A Study of Significant Late Season Snow and Precipitation Events in the White Mountains

George Mousmoules

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Abstract

There have been multiple studies conducted based on both observational data and climate modeling that indicated significant snow events will likely continue at a steady or increasing rate in the Northeastern U.S. This was despite a shortening winter season in the region due to climate change. This study investigated how significant late-season snow and precipitation events have been changing in frequency, intensity, and duration in the White Mountain region. This investigation analyzed data from 1995 to 2024, focusing on the period of March 1st to June 30th for each year. Data originated from the B16 daily archives kept at the Mount Washington Observatory and observations collected at the Pinkham Notch Visitor Center. This included daily snowfall, precipitation, and snow depth recorded for each day during the period of study. 90th percentiles were calculated for daily data and separately calculated for three and five-day running averages to capture multi-day events. Code was generated using Python to run calculations and generate visualizations. Multi-day events were verified manually using upper-level and surface charts along with radar data from the National Center for Environmental Information. Significant snow and precipitation events stayed consistent at MWO while snowfall events slowly increased and precipitation events remained the same at the Notch. Event intensity was similar between MWO and the Notch with MWO observing more outlying events. Significant events typically lasted two to three days and no longer than five days. Understanding these trends can increase forecast knowledge and accuracy and better inform the public about these impactful events.

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1. Introduction

New England is known for its rapidly changing weather and the wide variety of significant meteorological events that strike the region across the four seasons. Among these, the large snow storms that frequent the area throughout the winter are the most infamous and often bring the largest impacts. Just one significant winter storm can impact millions of people, close schools and businesses, shutdown transportation, wreak havoc on utilities, and endanger the lives of everyone in its path. Forecasting these storms is always a major priority and challenge for meteorologists in the region. The Mount Washington Observatory (MWO) is no stranger to significant winter storms, with new storm systems passing through roughly every three days in the winter. Pinkham Notch, located just four miles to the west and about 4,250 feet lower than MWO, also experiences many of these storms. Conditions are often significantly more intense at MWO than in Pinkham Notch (hereafter called the “Notch”). Yet these storms can still bring multiple feet of snow at a time and shutdown all access to the Notch. It is critical that observers are able to forecast for these events accurately to ensure the public is aware of the extreme conditions that accompany such storms in the White Mountains.

In the last few decades however, there has been a noticeable change in the winter season at both MWO and the Notch. Notably at the Notch the end of the snow season has declined by 1.7 days per decade, along with total snowfall declining 20.7 cm (8.2 in.) per decade. The Notch has also seen 2.7 fewer ice days and 1.7 more thaw days per decade, while MWO has observed 1.8 fewer ice days and 1.4 more thaw days per decade. This can be attributed to a progressively warming climate at both sites, with MWO experiencing a warming rate of

0.10˚C per decade and the Notch recording a 0.14 ˚C warming rate (Murray et al 2021). These findings align with what has been observed previously in broader studies regarding the climate of New Hampshire and the Northeast as a whole (Murray et al 2021). This warming along with a shortening in the end of the snow season suggest an overall decrease in winter storms in this region going forward. Late season snow storms appear most likely to decrease in frequency and intensity as the late winter season shifts further back.

Despite this there have been multiple studies indicating that over the next few decades, significant snow events are likely to remain just as prevalent as they are today. Across multiple warming scenarios, levels of significant snow event activity remained similar to those currently observed (McCray et al 2023). In fact, some studies indicate a high probability of an increase in major snow events across the region by mid to late century (Zarzycki 2018). These studies implement various forms of climate modeling to generate simulations of future winter seasons in the Northeast. There have also been investigations conducted based on observational data regarding overall extratropical cyclone activity in the cold season for the midlatitudes in the Northern Hemisphere. Such investigations suggest an increase in both frequency and intensity of overall winter cyclone activity (McCabe et al 2001; Vose 2014).

These studies, both observational and model based, focus on synoptic scale trends that neglect to factor in the White Mountains' unique topography. The mesoscale and microscale processes within these storms are also ignored by many of these models. However, with such strong findings across multiple studies there is a clear need to investigate if significant late season snow events are in fact occurring at a steady or increasing rate despite an observed shortening in the late snow season at MWO and the Notch. This investigation will be based on observational data from MWO and the Notch to determine if significant late season snow events are changing in the White Mountains. These findings will then aid in helping build a more complete picture in how the winter season is changing in the White Mountain region. This will help forecasters both at MWO and throughout the region be able to better anticipate the frequency and intensity of large snowstorms at the higher summits and in the surrounding valleys. Ultimately, this study will help the public gain a greater understanding of how major winter storms have historically and will continue to impact the region and their lives.

2. Literature Review

The premise of this study was inspired by previous investigations that focused on predicting future trends in winter storm activity. One such investigation was conducted by McCray et al. (2023) which used "two sets of climate model simulations" to identify changing snowfall amounts and snowstorm activity in a warming climate. The models used in this study were applied to the entire Northeastern U.S and eastern Canada region. To identify the models' accuracy, they were first applied to previous snowfall data in the winter to see how well they could replicate real observations. It was noted that though the models performed well, they both produced "the largest errors" at "high-elevation stations (e.g., Mount Washington, New Hampshire)" (McCray et al. 2023). Both models were tending "to underestimate snowfall" for the 29 stations above 750 m included in the study. The specific mention of the MWO station is very significant, as it indicates that any trends these models produce may not be applicable to the higher summits of the White Mountains. It was also found that a "negative bias" was present in simulations of snow associated with snowfall events meeting or exceeding the 95th percentile (McCray et al. 2023). One of the main explanations for this bias was that the models had difficulty incorporating "the mesoscale physical processes associated with extreme snow" (McCray et al. 2023). Storm systems in the White Mountains undergo multiple mesoscale and microscale processes that often enhance precipitation and snowfall amounts. This makes the comparison of model trends with observational data regarding significant snow events specifically even more necessary. The paper also mentions the "assumption of a 10:1 snowfall ratio" as an inadequacy of the models, which is an active area of research that MWO is currently investigating in a separate study.

Another study focusing on a similar principal of modeling future major winter storm trends in the Northeast U.S was done by Zarzycki (2018). The model used also found that major snow storms were occurring "at the same number" as what was observed between 1990 and 2005 for the region. Notably it was seen that there was an "increase in the total precipitation associated with cyclonic storms" and that this was "particularly notable for extreme snowstorms" (Zarzycki 2018). It was found that while atmospheric warming promoted reductions in snowstorms, "a systematic shift toward higher total precipitation" offsets this reduction as storms will have higher snowfall rates when synoptic conditions allow (Zarzycki 2018). This study supports the findings of McCray et al. 2023 that an increase or steady rate of significant snow events is likely in the future across the Northeast U.S despite a warming climate. This consensus across multiple climate models thus promotes the need to investigate if similar trends have been observed in the White Mountains specifically to identify how this region may or may not be affected differently than the overall region.

3. Data and Methods

3.1 Data Sources

The MWO dataset included daily precipitation, snowfall, and snow depth measurements recorded by observers at the MWO itself. The B16 Daily Archives kept by MWO contained this data and were downloaded for the period of March 1st through June 30th for each year from 1995 to 2024. This date range was selected because the majority of the late season snowfall occurs in this period, with very few events occurring after June 30th. Due primarily to the higher altitude of MWO, the snow season extends through May which necessitated the expansion to June as this would be considered a shoulder month between the end of winter conditions and the start of spring conditions. When identifying multi-day snow events, surface and upper air maps along with radar reflectivity were examined from the National Center for Environmental Information (NCEI). This provided a synoptic-level perspective that confirmed whether back to back days of significant snowfall and/or precipitation were from separate systems or one larger system. In instances where a multi-day event occurred it was ensured in the developed code that the event was only counted as one event rather than two or three. This process was also applied to the Notch dataset to certify these long-duration events were not counted multiple times by the code.

The dataset from the Notch was downloaded from the Northeast Climate Center CLIMOD 2 database. The data included in this study was collected at the Pinkham Notch station located next to the Joe Dodge Lodge at the Pinkham Notch visitor center at an elevation of 2,025 feet. Its location with reference to the MWO and surrounding topography is visualized in Figure 1. The same time period as what was used for MWO data was used for the Notch to ensure consistent results. Again daily precipitation, snowfall, and snow depth were what was analyzed in the dataset to gain accurate comparisons with MWO. This data was also collected by volunteers at the visitor center, further certifying the validity of the values. It is worth noting that snow depth for both the Notch and MWO was only used as a sanity check when analyzing snowfall amounts. The Notch will often receive blowing snow from the surrounding summits, resulting in deeper snow depth readings than would be expected. Conversely MWO often has a lower than expected snow depth due to the winds carrying snow off the summit. Thus, only precipitation and snowfall were analyzed when determining the frequency of significant snow events.

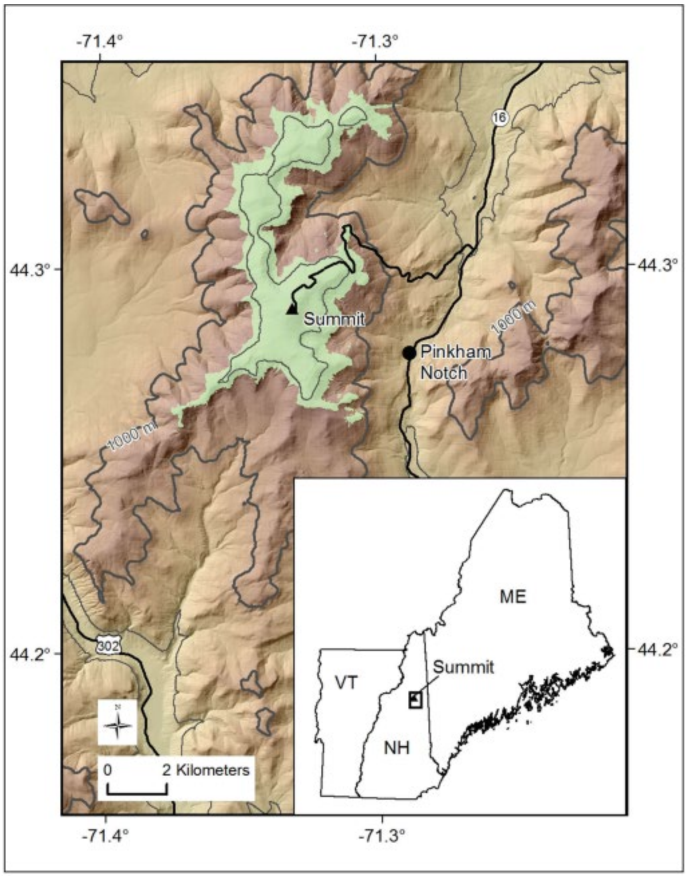

Figure 1: Location of Mount Washington summit and the Notch. The green shading designates an alpine area with topography included (Murray et al. 2021).

3.2 Data Description

For each day between March 1st and June 30th, one recording of daily precipitation and snowfall was produced. This resulted in 121 values which over the course of 30 years meant that 3,630 data points for snowfall and the same number for precipitation. When values of a trace were recorded, they were treated as though a value of zero was recorded as this did not indicate a significant event and rounded down to zero numerically. This ensured that code calculations were not skipping days or misinterpreting the data. On the occasions where data was marked as missing, no value was included regardless of comparable values on neighboring days to ensure data accuracy. The total amount of missing data proved statistically insignificant and thus had no impact on results.

3.3 Analysis Software & Code

Python v3.12 was used to clean data, perform statistical calculations, and create data visualizations. All plots were produced using Matplotlib. Manual calculations were performed to ensure the code was functioning properly.

3.4 Methodology

This motivation for this study was to determine how often significant snow events occur at the summit of Mt. Washington and the surrounding valleys. In order to calculate these statistics, parameters had to be developed to quantify these significant events. It was ultimately determined that the 90th percentile would be calculated for both precipitation and snowfall for the entire dataset. This percentile did not factor in measurements of zero or missing data points to better capture the threshold for a significant event. This percentile would then be applied to each year so that there was a standard value indicating a significant event across the entire study. The dataset was then broken up by year and the 90th percentile values were applied to each data point. Precipitation and/or snowfall measurements that met or exceeded this percentile were then sorted into a separate document where they were checked for being part of a single or multi-day event.

The total number of significant events were then calculated for each year and plotted on a chart to identify a trendline indicating how storm frequency was changing. The process was then repeated for the Notch with results then compared to identify any major discrepancies.

Following this, three and five-day simple running averages were calculated for the original datasets for both MWO and the Notch. The formula for this can be seen in Figure 2 below. These averages were used to better capture multi-day events and represent the total event snowfall that fell over its duration. 90th percentiles were calculated based off these running averages and then applied to these values to identify significant events. These resulting findings were compared to the original daily measurements to gauge the likelihood of a multi-day event. The days that contained running average calculations meeting or exceeding the associated 90th percentile were then filtered into a new document and plotted to analyze frequency. This allowed for the identification of patterns involving the frequency of longer and shorter multi-day events.

$$SMA_k = \frac{p_{n-k+1} + p_{n-k+2} + \cdots + p_n}{k} = \frac{1}{k} \sum_{i=n-k+1}^{n} p_i$$

Figure 2: Simple Moving Average (SMA). The unweighted mean of the last ***k*** data points with ***n*** total entries.

Based on the total amount of significant snow events for the 30-year period at MWO and the Notch, charts were created to represent the intensity range of significant storms. This intensity is being based purely off precipitation and snowfall amounts, rather than surface pressure. The intent for this data is for the larger significant events to be studied on an individual basis to determine any common traits and/or causes for these systems. This can also be used to identify the most common tracks for significant late season storms and how they may be changing over time, which can aid in forecasting these events.

4. Results

4.1 Percentiles

The 90th percentile values for both the MWO and the Notch indicated a relatively consistent pattern in significant event quantification. The MWO consistently generated higher 90th percentile values than the Notch for both snowfall and precipitation. However, for the daily percentiles the MWO had a slightly higher percentile for both snowfall and precipitation than the Notch. This is especially apparent for snowfall, with MWO significant events recording a minimum of 5.5 inches and the Notch recording 6.0 inches of snow. Figure 1 clearly depicts the difference between the two locations regarding this metric. The leading theory for this is that blowing snow from the surrounding mountains falls into the Notch during larger storm systems. Thus, the MWO will record less daily snowfall due to some snow blowing off the summit while the Notch then receives some of this extra snowfall. Further research regarding this possibility is needed to understand the exact causes behind this phenomenon.

90th Percentile Values	Summit (in.)	Notch (in.)
Daily Snowfall	5.5	6.0
Daily Precipitation	0.96	1.02
3-Day Running Average Snowfall	3.5	3.4
3-Day Running Average Precipitation	0.62	0.58
5-Day Running Average Snowfall	3.0	2.4
5-Day Running Average Precipitation	0.53	0.44

Table 1: 90th Percentile Calculations. Each value represents the minimum amount of snowfall or precipitation that indicated a significant event for the dataset.

90th percentiles calculated for this study were not only key in identifying significant snow and precipitation events, but also in understanding the scale of these events. The amount of snowfall during significant events must be understood so that future researchers can recognize these events. The White Mountains receive significant amounts of snow every winter. However, much of this snow falls from multiple smaller events that can make it difficult to keep track of each event independently. The difference between 5.0 and 5.5 inches of snow in one day may seem insignificant to an observer at MWO. Yet this distinction makes all the difference in cataloging and investigating the most significant events.

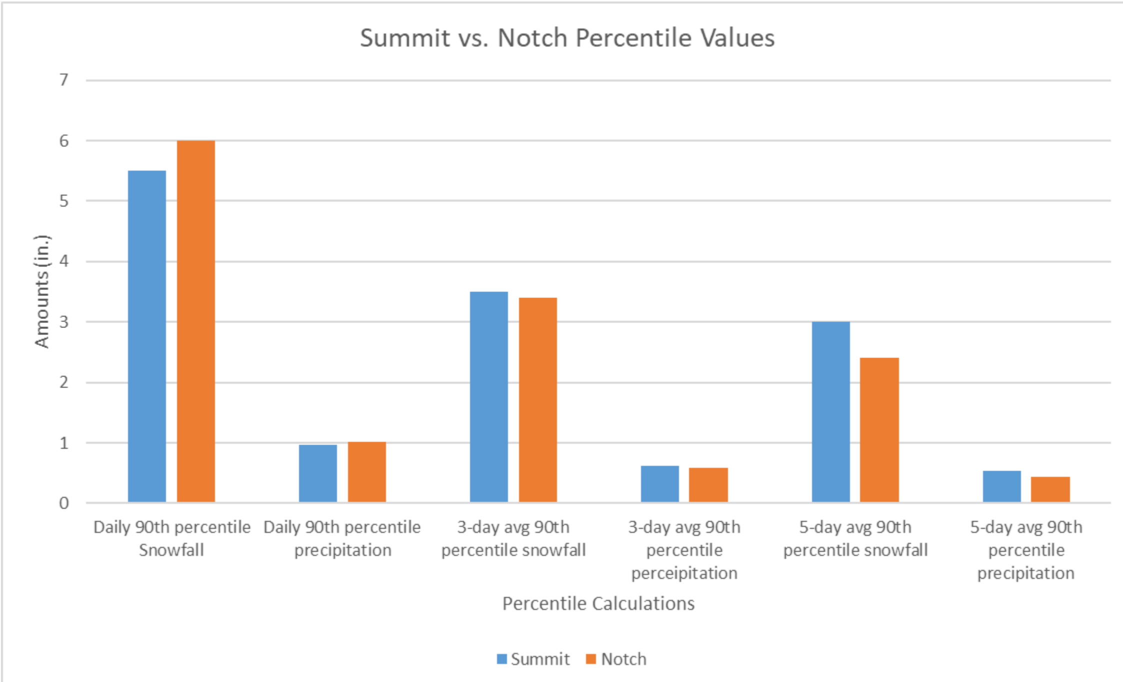

Figure 3: 90th Percentile Comparisons Between the MWO and Summit. Values from Table 1 are plotted on this chart to visually compare calculations.

4.2 Frequency of Events

At the MWO, the amount of late season significant snow events in the last 30 years has remained consistent. Figure 4 demonstrates this as the trendline is nearly zero, with the overall amount of events per year between three and four. There were some peaks in the amount of events, the highest being 11 events in 1997 but with the majority of peaks occurring in the last eight years. There was also a consistent amount of precipitation events at MWO during the same period. The slope of the trendline was exactly zero, with the amount of significant events matching what was observed with snowfall at three to four per year

(Figure 5). As with snowfall, 1997 experienced the most significant precipitation events at nine. Despite MWO precipitation event occurrences having lower peaks than snowfall, the overall average per year remains about the same.

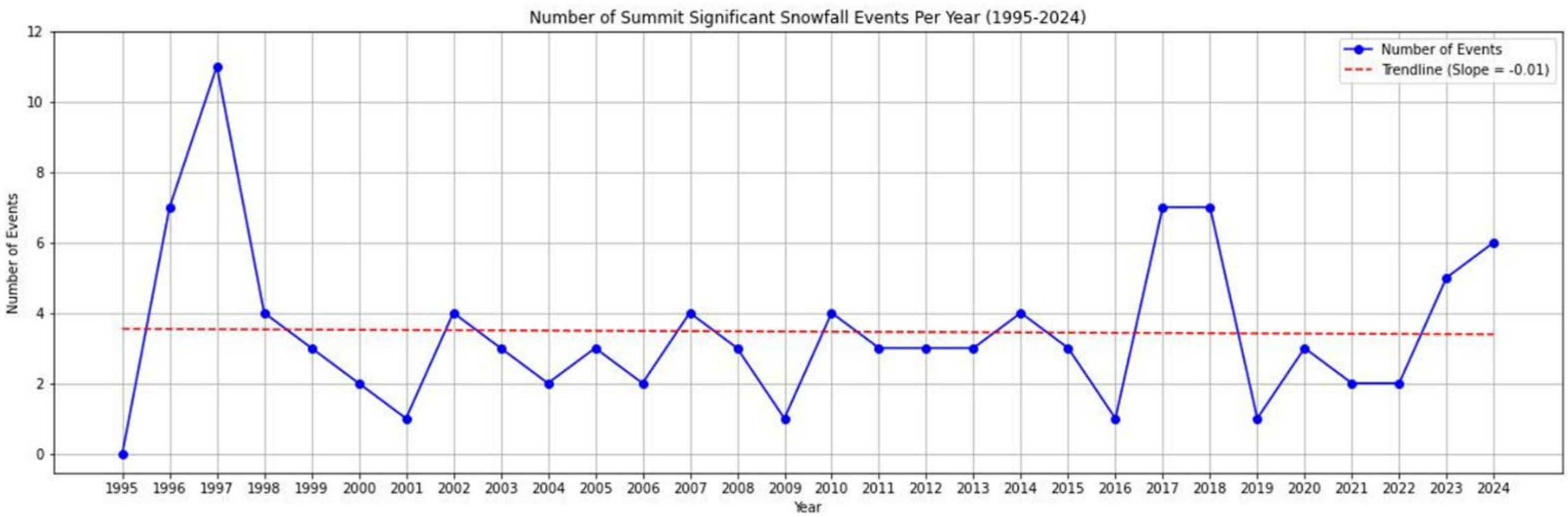

Figure 4: Frequency of Significant Snowfall Events at MWO. The amount of events are plotted with a trendline indicating the consistent number of events since 1995.

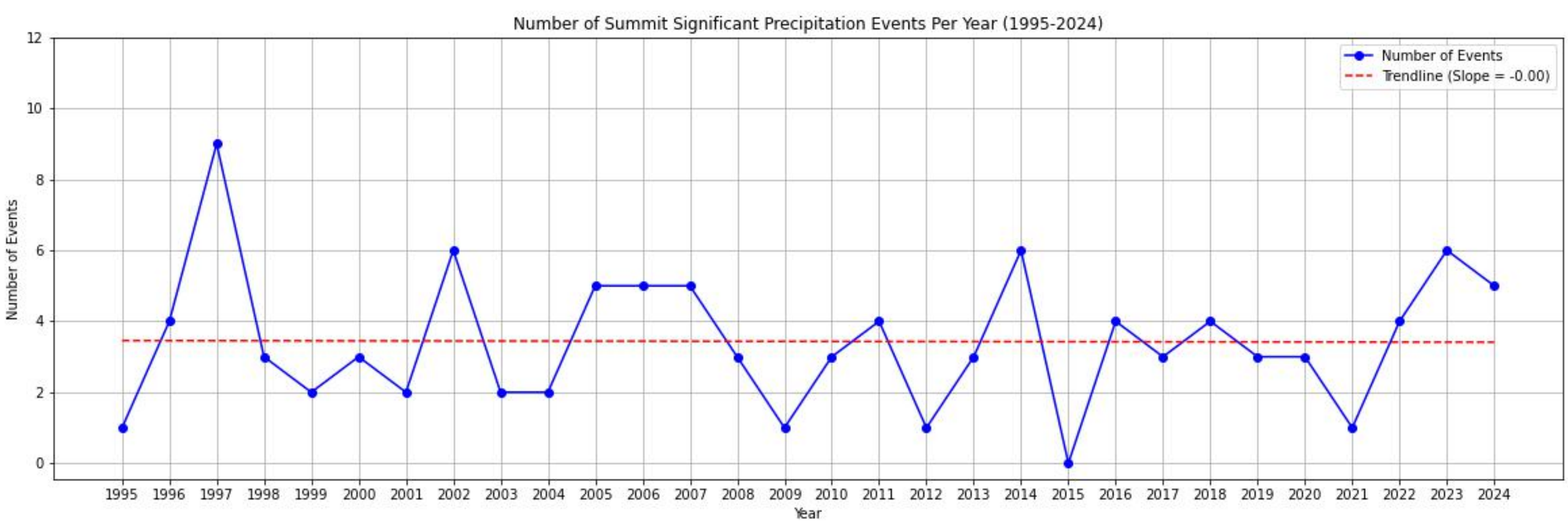

Figure 5: Frequency of Significant Precipitation Events at MWO. The amount of events are plotted with a trendline indicating the consistent number of events since 1995.

The Notch meanwhile has been experiencing a slight increase in significant snowfall events during the late snow season. There is now roughly 1 more snowfall event per year than there was in 1995 in the Notch (Figure 6). Peaks in events are unsurprisingly lower than at MWO with the highest of four being in 1995, 2017, 2023, and 2024. Though like what was observed at MWO, the majority of the highest peaks occurred in the last eight years. On a yearly basis, the Notch experiences between one and two significant snow events in the late snow season. This number does fluctuate heavily though, with eight of the years studied recording no significant snow events.

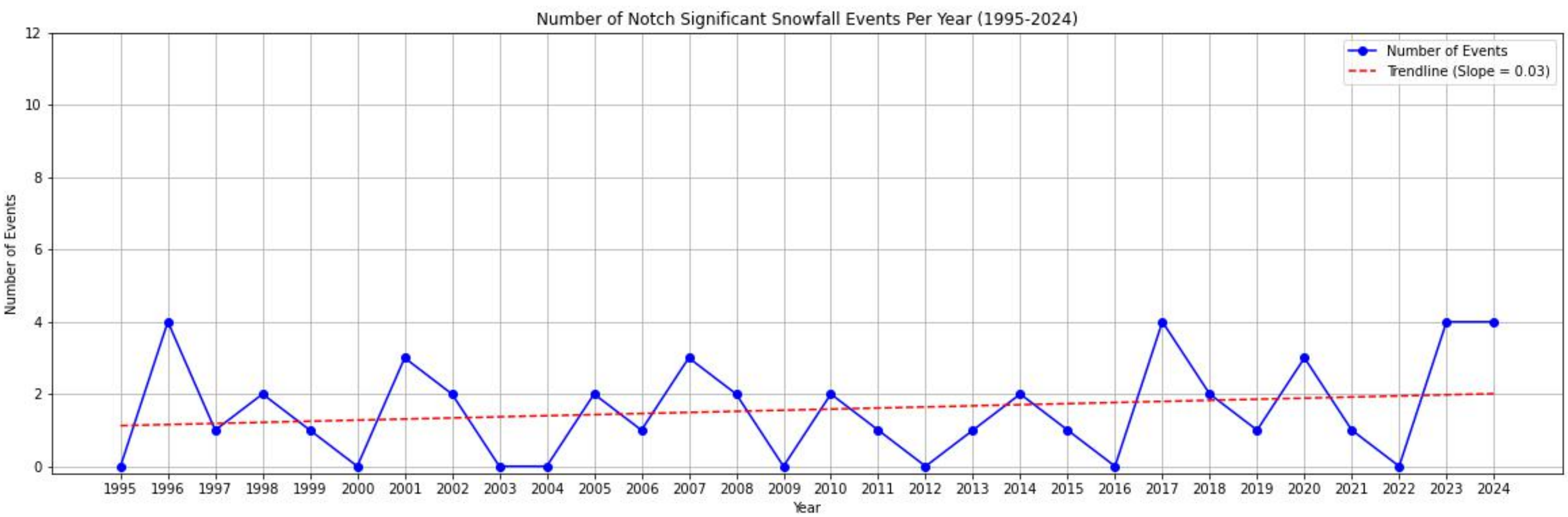

Figure 6: Frequency of Significant Snowfall Events at the Notch. The amount of events are plotted with a trendline indicating the slight increase in number of events since 1995.

Similar to MWO trends, the Notch also experienced a relatively consistent rate of significant precipitation events. There was a nearly flat trendline calculated for this data which indicated that between one and two of these events could be expected at the Notch in any given year. These events were akin to the Notch's snowfall events in that they varied in frequency more significantly, with five year observing zero events. The maximum amount of these events was five which was observed in 2005 and 2020. Interestingly, unlike snowfall events there was not a large surge in precipitation events observed over the last few years though.

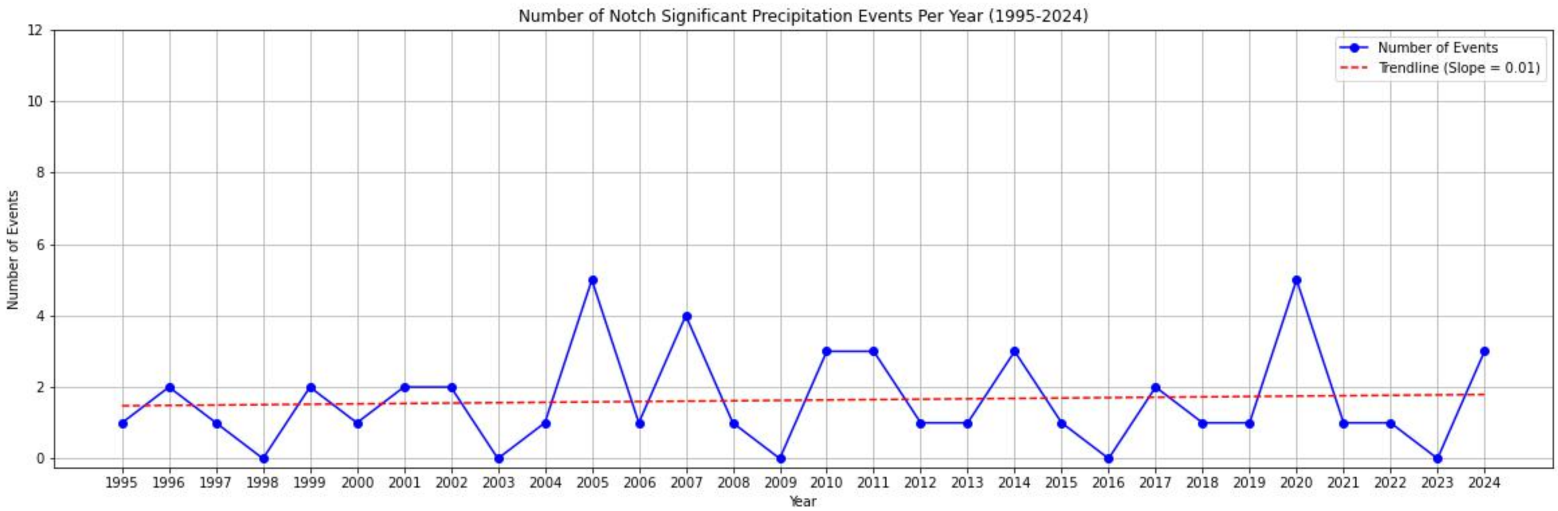

Figure 7: Frequency of Significant Precipitation Events at MWO. The amount of events are plotted with a trendline indicating the consistent number of events since 1995.

4.3 Intensity of Events

To represent the typical intensity of these events, box and whisker plots were produced to identify quartiles and median snowfall and precipitation for MWO and the Notch. The intensity of significant snowfall events was slightly higher for the Notch than MWO when analyzing daily measurements. Figures 8 and 9 indicate demonstrate this, though first quartile values are similar with 6.3 inches for MWO and 6.2 inches for the Notch. Besides this though, the Notch had a higher median, third quartile, and maximum value than MWO. The MWO did have more outlier events than the Notch however, with one group between 15 and

18 inches and another between 23 and 24 inches. This indicated that MWO will very rarely observe daily snowfall in excess of 20 inches, with the majority of these larger events producing storm totals over the course of multiple days. For both MWO and the Notch daily snowfall during significant snow events typically ranges between six and eleven inches. As mentioned previously, a possible contributor as to why the Notch experienced higher daily snowfall is the effects of blowing snow off the surrounding mountains and into the valley.

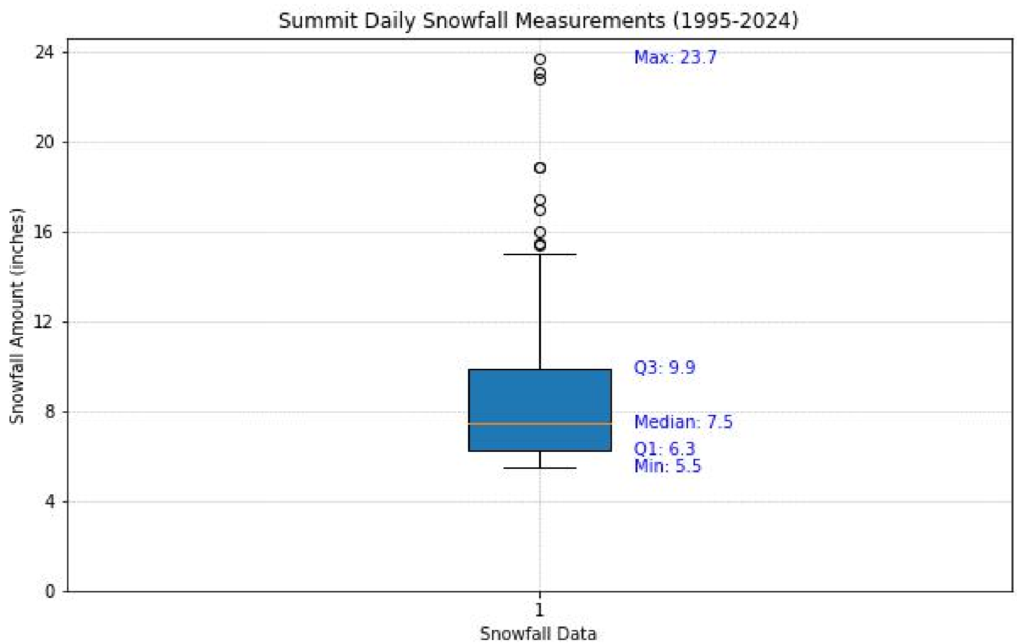

Figure 8: Intensity of Significant Snowfall Events at MWO. Values indicating the first and third quartile values, the median, along with maximum and minimum values are depicted to the left of the plot. Outlier events are represented by the circles above the upper whisker limit.

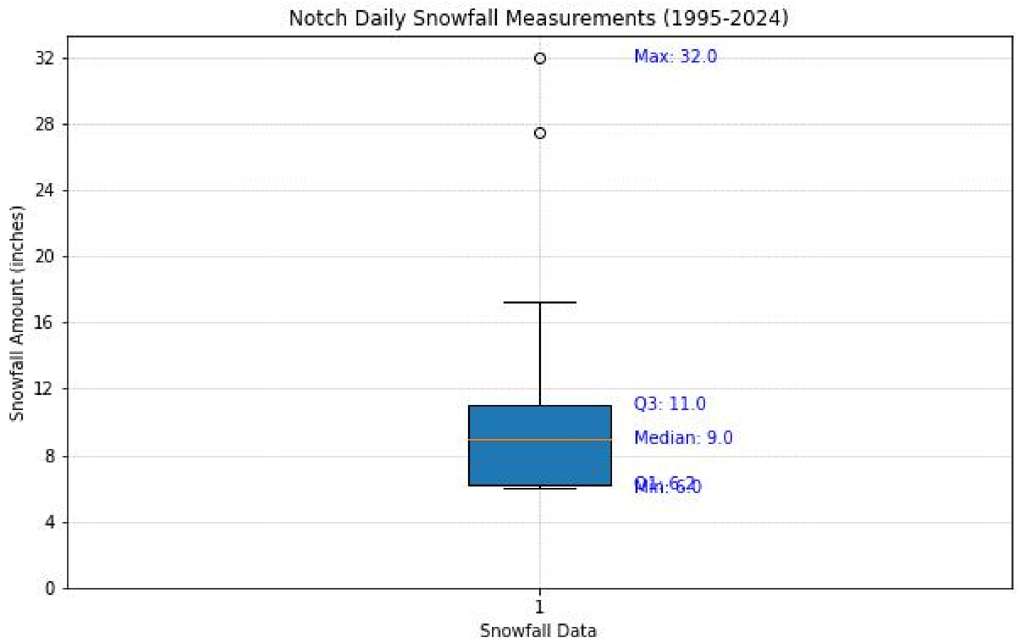

Figure 9: Intensity of Significant Snowfall Events at the Notch. Values indicating the first and third quartile values, the median, along with maximum and minimum values are depicted to the left of the plot. Outlier events are represented by the circles above the upper whisker limit.

For precipitation events, the Notch and MWO had similar median and quartile values (Figures 10 and 11). MWO had much more outlier events than the Notch again, however MWO also had the highest outlier at 6.0 inches. The precipitation measurements were slightly higher in the Notch, though overall much closer to the MWO than snowfall measurements were. The typical daily precipitation associated with significant precipitation events ranges between 1.1 and 1.6 inches for MWO, with the third quartile extended to 1.8 inches for the Notch. MWO will experience outlier events that usually range from about 2.4 to 3.0 inches of daily precipitation with outliers up to 6.0 inches. The Notch will experience outlier events ranging from about 3.1

inches to 3.4 inches. This is higher than what MWO typically experiences, though MWO does get more extreme precipitation events than the Notch.

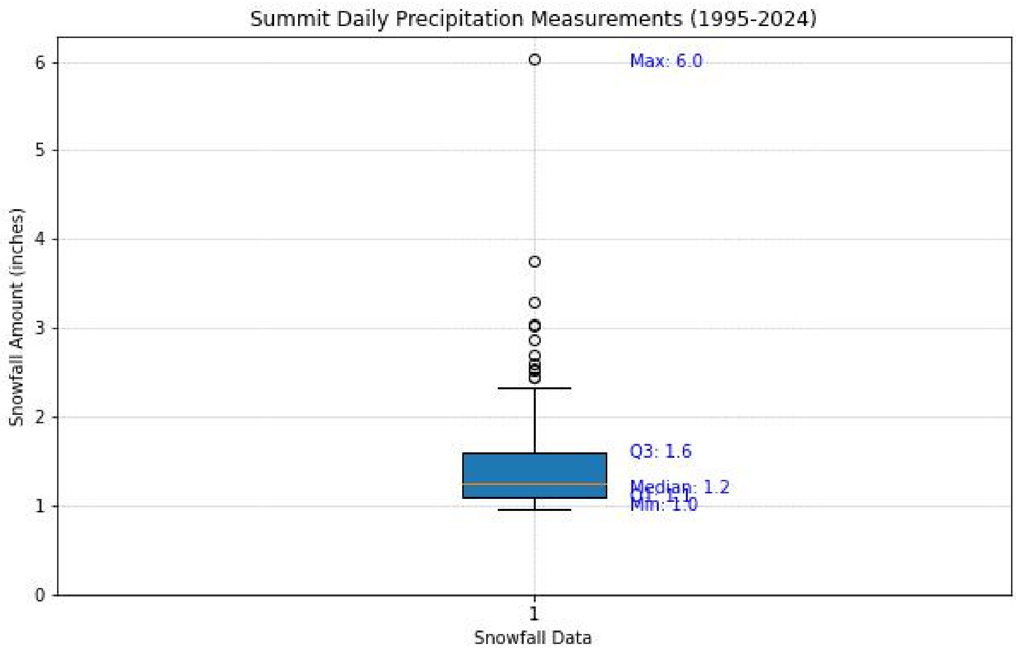

Figure 10: Intensity of Significant Precipitation Events at MWO. Values indicating the first and third quartile values, the median, along with maximum and minimum values are depicted to the left of the plot. Outlier events are represented by the circles above the upper whisker limit.

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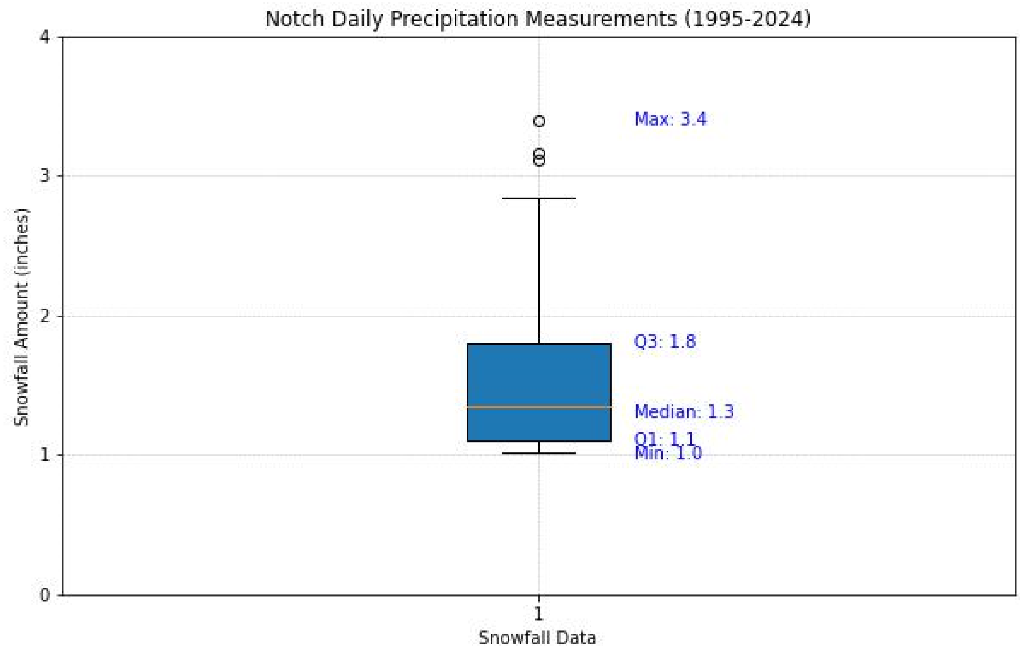

Figure 11: Intensity of Significant Precipitation Events at the Notch. Values indicating the first and third quartile values, the median, along with maximum and minimum values are depicted to the left of the plot. Outlier events are represented by the circles above the upper whisker limit.

4.4 Duration of Events

In order to establish how long systems lasted at the Notch and MWO, 3 and 5-day running averages were used. The years that recorded more days with a 3 or 5-day running average were years that experienced not just more significant events, but also more long duration events. Initial calculations revealed that it was much more common for a single event to last for two or three days than it was for it to last four or five days. Thus, the 3-day running average proved to be the best way to determine and isolate significant events that lasted multiple days.

However, both calculations were used in the study as there were events that lasted longer than three days but none that lasted beyond five days. When plotted together, these averages revealed an interesting trend. During years that experienced more significant events, there were more long duration events. This proved the case for both snowfall and precipitation at MWO and the Notch (Figures 12-15). There were also often more days meeting the 90th percentiles for the 5-day averages than the 3-day averages. This was very noticeable for the Notch, but also apparent for the summit as well. This is likely due to certain year experiencing more individual events within a short time span that then skewed the averages to be higher for longer.

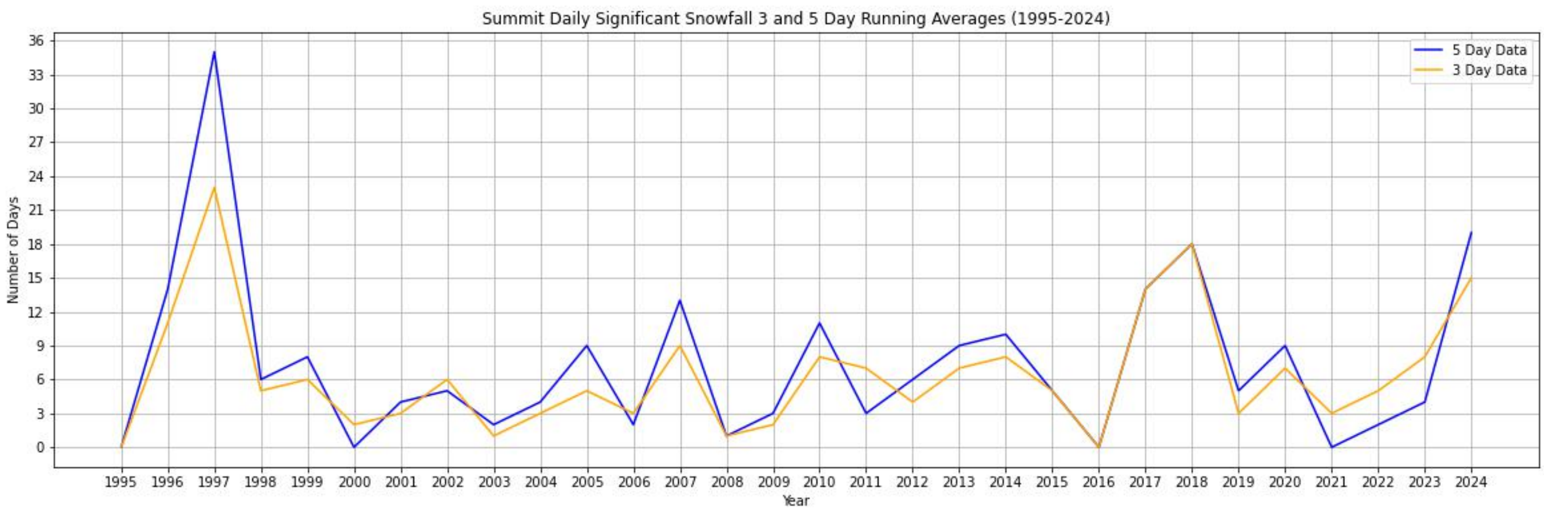

Figure 12: Duration of Significant Snowfall Events at MWO. The amount of days meeting or exceeding the 90th percentiles calculated based off the 3 and 5-day running average values.

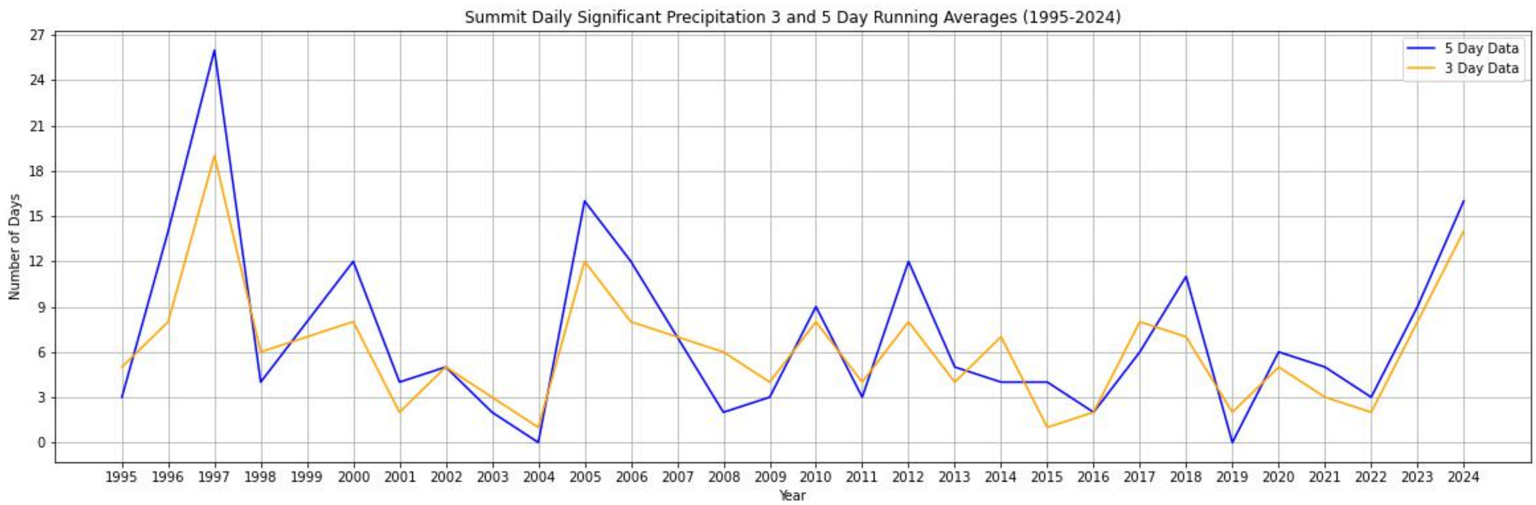

Figure 13: Duration of Significant Precipitation Events at MWO. The amount of days meeting or exceeding the 90th percentiles calculated based off the 3 and 5-day running average values.

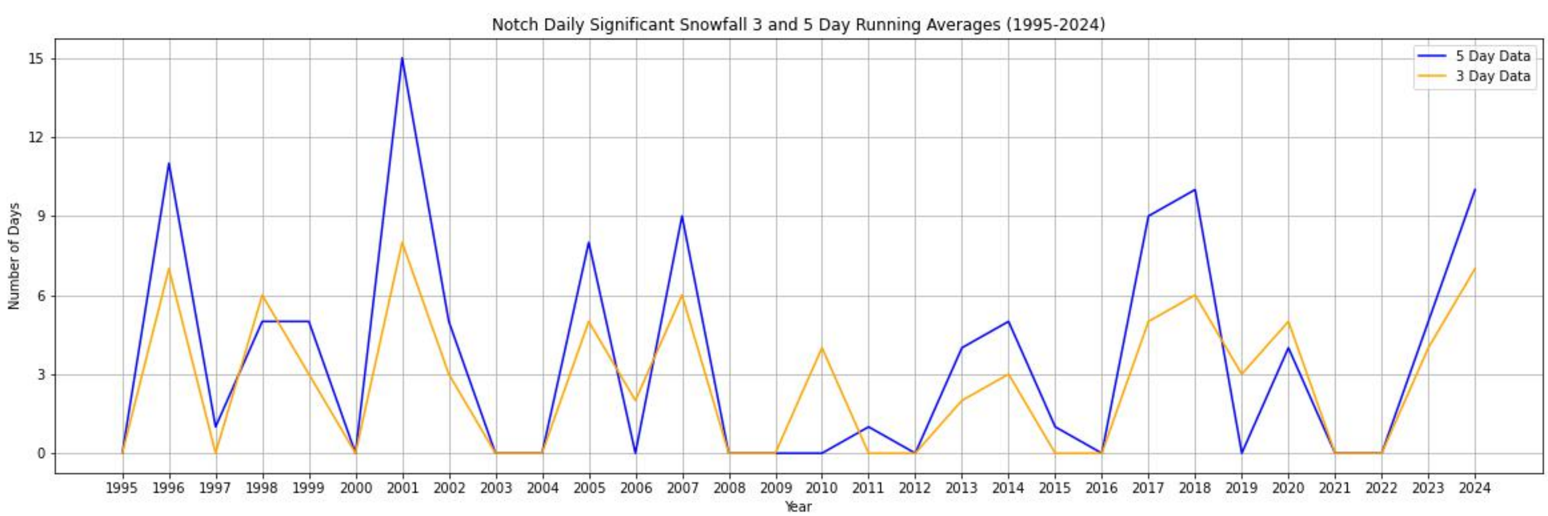

Figure 14: Duration of Significant Snowfall Events at the Notch. The amount of days meeting or exceeding the 90th percentiles calculated based off the 3 and 5-day running average values.

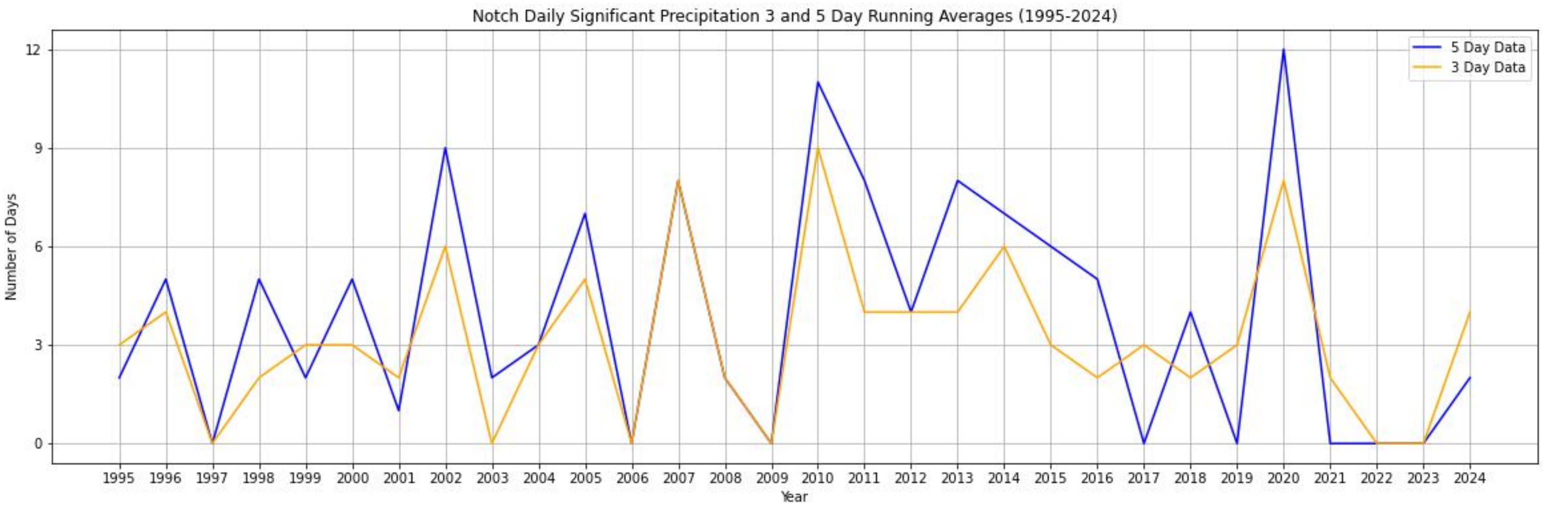

Figure 15: Duration of Significant Precipitation Events at the Notch. The amount of days meeting or exceeding the 90th percentiles calculated based off the 3 and 5-day running average values.

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5. Conclusions

The findings of this study support previous predictions by climate models indicating a steady or increasing rate of significant snowfall events. MWO has been experiencing a consistent rate of 3-4 significant late season snow events over the last 30 years and 3-4 significant precipitation events in the same period. Meanwhile, the Notch has observed a slowly increasing amount of late season significant snow events and a steady amount of significant precipitation events during this time. This has occurred despite a shortening winter season in both locations, with the back end of the snow season being especially impacted. Such trends defy expectations that with a shortening snow season, large snowstorms would decrease in frequency and intensity from s pure snowfall perspective. The White Mountains appear to be a region that will continue to receive significant snow events in the years to come despite a warming climate. The recent increase in snowfall events in the last decade at both locations is further evidence of this. While overall season snowfall may be on the decrease, the significant snow events will continue at a frequency and intensity that many are used to.

Significant snow and precipitation events also vary in frequency on a yearly basis, especially at the Notch. Despite trends indicating these events will maintain or increase in frequency, there will still be years that experience very few to no events. However, years that do experience a high volume of storms are likely to have storms that last longer. This can help forecasters with understanding the general expectations associated with more or less active storm patterns during the late snow season. These late season events are more likely to catch people off-guard, especially in the Notch. Thus, it is especially important to get these forecasts for significant events out to the public as accurately as possible. Understanding the trends with these systems will aid forecasters in this task.

The common intensities of these larger events can also help forecasters gain a better understanding of forecasting snowfall and precipitation amounts. During the late snow season, most significant snow events produced 6-11 inches of snowfall. The snow-to-liquid ratios during these late season events often varies significantly, even within a single event. Though it will change from year to year and event to event, knowing the general average snowfall and/or precipitation intensity of these storms can prove extremely useful. There is active research into these snow-to-liquid ratios at MWO being conducted, which paired with the findings of this study will aid in forecasting specific snowfall amounts at MWO and the Notch.

There remain multiple different avenues this work could be taken for the future research. The windblown snow potentially causing increased daily snowfall amounts in the Notch compared to MWO is one aspect that should be looked at. This may result in necessary changes in how snow measurements are taken at the Notch and also explain why MWO has observed lower daily snowfall than the Notch. It is also prudent to investigate the causes for the increases and decrease in significant events between years. This may involve analysis of climate oscillations or jet stream patterns and where most of these significant events originate from. Case studies could be performed on the highest precipitation and snowfall events which could explain the groups of outliers observed in this study. There is also the possibility of expanding this dataset further back in time to establish stronger trends in event frequency and intensity. Both locations have climatological data extending back to the 1930s and as such it would be relatively straightforward to do this. Including more stations within the White Mountain region would also help generate a better picture for how significant late season snow and precipitation events are changing in the area. The variety of applications this study can be applied to demonstrates the necessity to investigate and understand these late season snow and precipitation events. As the climate continues to change, it is critical that both forecasters and the public understand the fluctuating nature of the most impactful storms that this region experiences both in the past and going into the future.

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