TRENDS IN 20TH CENTURY U.S. SNOWFALL USING A QUALITY-CONTROLLED DATA SET

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ABSTRACT

A quality assessment has been undertaken of all U.S. long-term stations in which the authors have made an expert judgment on the quality of each station. Through this process, we have identified a set of stations we believe to be suitable for analysis of trends. We have analyzed snowfall variations back to 1900. Snowfall has generally decreased nationwide since peaks in the 1970s. At low snowfall stations, snowfall during the last 15 years has been lower than at any time since 1900. However, at moderate and high snowfall stations, snowfall was lower in the 1920s and 1930s. Since the late 1980s, extreme high snowfall years have been rather infrequent, while extreme low snowfalls have occurred at a near-average frequency. There are statistically significant relationships between temperature and the frequency of extreme snowfall years.

INTRODUCTION

Routine keying of data from the National Weather Service's Cooperative Observer Network began in 1948. For many years, most of the data, including snowfall, were keyed under the Climate Database Modernization Program (Kunkel et al., 2006). Kunkel et al. (2006, 2007) described a number of issues with snowfall data that potentially affect long-term trends analysis. Changes in station location, observer, and measurement practices are among the factors that can introduce temporal inhomogeneities into the data time series. The central objective of this project is to study long-term trends in snowfall. To that end, it is necessary to carefully screen the data to identify stations with suitable temporal homogeneity.

METHODS

The primary method for determining a station's quality was through expert assessment by a team of scientists experienced in the use of snow data. The expert assessments were supported by a number of objective tests and graphical tools available on a web site accessible by team members.

Stations were first screened based on missing data. In order to be considered as a candidate, missing data days had to constitute less than 10% of the total number of days for the period 1930-2004 during the months of October through May. A refinement of this criterion was applied after it was discovered that for some stations during some periods only non-zero amounts were keyed while the rest of the days in the month were entered as missing. This appears to represent a misinterpretation of the form. In many cases, observers left the snowfall column blank when a zero value was implied. Therefore, when a month of data for a specific station included non-zero snowfall values, while all other days were entered as missing, we replaced these missing values with zeroes when one of the following criteria were met: (1) total precipitation was entered as zero, or (2) precipitation was non-zero, but the minimum temperature was greater than 32°F.

A second screening criterion required that the 1971-2000 long-term mean snowfall be in excess of 5 inches, eliminating southern areas where snowfall is very infrequent and not a central aspect of the climate.

Paper presented Western Snow Conference 2007

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To support the quality assessment, two graphs were prepared for each station. One showed time series of annual snowfall for the station and the 14 nearest stations with at least 30 years of data. The second showed time series of the difference between the annual snowfall anomaly for the reference station minus the annual snowfall anomaly for a nearby station for the same 14 stations as shown in the annual snowfall time series graph. The times of station moves or observer changes recorded in station histories were noted on the graphs.

Each station was assessed by each of the authors and put into one of 3 categories: "homogeneous: (suitable for trends analysis), "inhomogeneous" (not suitable for trends analysis, and "questionable" (the time series exhibited some questionable behavior but may be suitable for some purposes, such as filling in an area with no other stations).

RESULTS

At this point, the assessment is at an advanced stage. Figure 1 show the distribution of the provisional list of 423 stations that have been given a homogeneous assessment by a majority of assessors. There is a reasonably complete coverage of the U.S., although the density of stations is rather low in some areas of the west. This network was used in all subsequent analyses.

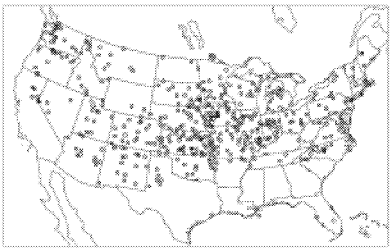

Figure 1. Locations of snowfall stations assessed as homogeneous by a majority of assessors.

Time series of total annual snowfall standardized anomalies from the 1971-2000 mean were generated for each station. Then climate division values were calculated by arithmetic averaging of all stations in the division. Finally, national values were generated by area-weighted averaging of the climate division values. National time series were generated for 3 categories of stations based on mean annual snowfall (5-20 inches, 20-80 inches, and >80 inches). These time series (Figure 2) show rather similar behavior to those shown previously using the entire set of stations (Kunkel et al. 2006, 2007). Prior to about 1950, there are substantial differences among the 3 categories. The light snowfall time series exhibits mostly positive anomalies while the heavy snowfall stations are generally below the 1971-2000 average, except during the 1910s. The moderate snowfall stations are mostly near average. From 1950s onward, the anomalies are very similar for the 3 categories. Anomalies increase from near average values in the 1950s to a relative maximum in the 1970s, followed by a downward trend into the early 21st Century. The low snowfall station time series exhibits the lowest values in the last 10-15 years.

Extreme snowfall years were identified for each station. These were defined as years with total snowfall less than the 10th percentile threshold or greater than the 90th percentile threshold; these thresholds were calculated from the station's entire period of record. The percentages of stations with high or low extremes were determined for each year. A time series of the percentage of stations with extreme high snowfall (Figure 3) manifests sizeable multi-decadal variability. Prior to about 1920, the percentage of high snowfall years was quite high. This was followed by a period of generally low percentages in the 1920s, 1930s, and early 1940s. The period from the late 1940s to about 1980 was characterized by moderately high percentages. The period since the mid 1980s has seen a number of years with very low percentages. A substantial portion of the interannual variability is related to temperature variability. There is a negative correlation between the percentage of stations with high snowfall and winter (December-February) temperature (Figure 4). Winter temperature explains about 34% of the variance.

The time series of percentage of stations with extreme low snowfall (Figure 5) exhibits behavior approximately, but not exactly, inverse to the extreme high snowfall time series (Figure3). There are high percentages in the 1920s and 1930s, low percentages from the 1940s to about 1980, and moderate values from the 1980s onward, approximately opposite to the results for extreme high snowfall. However, there were high

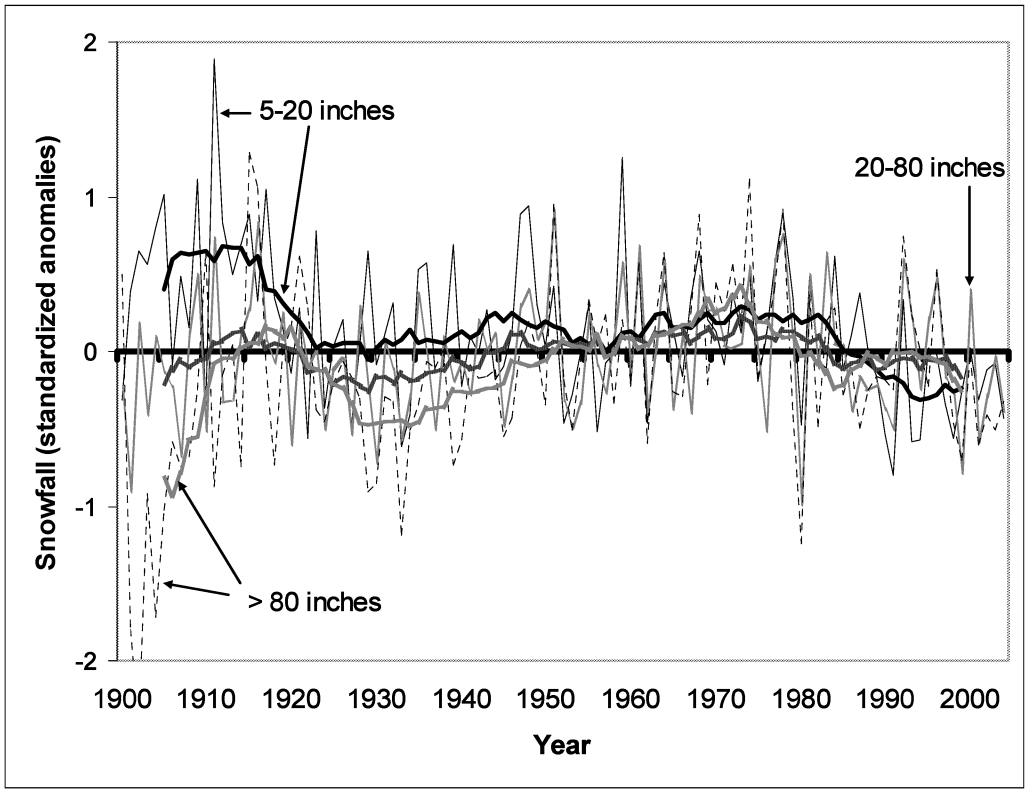

Figure 2. U.S. average time series of snowfall (expressed as standardized anomalies) for long-term stations shown in Figure 1. Separate time series are shown for stations with mean annual snowfall of 5-20 inches (light solid line), 20-80 inches (dotted line), and >80 inches (dashed line). 11-year running averages are shown by the heavy solid line (5-20 inches), dark shaded line (20-80 inches), and light shaded line (> 80 inches).

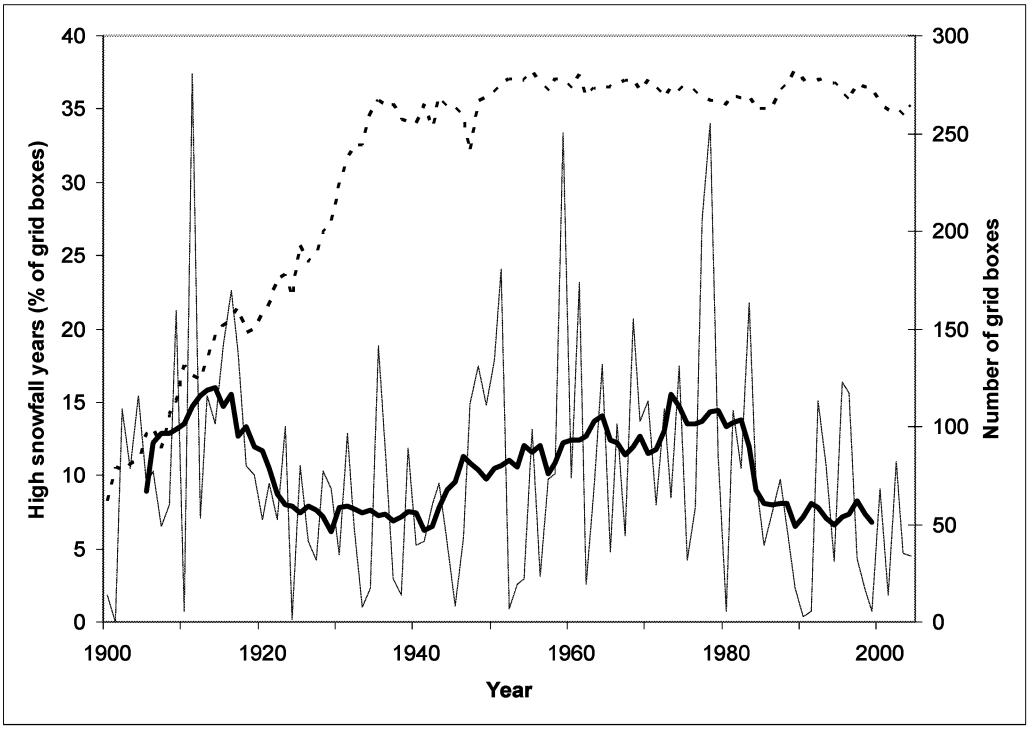

Figure 3. Time series of percentage of stations with annual snowfall above the 90th percentile threshold (thin line). The 11-year moving average is shown by the thick line. The time series of the number of stations with data is shown by the dashed line.

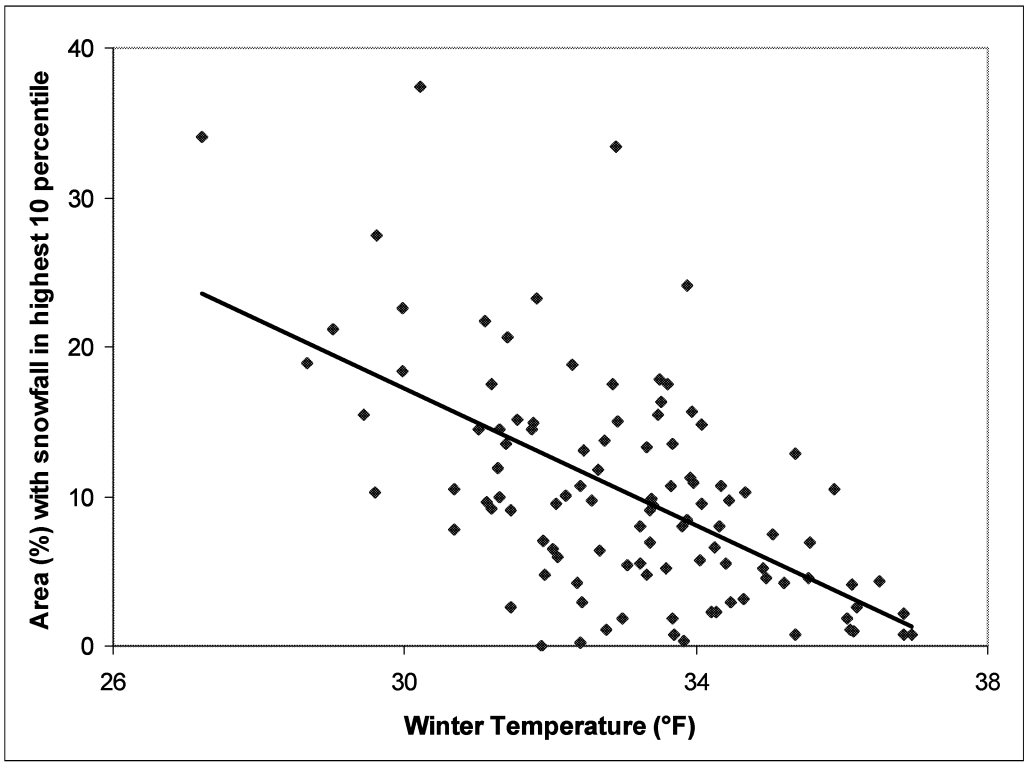

Figure 4. Scatter plot of percentage of stations with snowfall above the 90th percentile threshold versus U.S. winter (December-February) temperature. Straight line shows a least-square fit.

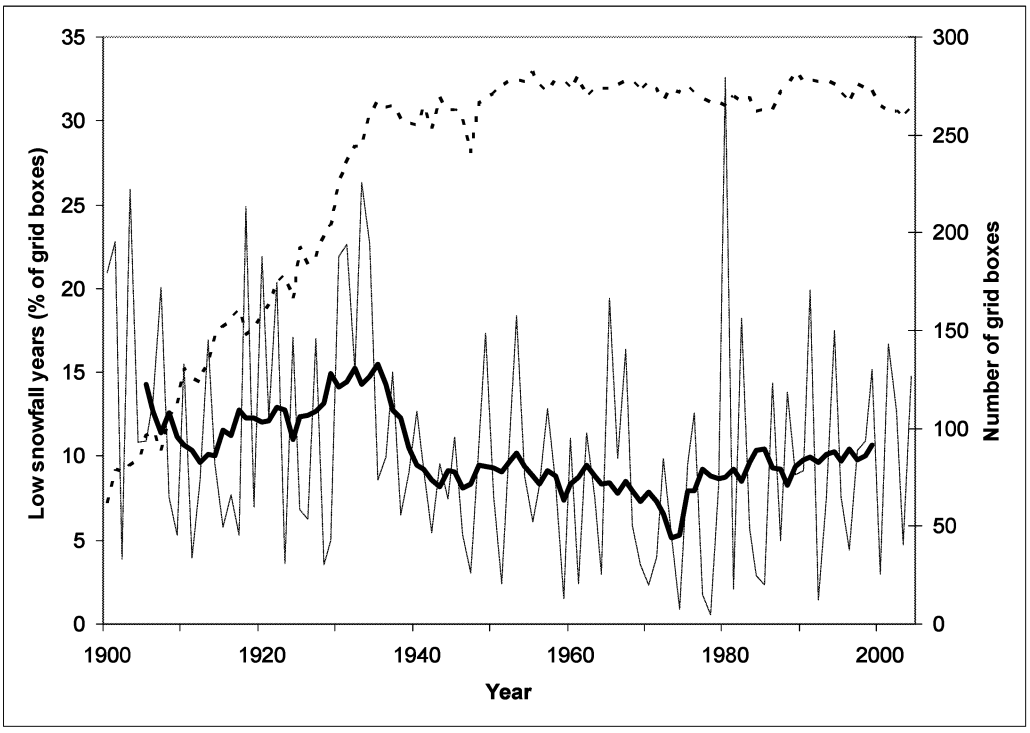

Figure 5. Time series of percentage of stations with annual snowfall below the 10th percentile threshold (thin line). The 11-year moving average is shown by the thick line. The time series of the number of stations with data is shown by the dashed line.

percentages of extreme low snowfall years prior to 1920, when there also were high percentages of high snowfall years. This result indicates that increased interannual variability may be present in the early records, and warrants

further investigation. There is a positive correlation between percentage of extreme low snowfall years and winter temperature (Figure 6). However, winter temperature explains less variance (18%) for extreme low snowfall than for extreme high snowfall (34%).

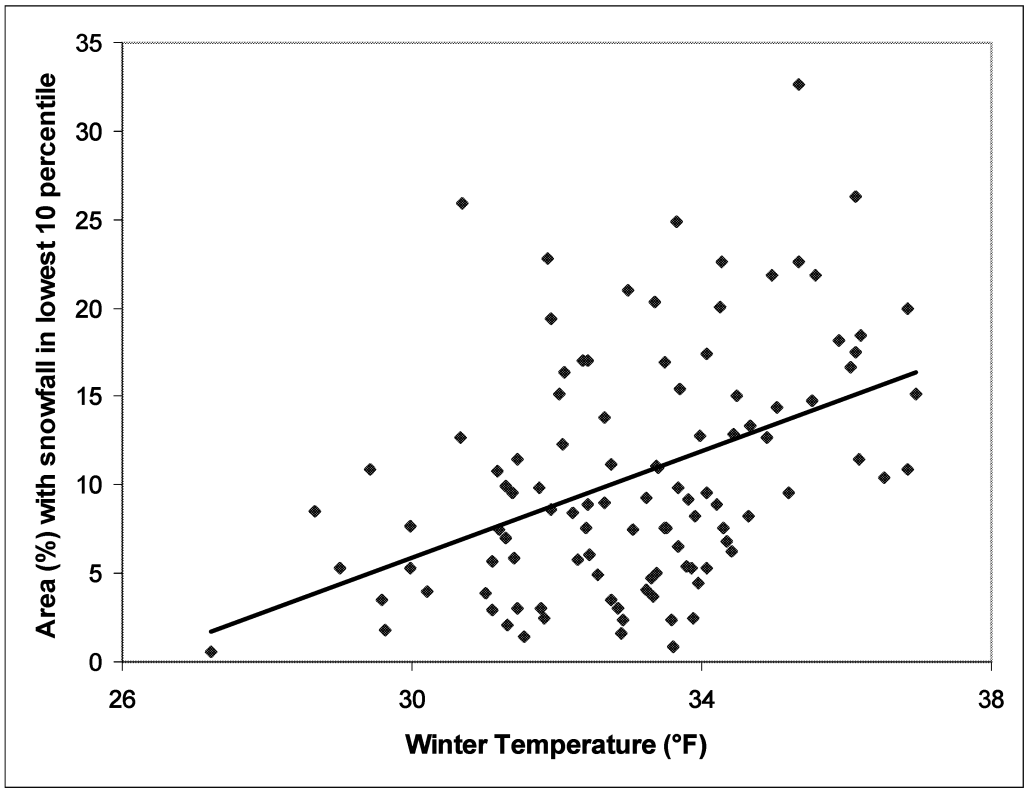

Figure 6. Scatter plot of percentage of stations with snowfall below the 10th percentile threshold versus U.S. winter (December-February) temperature. Straight line shows a least-square fit.

CONCLUSIONS

Snowfall has generally decreased nationwide since peaks in the 1970s. At low snowfall stations (mean snowfall in the 5-20 inch range), snowfall during the last 15 years has been lower than at any time since 1900. However, at moderate and high snowfall stations, snowfall was lower in the 1920s and 1930s. At high snowfall stations, snowfall was very low in the first decade of the 20th Century, although there were very few stations in operation at that time. Since the late 1980s, extreme high snowfall years have been rather infrequent, while extreme low snowfall years have occurred at a near-average frequency. There are statistically significant relationships between temperature and the frequency of extreme snowfall years.

ACKNOWLEDGEMENTS

This work was partially supported by National Oceanic and Atmospheric Administration Office of Global Program award NA05OAR4310016. Additional support was provided by NOAA cooperative agreement NA17RJ1222. Any opinions, findings, and conclusions are those of the authors and do not necessarily reflect the views of NOAA or the institutions for which they work.

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