:1. Similarly, the daily averages for 2023 (Fig. 4b) the most common SLR value was found to be between 8 and 10 with a frequency of 28 observations, with the second most common SLR value between 6 and 8, with 26 observations. The red-dashed line in the figure represents the median value for the daily averages, which is the value of 9.0:1. These histograms confirm the results of running average plot that the most common SLR values lie between 8:1 to 10:1 for 2023.

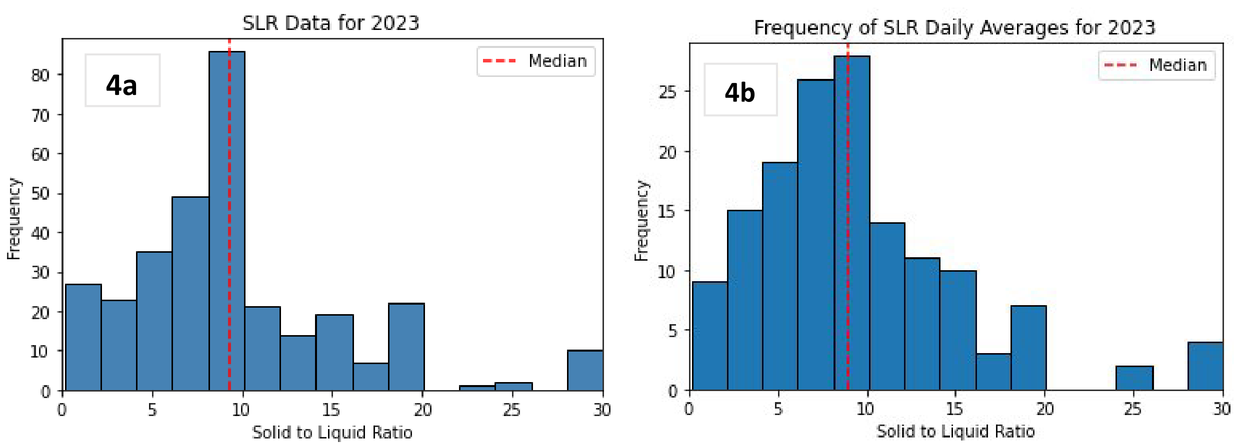

Figure 4: Synoptic SLR frequency chart (4a) and daily averages of SLR frequency chart (4b), both plots have a condensed x-axies to increase readability. This excluded one value greater than 30:1.

To determine if there was a relationship between SLR and temperature a scatter plot was made using the mean 6 hourly temperature and its coinciding SLR value (Fig. 5). A linear regression was then performed to determine its strength. The least-squares trend line derived from the regression is displayed on Figure 5 as a red line, along with the slope (-0.46/°F) and R-squared value (0.21). The correlation coefficient (r) value of -0.46 demonstrates there is a strong negative relationship between these two variables, meaning that as temperature increases SLR decreases.

The linear regression analysis confirms the link found between surface temperature and SLR found in prior studies.

Another way to examine the characteristics of SLR are shown in Fig 6a and 6b by comparing the calculated SLR values to the amount of solid (Fig.6a) and liquid precipitation (Fig. 6b) measured at the time of each 6-hourly observation. Fig. 6a shows that the most frequently measured snowfall accumulations are between 0.1-1.0 inches. The relationship between solid accumulation in inches and SLR looks to have an inverse trend, with high SLR values generally associated with low accumulations. There is a large spread of SLR at very low accumulations, with the highest SLR values 25:1 and above, found only during observations with accumulations of less than 0.5 inches. Similarly, liquid equivalent is also plotted with SLR (fig 6b). The most common values are 0.01-0.25 inches, and again look to have an inverse relationship. Similar to the figure 6a, the highest SLR values are only found at very low liquid equivalents. At lower liquid equivalent values there is a large spread of values, while at higher liquid equivalent values there is a lesser degree of variation. To better analyze this relationship in further work, increasing the thresholds of solid and liquid equivalent precipitation from the 0.1'' and 0.01'' displayed in this study may result in clearer relationships with other atmospheric variables due to degree of variation seen at low precipitation amounts.

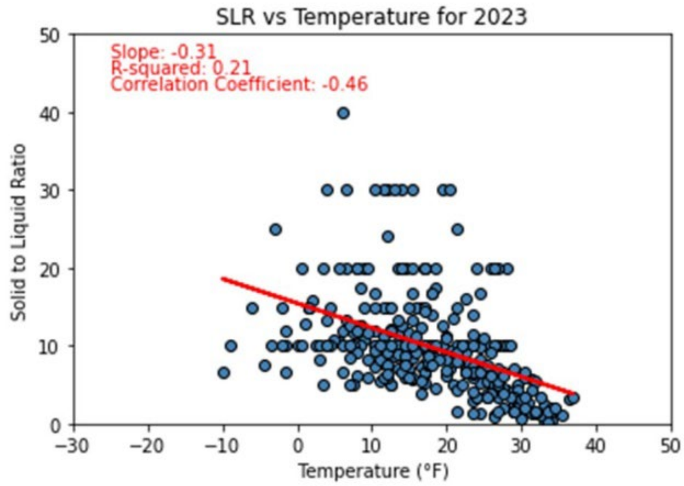

Figure 5: SLR versus temperatures for 2023 with trend line

6a)

6b)

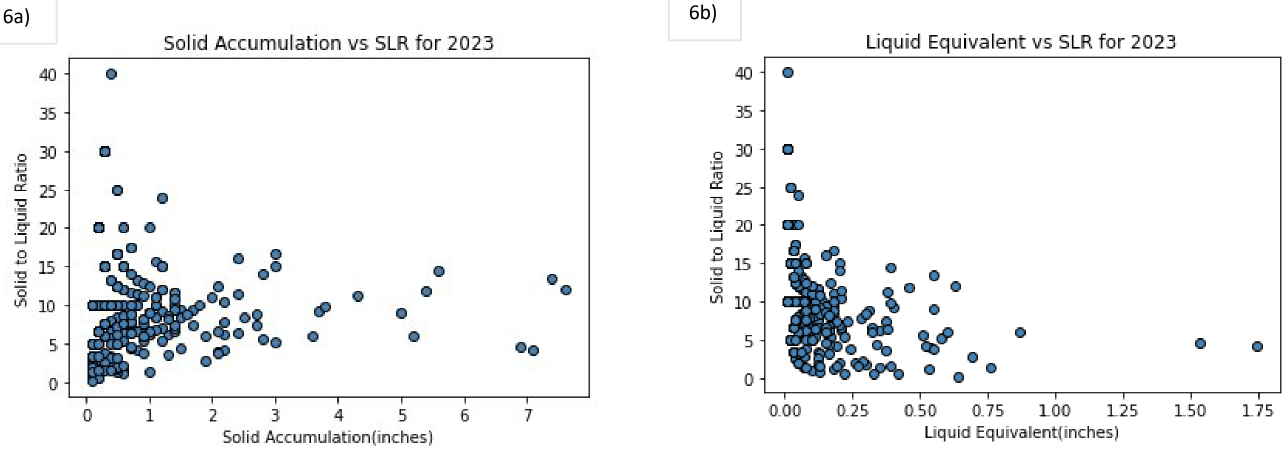

Figure 6: SLR versus solid accumulation (6a) and SLR versus liquid equivalent (6b) for 2023

Wind speeds and directions were also analyzed. A frequency plot of average 6-hourly wind speeds when snow and snow showers were present according to hourly B-16 data (Fig. 7). The most frequent wind speeds during observations with snowfall are approximately 35 mph and 42 mph. However, other than these two peaks, the wind speed distribution is relatively constant between approximately 25 mph through 65 mph. Similarly, a wind speed box and whisker plot for each wind direction was created to provide a better understanding of the wind speed distribution by direction (fig. 8). Westerly and northwesterly winds had higher median wind values than the other directions. To continue the wind analysis, the 24 hour average wind speeds are plotted with the daily SLR for 2023 (Fig 9). There is little visual trend between wind speeds and SLR Since SLR was strongly correlated with temperature, it appears that its relationship to wind speed is not nearly as strong, with the influence of temperature predominating over the influence of wind. Including higher thresholds to calculate SLR, as well as grouping SLRs measured at similar temperatures may help in future analyses.

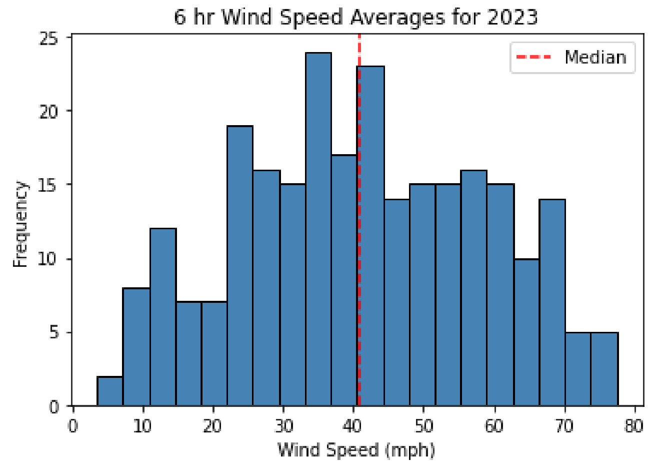

Figure 7: Average 6 hour wind speed frequency for 2023

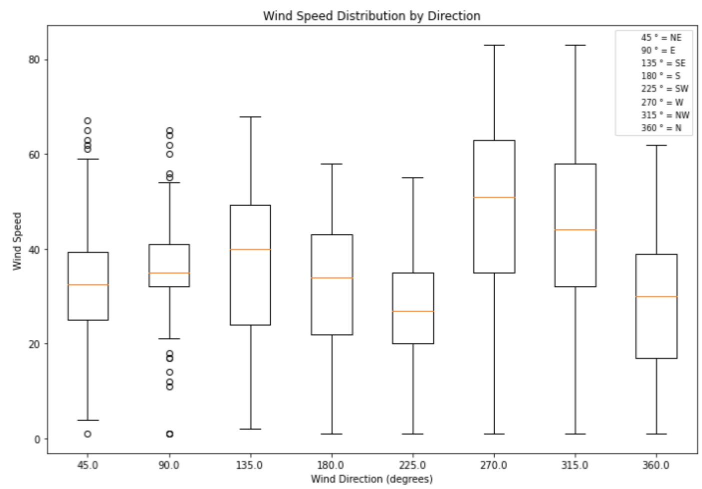

Figure 8: Wind speed distribution by direction for 2023

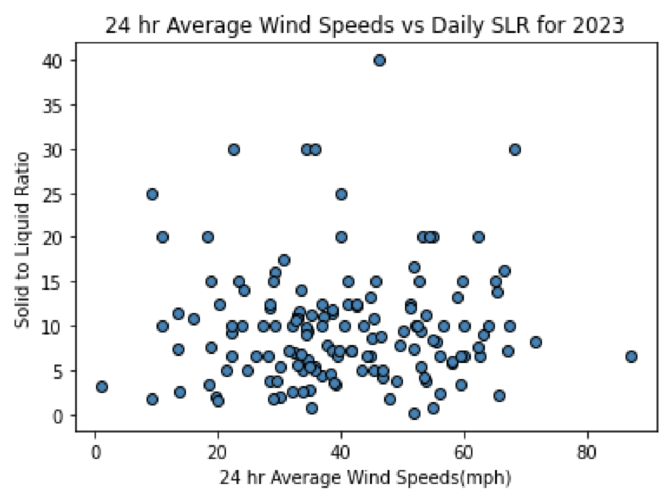

Figure 9: 24 hour average wind speed versus SLR for 2023

Discussion and Future Work:

When looking at the seasonality of SLR in 2023, the low and reduced variability found in SLR values during the shoulder seasons with higher potential mixed precipitation is an interesting finding to further explore. Our results demonstrate SLR is negatively correlated with temperatures on the summit of Mount Washington in 2023, aligning with the relationships seen in prior research.

Inspecting the SLR versus amounts of sold/liquid precipitation measurements showed that the summit generally receives snowfall in increments of less than 1 inch of solid precipitation or less than 0.25’’ of liquid equivalent precipitation per 6 hour period.

The 6 hourly average wind analysis emphasizes the generally common frequency between of winds between 25 mph- 65 mph. This large range of nearly uniformly distributed winds during snowy conditions was unexpected. Currently, the wind and SLR analysis does not show a trend, but dividing up the data according to the temperature and performing the same analysis with more data may permit a more nuanced interpretation.

During the analysis for SLR versus time plots for 2023 for both time scales, there are an abundance of SLR values at exactly 10:1, 20:1 and 30:1. Thus the question naturally arises; what effect do estimated solid accumulation/liquid equivalent values have on these results? To continue expanding on this analysis, future work could be done to determine how often snowfall accumulation is estimated and the reasons for the estimation. The analysis could then be repeated after excluding the estimated values to determine if they have any substantial effect on the results presented here.

When examining the relationship between SLR and temperature, a linear regression was performed, however going forward doing a logistic regression may likely be more beneficial. The negative relationship between SLR and temperature is a relatively strong, but the shape, as found in other studies may not be linear and may become more apparent as more years of data are added to this analysis.

Another avenue to continue this research involves filtering the data to include time periods when only snow or snow showers were present, *and* excluding any freezing, frozen, or liquid precipitation other than snow using the present weather data from the B-16. This could change the research to focus on the snow-to-liquid ratio rather than present solid-to-liquid ratio. This would filter out a significant amount of data points, but it may provide more clarity concerning the relationship of each atmospheric variable to the SLR measured on Mount Washington. An alternate analysis which could be performed involves creating stacked histograms of the calculated SLRs with the categories delimited by the amount of solid or liquid precipitation which fell during the given 6-hourly interval (e.g. <0.5’’, 0.5’’-1’, 1-1.5’’, 1.5’’-2.5’’, 2.5’’-4’’, and >4’’ for solid and <0.05’’, 0.05’’-0.1’’, 0.1—0.25’’, 0.25-0.5’’, and >0.5’’ for liquid equivalent) Performing this kind of analysis would help illuminate how the quantity of solid and liquid precipitation relates to the calculated SLR . Understanding these relationships may produce operationally useful results when forecasting snow accumulations, especially if the forecasted QPF is tightly constrained.

Finally, an important expansion to this project would be to create a synoptic set up analysis of the SLR. This would consist of looking at regional circulation patterns, determining what regime the summit was experiencing, then grouping the SLR ratios measured during each regime. This can provide insight on the predominant circulations, whether it was from upslope showers, and better understand the types and tracks of typical winter storms that affect the White Mountains area.

Continuing this research may allow the development of a comprehensive climatology over the full dataset rather than only 2023. This would allow all existing analyses to be extended over decades as well as determine if the mean and the seasonality of SLR has changed over time. Once a full analysis of 2023 has been completed, broadening it back several decades would enable us to greatly increase the amount of data used to generate the existing figures and more finely examine both how SLR relates to each of the atmospheric variables, as well as how these relationship may have evolved.

Conclusion:

The analysis of solid-to-liquid ratios on Mount Washington has provided valuable information on a difficult to forecast meteorological phenomena. Through this research, influence of various factors such as temperature, time of year, wind speed, and wind direction has been examined for 2023. The findings include a negative relationship between temperatures and SLR, with relatively higher temperatures associated with relatively lower SLRs. Currently the amount of precipitation that fell, solid accumulation and liquid equivalent, indicated the mean summit SLR value was 9.9:1, nearly identical to the commonly used 10:1 ratio, though significantly lower than 13:1, the mean value for the contiguous US (Baxter, 2005). Further exploration into the seasonal variance of SLR is necessary by comparing SLR values over seasons/month is necessary to determine how variable or stable this relationship has been in the past. Though this research began to give insights into the solid-to-liquid ratio's relationship to various atmospheric variables, it has also opened the door to many unanswered questions as detailed in the further work section above. Further exploration of the interaction between SLR and different meteorological parameters for 2023 is still necessary, and the Mount Washington Observatory's vast dataset allows the expansion of this project to go back through 1932. This gives the opportunity to grow this research from a one year study to a climatology.

If the Tricia Hutton folder gets moved into Past Interns, the path for the data will need to be edited—two data sets are called at this point 2023 B16 and 2023 Synoptic

References:

Alcott, T.I. & Steenburgh, W.J. (2010) Snow-to-liquid ratio variability and prediction at a high-elevation site in Utah's Wasatch Mountains. *Weather and Forecasting*, 25(1), 323–337.

Baxter, M.A., Graves, C.E., & Moore, J.T. (2005). A Climatology of Snow-to-Liquid Ratio for the Contiguous United States. *Weather and Forecasting*, *20*(5), 729–744.

Ware, E.C., Schultz, D.M., Brooks, H.E., Roebber, P.J., & Bruening, S.L. (2006). Improving snowfall forecasting by accounting for the climatological variability of snow density. *Weather and Forecasting, 21*(1)*, 44*(9), 94–103.