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Article

The role minor and major snowfall events play in New Jersey snowfall over the past 126 years

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SUMMARY

Climate records indicate that there has been a trend of decreasing annual snowfall totals throughout the United States during the peak winter season. However, some states do not fit this trend. For example, New Jersey has seen a significant increase in snowfall over the past 126 years of recorded observations. This snowfall increase does not fit with the trend of increasing temperatures in New Jersey. One reason for this disconnect may be that annual snowfall may not tell the full story. We hypothesize that although annual snowfall has remained the same on average, the frequencies of major and minor snowfall events have noticeably increased. To examine this, we used the New Brunswick, NJ Cooperative Weather Station daily data, which consists of snowfall, precipitation, and temperature observations dating back to 1895. We utilized statistical tests to identify significant trends and predict future trends. In summary, we found that there was no significant evidence for an increase in the frequency of minor events (1.1-inch to 4.0-inch events), but there was evidence for an increase in the frequency of major events (4.1+ inch events). The results imply that a warming climate might be opening up opportunities for more snowfall.

INTRODUCTION

Scientists understand that global warming has led to varied changes in Earth's atmosphere. According to an ongoing temperature analysis conducted by scientists at NASA's Goddard Institute for Space Studies (GISS), the average global temperature has increased by slightly more than 1° Celsius (1.8° F) since 1880 (1). One of the effects of this increase in temperature has been the change in weather patterns over the past few decades, ranging from increasingly severe and long-lasting droughts to more potent and frequent tropical systems (2). Some US temperate climate areas (e.g., the state of New Jersey) have experienced greater variability in climatic events as compared with the rest of the world. For instance, New Jersey (NJ) has seen about a 2°C increase in temperatures over the past century (0.02°C / year), which is larger than the global average increase (1).

These temperature anomalies have had a profound impact on the winter season and winter precipitation in the United States. In recent decades, several southern states have reported significant reductions in winter precipitation due to fewer instances of temperatures falling below the freezing point. (3). On the other hand, many US northern-latitude areas like upper New England and upper Midwest have experienced either no change or even slight increases in snowfall due to the environment continuing to be favorable for snowfall despite gradual warming (4). Mid-latitude regions in the US have seen mixed results, including significant decreasing trends or no change at all (4). The snowfall trend from 1895 to 2020 in NJ was highly dependent on specific monthly observations. In NJ, measurable snowfall typically falls between the months of October and April (5). The probability of a snow event occurring outside the seven-month period is exceptionally low, and there is an even lower chance that these events are large enough to alter the trend line of annual snowfall over the 126 years of snowfall data collected.

This study considers the general snowfall trends over the past 126 years and makes specific conclusions on what can explain the New Jersey snowfall trend. The snowfall trends found in other US states gave us reason to hypothesize that although annual snowfall has remained the same on average, the frequencies of major and minor snowfall events may have increased. Our study verified our hypothesis that NJ annual snowfall has not changed noticeably over the past 126 years due to no substantial change in minor snowfall events and considerable change in major snowfall events. These findings help illustrate how a warming atmosphere has made room for extreme events. Yet in the light of increasingly variable snowfall, no changes in net precipitation have occurred. These findings can be helpful for researchers who are studying how climate change has impacted precipitation and make better hypotheses in regions that may be witnessing different trends in snowfall or other types of precipitation.

RESULTS

We approached our hypothesis by first establishing a sense of what the general snowfall trend could look like, and then used statistical programming to construct hypothesis

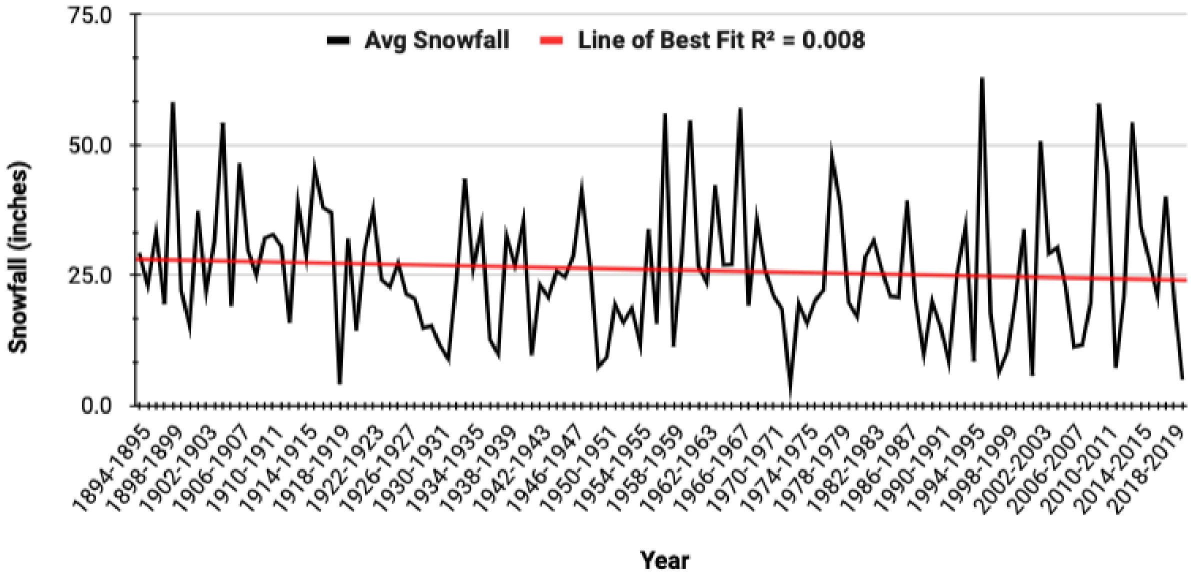

Figure 1. New Jersey Average Snowfall Time Series (1895-2020) from October - April. Shows the progression of average snowfall in Northern, Central, and Southern NJ from 1895-2020. Year (x-axis) is each winter season and snowfall (y-axis) is the total snowfall measured in inches.

tests to obtain actual results. To establish an intuition for what the general snowfall trend could look like, a brief comparison was made between the arithmetic means of annual snowfall from the winter of 1995 to the winter of 2020 period and from the winter of 1895 to the winter of 1994 (**Table 1**).

What can be observed from this analysis was that average snowfall has not changed from recent decades when climate change has been named a tangible threat and the century prior.

It might be plausible to believe that since average temperatures have been on the rise for NJ, this could translate to a gradual, yet significant decrease in snowfall totals over the past century. Examining the snowfall time series, we found a slightly negative correlation. The calculated r value indicated little variability in general during the last 126 years. In fact, we calculated an r-value of (0.008)^(½) = -0.09 (the negative result is due to the negative correlation), which means that there was little to no change in the average snowfall over the past century (**Figure 1, Table 3**). It is important to note that when we say, "not much variability in general," we are referring to the overall snowfall trend being quite stagnant. But if we compare annual snowfall values from year to year, the variability of annual snowfall is rising. We saw many more definitive "spikes" in the snowfall time series starting from the mid-1990s. Despite this, the increased variability still was averaging out to annual snowfall amounts similar to what was seen prior to the mid-1990s.

The slight difference in arithmetic means (26.1 inches of snow per year versus 26.0 inches of snow per year) suggested that although the variability in annual snowfall from the past two to three decades has been quite high compared to annual snowfall around a century ago, the average snowfall in the past few decades is still consistent with the average snowfall from earlier decades (**Table 1)**. With this finding, we sought to examine why NJ snowfall has proven to have no statistically significant change for over a century. We hypothesized that the nature in which snow is falling, more specifically trends in the frequencies of major and minor events, may be leading to this stable annual regime.

Upon examination of each of the histograms, we identified an increase in minor (0.1-2.0 inch) and moderate (4.1-6.0 inch) snowfall events. However, there was some evidence for a decrease in the number of events between those two levels (2.1-4.0 inch) **(Figure 2)**. All the other levels suggest little to

Table 1. Analysis of Arithmetic Means (1895-1994, 1995-2020).

Year Range	Calculations (total inches of snow / total number of years)	Arithmetic Mean (average inches of snow / year)
1895-1994	**2610.0 inches / 100 yrs**	**26.1 inches / year**
1995-2020	**675.2 inches / 26 yrs**	**26.0 inches / year**

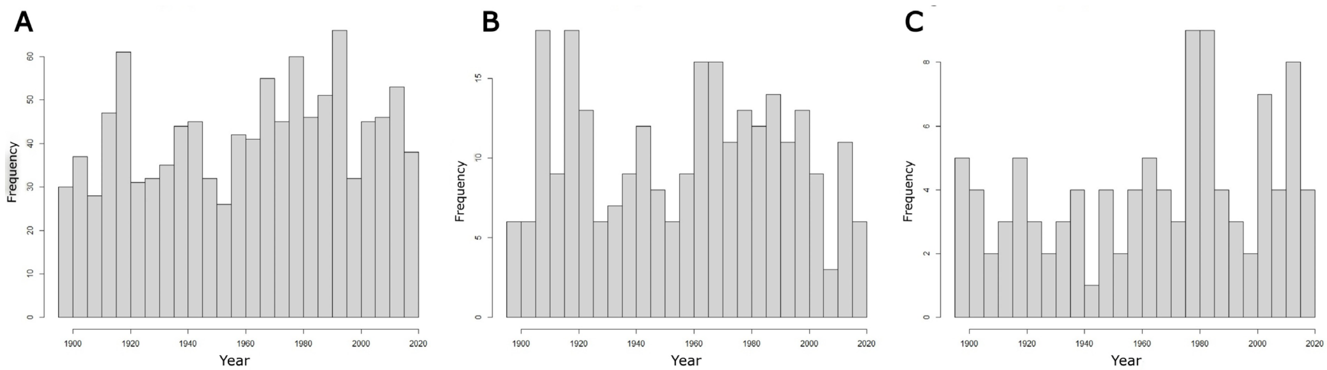

Figure 2. Frequency Histograms of Minor to Moderate Snowfall Events. a) Frequency of 0.1-2.0-inch snowfall events **b)** Frequency of 2.1-4.0-inch snowfall events **c)** Frequency of 4.1-6.0-inch snowfall events. All 3 graphs show the progression of specific snowfall events over the past 126 years. All 3 graphs have different scales of frequency, but the year gaps are all the same.

no correlation. However, there was an increase in events higher than 15 inches **(Figure 3)**. The most major snowfall events in the past 126 years have all occurred in the past 60 years (**Figure 3**). This increase in major events suggested that snowfall may be more consistent rather than earlier decades having more snowfall compared to recent decades.

To expand on the output found in **Figures 2** and **3**, we first combined some of the levels together to conduct regression analysis into two groups, minor snowfall events and major snowfall events. This was done to consolidate the six small groups that were formed, as well as collect enough data points to conduct a more accurate analysis. We examined the Analysis of Variance Minitab output for both the minor and major event dataset. Although there was evidence of a slight decrease in the frequency of minor events, the decrease was not statistically significant (p = 0.821). On the other hand, there was evidence to suggest that major snowfall events have increased over time (p = 0.019, R-Squared = 0.044). We visualized the progression of the frequency of minor and major events per year using a one-way ANOVA test. All the 126 years of snowfall data were spliced in three random ranges of years, yielding four groups: (Group 1: 1895-1931, Group 2: 1931-1962, Group 3: 1962-1987, Group 4: 1987-2021). Then, the mean frequency of minor and major events per year was calculated for each of the four groups, and it was determined whether any one of the means was statistically significant from the other three. The confidence intervals show all plausible mean values of each of the four groups to visualize and verify the statistical significance (**Figures 4**, **5**).

The main takeaway from this data was finding that there was an increase in the mean number of major snowfall events, but not minor events. There was no evidence to suggest any mean differences from the rest for minor events (p = 0.094, **Figure 4**). Although there was no statistically significant difference in the frequency of major snowfall events, our data suggested that there was a trend toward increasing the frequency of these events (p = 0.13, **Figure 5**). The general lack of a trend in the frequency of minor events and the steady increase in the frequency of major events could explain why NJ annual snowfall has not decreased despite the temperature increases over the past 126 years.

DISCUSSION

To look at how the NJ annual snowfall trend remained stagnant over the past 126 years, we wanted to examine whether the effects of climate change are involved. Therefore,

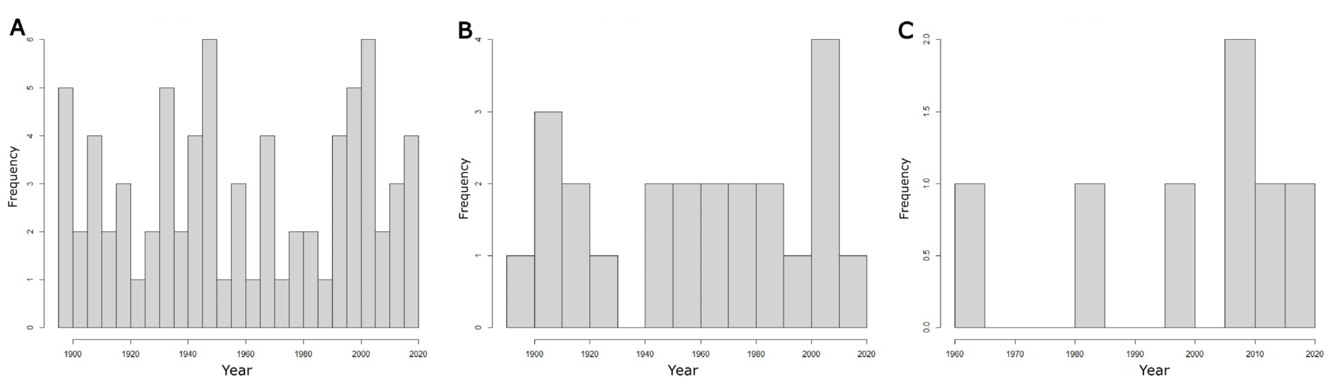

Figure 3. Lifespan activity of control and Aβ_{42} overexpressing flies (n = 300) that were fed plant extract combinations (ALDC) and regular corn meal

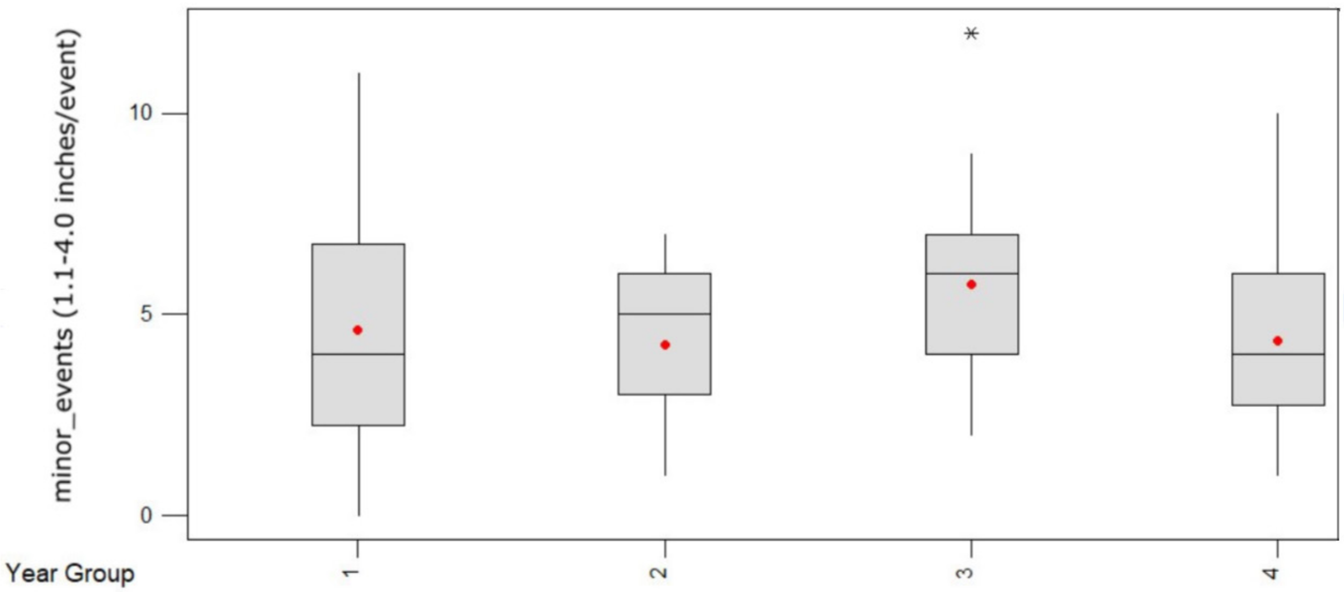

Figure 4. ANOVA on Minor Events. One-Way ANOVA: minor_events versus Year Group. Minitab output describes the mean frequency in minor events for each group with random length. 95% confidence intervals, as depicted by the box-whisker plots, show the spread of the data and how different the plausible means are from one group to another. Means of a single year group are denoted as the red dots. Year Group 1 consisted of snowfall data from 1895-1930, Year Group consisted of snowfall data from 1931-1961, Year Group 3 consisted of snowfall data from 1962-1986, and Year Group 4 represented snowfall data from 1987-2020. Year Group 1 shows a mean frequency of 4.61 ± 3.08 events, Year Group 2 with 4.26 ± 1.84 events, Year Group 3 with 5.76 ± 2.19 events, and Year Group 4 with 4.35 ± 2.27. *p*-value = 0.094.

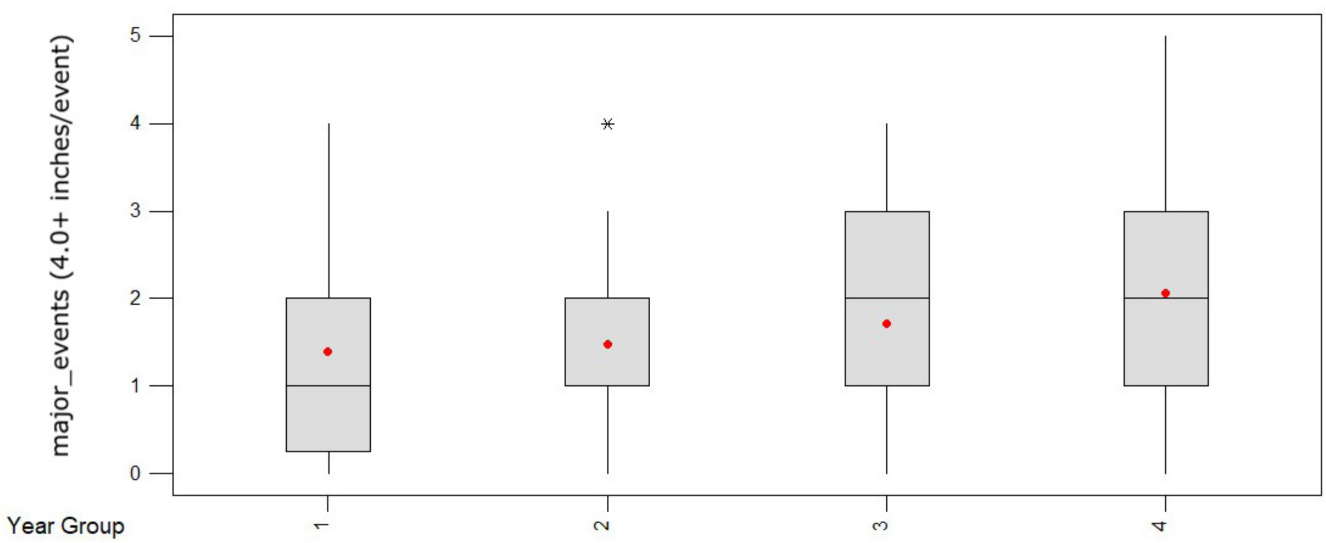

Figure 5. ANOVA on Major Events. One-Way ANOVA: major_events versus Year Group. Minitab output describes the mean frequency in major events for each group with random length. 95% confidence intervals, as depicted by the box-whisker plots, show the spread of the data and how different the plausible means are from one group to another. Means of a single year group are denoted as the red dots. Year Group 1 consisted of snowfall data from 1895-1930, Year Group consisted of snowfall data from 1931-1961, Year Group 3 consisted of snowfall data from 1962-1986, and Year Group 4 represented snowfall data from 1987-2020. Year Group 1 shows a mean frequency of 1.39 ± 1.20 events, Year Group 2 with 1.484 ± 1.15 events, Year Group 3 with 1.72 ± 1.17 events, and Year Group 4 with 2.06 ± 1.46. *p*-value = 0.130.

we thought of categorizing snowfall events based on how extreme they are. We decided to approach our hypothesis by looking at minor and major snowfall events and looking at how the frequency in these two types of events have changed. We saw that minor event frequencies did not change significantly, whereas major event frequencies did change considerably.

The first group (minor_events) was snowfall events that produced 1.1 to 4.0-inch snowfall events and the second (major_events) was all snowfall events above 4 inches. We named these groups in the context of how NJ snowstorms are usually classified as, not a general classification that was mentioned before. In NJ, minor snowstorms are usually snowfall events where around 4 or fewer inches fall. The reason for omitting any snowfall events below an inch is due to potential observation biases that can result from minor accumulations (6).

Examining the Minitab output of the frequency in 1.1 to 4.0-inch events, the frequency of minor events does not change significantly over the 126-year period (p = 0.821). The corresponding ANOVA test with the confidence intervals allows for other plausible hypotheses to be made. Looking at the confidence intervals in the minor event ANOVA test, Year Group 3 stood out as relatively different from the rest of the groups (p = 0.13, **Figure 4**). While Year Group 3 was near statistical significance, this difference does not indicate that there was an increase in the frequency of minor events, but that Year Group 3 was significantly different from the other year groups. It does not necessarily indicate that minor events have seen significant differences. The wavering nature of four confidence intervals provided further evidence that the frequency of minor events was not enough to make definitive conclusions about any trend. Overall, our results suggest that minor snowfall events are not getting more or less frequent in NJ.

However, our results suggest that major snowfall events are getting more frequent in NJ. When examining the frequency histogram of snowfall events exceeding four inches, the R-squared value of 0.044 suggests that there was evidence for an increasing trend in major events. What seemed interesting was that the line of best fit slope is remarkably close to zero. However, the p-value derives from the standard deviation and the number of observations in the dataset (**Figure 5**). Since the standard deviation in the major event dataset is smaller than the minor event dataset combined with the fact that there are fewer major events than minor events, this explained the exceedingly small p-value of 0.019 when compared to alpha values of 0.05 or 0.1. Although the ANOVA results clarified that the mean frequencies among the four groups do not have significant differences, the increasing nature of the center of the confidence interval as well as the general rightward shift of the interval itself begged the question of whether this trend is likely to continue (**Figure 5**). It is important to note that the results of an insignificant decreasing trend in minor events and significant increasing trend in major events still explained the absence of a long-term trend in NJ snowfall. Despite the minor events showing no change, the large dataset of minor event frequencies coupled with the small dataset of major event frequencies does explain the stagnant trend seen in **Figure 1 (Table 3)**. The key component in this conclusion was to realize that there are many more minor events that occur when compared to major events.

This conclusion supports assertions that the advent of climate change is contributing to potential increases in snowfall in northern US states and will continue to become more pronounced if trends like the one we are seeing with New Jersey hold (7). Possible explanations for major event frequencies increasing in NJ could be that the warmer temperatures have resulted in more opportunities for snowfall events because of a possible increase in atmospheric moisture (8). While this increase is happening, the warmer temperatures are also reducing opportunities for snowfall events because of more days for temperatures to be above the freezing point. But even in an environment where there is a noticeable reduction in below-freezing days, it only takes a few days where the temperature is below freezing combined with a large buildup in atmospheric moisture to produce more extreme snowfall.

Another experiment that would be related to this would be to examine the conditions in which minor and major snowfall events occurred. Exploring if the mean temperature in minor and major snowfall events have changed over the course of 126 years or looking at winter precipitation numbers may help us answer the questions relating to the potentially changing moisture amounts in the atmosphere.

The dataset used in this study would yield even more accurate findings if a clearer measurement of snowfall was used during the decades where recorded measurements were taken. Over the past decades, the instruments used to measure precipitation have become much more advanced. Also, since most of the data collection was done manually, there is a chance for human error to exist. Finally, since snowfall measurement was done at a certain time in the day, there may be cases where snow may have melted before researchers measured the snow on a given day. Regardless, it is unlikely that any of these sources of error would produce different results than our study found.

METHODS

To further address our hypothesis, we obtained daily climate observations from the New Brunswick, NJ National Weather Service Cooperative Weather Station **(6).** The New Brunswick Cooperative Weather Station data **(6)** was used in this study for two reasons. First, this station is in Central Jersey, which means that the observations would be able to better represent the average snowfall between Central, Northern, and Southern observation stations. The second reason was the confidence of the accuracy in the observations. Therefore, we were confident that the measurements gathered at the New Brunswick station accurately depict the daily totals in snowfall and the daily temperatures in NJ. These reasons

Table 2. Level Partitions of Snowfall Events.

Level	Snowfall (inches)
1	0.1-2.0
2	2.1-4.0
3	4.1-6.0
4	6.1-10.0
5	10.1-15.0
6	>15.0

combined made this station a useful source to analyze data and make conclusions from.

We aimed to determine the frequency of snowfall events of different magnitudes based on daily snowfall observations. Days where snow fell were partitioned into 6 levels, representing a spectrum of minor to major snowfall events (**Table 2**).

To separate the observations into such levels, we used the statistical language R to filter out the days when no snow fell and to partition the days when snow fell into the six levels. Once the observations were sorted and placed into their respective "levels," there were six sub-datasets, one for each level. To visualize how the frequencies of these snowfall events have changed over time, a histogram was created where the year was the independent variable and the frequency of events in a certain year or group of years was the dependent variable.

The dataset used in this study can be accessed for free through a NOAA website (6). The variable we were interested in is daily snowfall. The months of interest are October to April as most of winter precipitation falls in this period, so the dataset was filtered by taking out the other five months. Using the R statistical software, the data were further cleaned by filtering such that only daily snowfall and temperature observations were left.

The 4.0.3 Windows version of R statistical software was used to analyze and parse through the NOAA dataset. The dplyr, ggplot2, and statsr packages were used in our analysis to construct histogram plots. For the ANOVA and regression output, we used the Minitab 20.1 version.

Once the seven-month min-max temperature data and daily snowfall data were organized, we first split the data into six different partitions based on snowfall amount to conduct preliminary analysis. Then, the six datasets were recombined to form two larger datasets, which represented the minor and major snowfall events. The R software calculated the frequencies of minor and major events each year and formulated a frequency histogram. Then, a manual approach was taken to produce appropriate bin widths, in this case being 25. The frequency of minor and major snowfall events over time was further analyzed by using linear regression tools in Google Sheets and Minitab, yielding the following equations: minor events = 4.60 + 0.001 * YEAR_1 (p = 0.821; R-squared = 0%), and major events = 1.20 + 0.007 * YEAR_1 (p = 0.019; R-squared = 3.6%). YEAR_1 represents the number of years after 1895.

To obtain the ANOVA output, we used the same spreadsheet in google. The 126 years of data were split into four groups of random, yet comparatively close lengths for each ANOVA test. Then the mean frequencies in each group were calculated, and 95% confidence intervals were created, showing and justifying the p-value of each test. All p-values were compared to the standard alpha value of 0.05. The boxplot accompanying each ANOVA test was also created in Minitab and serves as another way to visualize the confidence intervals. The box plots comprise the 25—75% (Q2—Q3) interquartile range, with whiskers expanding to the lower (Q1) and upper (Q4) quartiles (5—95%). The median was represented by a horizontal line inside the box and the mean is represented by a solid red circle. In our analysis, there were two outliers, one in the minor and one in the major event analysis. We used the outliers in the analysis because there were more than enough data points (126) that would offset the effect of the outliers.

Table 3: Corresponding regression output for Figure 1.

Source	DF	SS	MS	F	P
Regression	1	171.4	171.399	1.01573	0.315
Error	124	20924.3	168.744		
Total	1225	21095.7			

NOTE: *The Source row represents the following values from left to right: DF = Degrees of Freedom, SS = Sum of Squares, MS = Mean Squares, F = F-statistic,* **P** *= probability. The* **p***-value of 0.315 indicates an insignificant slope change.*

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