An Historical Analysis of the Climate in Minnesota: *1886 through 2012*

Introduction

This report analyzes patterns in the climate of Minnesota between 1886 and 2012. The data is taken from "Global Historical Climatology Network - Daily", a publicly-available database published by the National Oceanographic and Atmospheric Administration (NOAA). It includes data from 75,000 weather monitoring stations in over 180 countries. The data for this report is from region **BBSBSBSB**, a 32,000 square kilometer area centered around Cohasset, Minnesota and includes parts of Canada and Lake Superior.

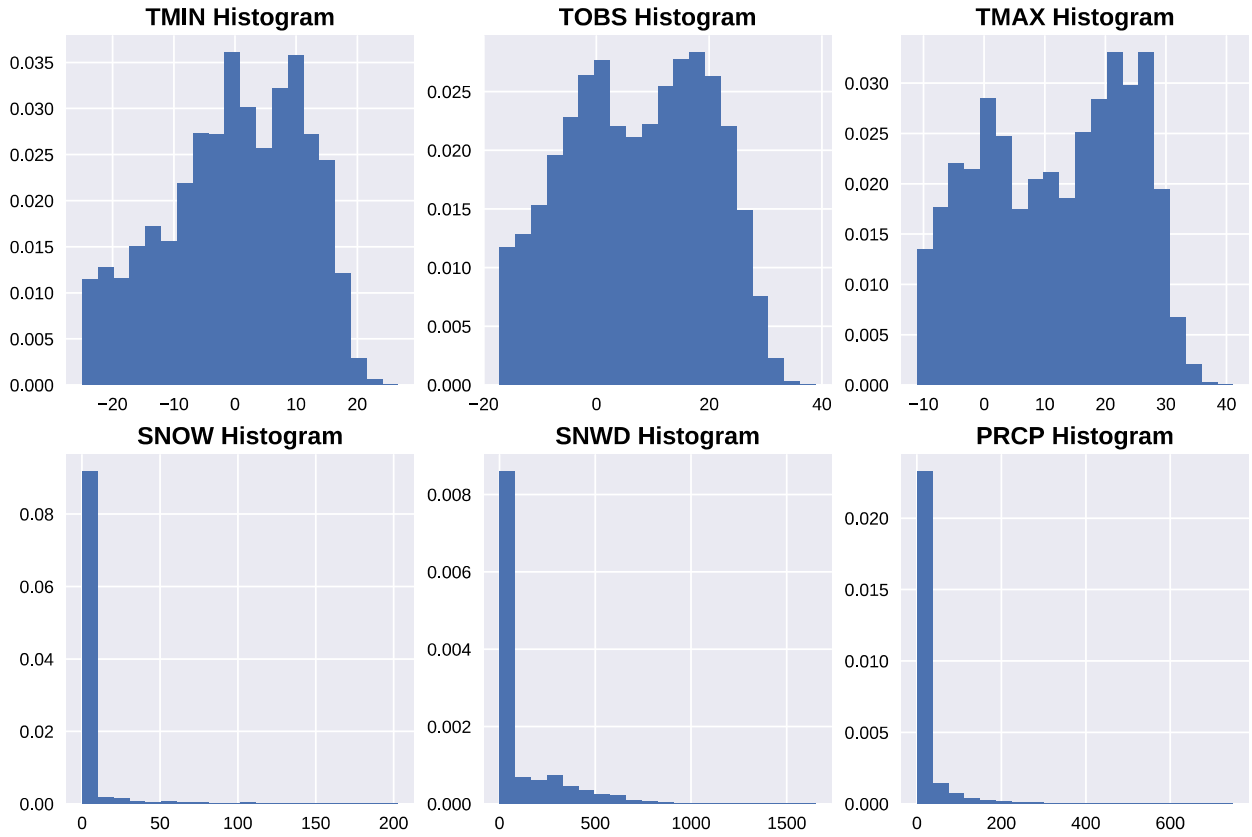

Figure 1: The six measurements.

The records include six atmospheric measurements: precipitation (*PRCP*, in mm); snowfall (*SNOW*, in mm); snow depth (*SNWD*, in mm); maximum daily temperature (*TMAX*, in tenths of ºC); minimum daily temperature (*TMIN*, in tenths of ºC); and observed temperature (*TOBS*, in tenths of ºC). Daily measurements were taken throughout the 126 year period.

The goal of this report is to identify patterns in these six measurements and determine if there have been changes to Minnesota's climate over the last century.

Data Preparation and Exploration

Our region included 105 of the 460 weather stations in Minnesota. There were 12,493 measurements. Not all stations kept a daily record for all six measurements. For a given year, approximately 16% (+/- 15% s.d.) of the days had at least one missing measurement. The number of observations increased dramatically around 1950 and has been fairly constant since then. This is directly related to the number of stations in operation as seen in Figure 2.

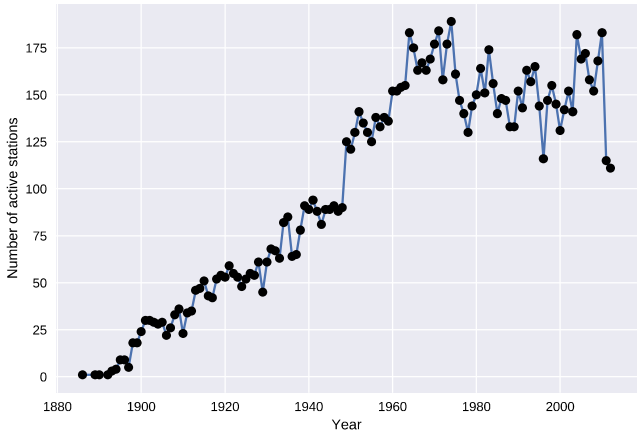

Figure 2: More stations were added over the century

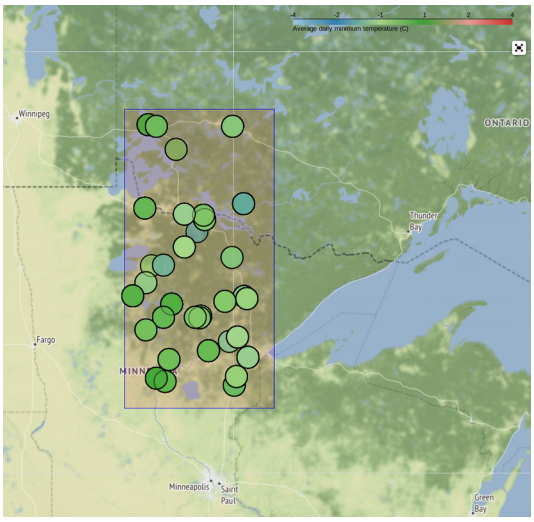

Figure 4: Average TMIN before 1950

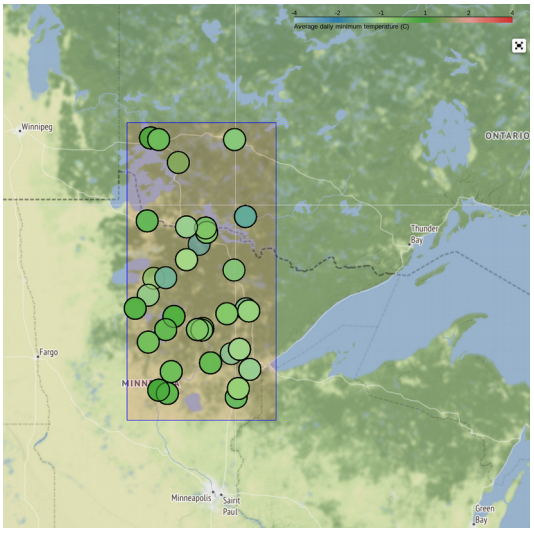

Figure 3: Average TMIN after 1950

Figures 3 and 4 show the distribution of the stations on the geographical map both before and after 1950. The circles are centered on the individual monitoring stations that were used in this analysis. They span the entire region. The color within the circles reflects the average minimum daily temperature (TMIN) for that station over the year. According to the NOAA website, TMIN for Duluth, Minnesota (a large city within our region) is 1.3 ºC. This is consistent with the data shown in Figures 3 and 4. Note well that the average value of TMIN is consistent across all monitoring stations within our region and appears to remain stable between the two time periods.

Nevertheless, the U.S. Environmental Protection Agency reports that climate change has increased the temperature in the Duluth region between 0.5 and 1.5 ºC over the last 100 years ("What Climate Change Means for Minnesota", EPA 430-F-16-025, August 2016).

Can we confirm the EPA's conclusion that TMIN has actually increased over 100 years?

Analysis - Temperatures

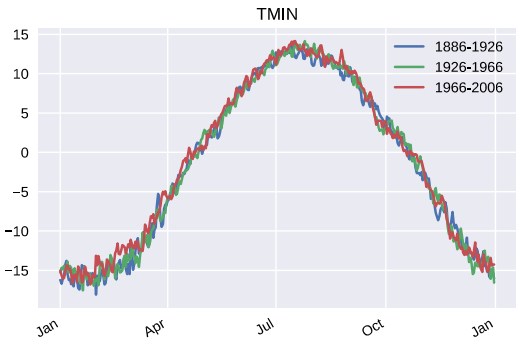

Figure 5: Average daily TMIN for three 40 year time periods

Figure 5 shows the average value for our TMIN data over a 365 day year for the forty-year periods of 1886-1926, 1926-1966, and 1966-2006. The three curves are nearly identical. As expected, the average minimum temperature is lowest in the winter months and highest in the summer months.

However, a 0.5-1.5 ºC change in TMIN would be very difficult to detect with only a casual inspection of the graph. To address this, I used the 20-year period of 1886-1906 as a baseline for the average TMIN. I then subtracted this baseline curve from the 20-year periods starting in 1906. Figure 6 shows a histogram of the residual changes between the 1886-1906 baseline TMIN and the succeeding 20-year epochs.

Epoch	Change in TMIN from 1886	P value for t-test
1906-1926	0.356	0.0002
1926-1946	0.459	< 0.0001
1946-1966	0.303	0.0011
1966-1986	0.363	0.0001
1986-2006	**1.056**	< 0.0001

Chart A: Comparing TMIN to 1886-1906

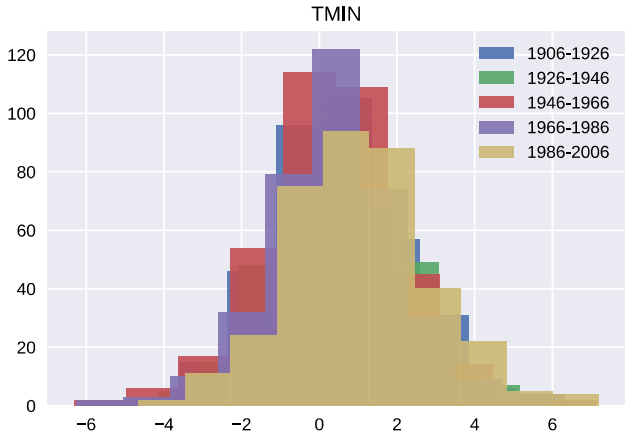

Figure 6: Histogram of residual change in TMIN (compared to 1886-1906)

Chart A shows the mean change in TMIN between the 1886-1906 period and the five other epochs. A one-sample t-test was used to determine if the change in TMIN was significantly different than the 1886-1906 baseline. Although all epochs had a statistically significant increase in TMIN, the period between 1986 and 2006 showed a mean 1.056 ºC increase in temperature compared to the period a century prior. This confirms the EPA's statement that climate change has increased the temperature in the region over the last 100 years.

The average observed daily temperature (TOBS) also had similar increases in the epochs between 1886 and 1986. However, the mean TOBS during the 1986-2006 epoch was not statistically different from the 1886-1906 baseline. The National Weather Service changed the observation time

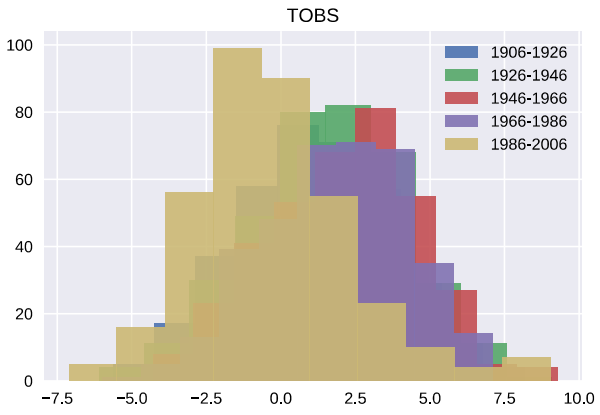

Figure 7: TOBS is unreliable.

from afternoon to morning starting around 1960 (Understanding Adjustments to Temperature Data, Berkeley Earth: Press & Opinions, 2017). Hence, it might be difficult to use TOBS to make any meaningful conclusions about climate change because this change in the collection routine may have introduced a sampling bias which could have skewed the results. For example, if the TOBS recordings in 1886 were taken during in the afternoon (when it is typically warmest), but the majority of TOBS recordings in 2006 were taken in the morning (when it is typically coldest), then we would expect TOBS of 1886 to be greater than TOBS in 2006. The fact that the two epochs have equal TOBS values may suggest that there was an increase, but that it was masked by the sampling bias. Ultimately, I concluded that TOBS is not considered a reliable measurement in this analysis and should not be interpreted any further.

More interestingly, a similar analysis on the average maximum daily temperature (TMAX) did not show a statistically significant change over any of the five epochs when compared to the 1886-1906 baseline. Taken together with the changes in TMIN, this suggests that the region is not getting "hotter" *per se*, but rather is having more difficulty cooling down at night (when TMIN is most likely to occur). In other words, this region in Minnesota is holding onto the heat more in the same way as a person does when they are insulated by an overcoat. Indeed, Peng confirmed that nighttime warming has increased faster than daytime warming over the last five decades (Peng, S. *et al.* "Asymmetric effects of daytime and night-time warming on Northern Hemisphere vegetation", *Nature*, Vol. 501, 5 Sep 2013, pp. 88-94.)

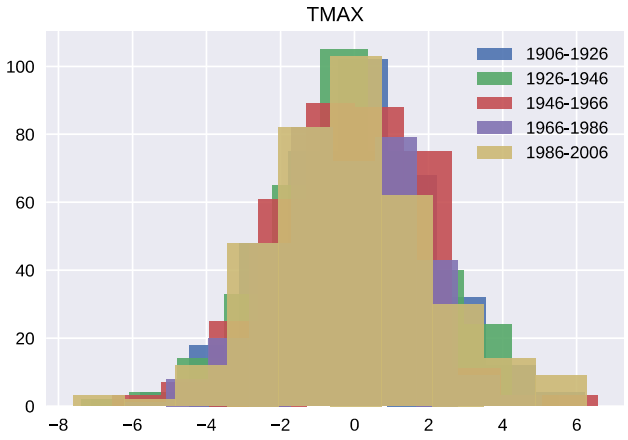

Figure 8: There has been no significant change in TMAX since 1886.

To test that climate change was preventing the region from "cooling down at night", I looked at the average snow depth (SNWD). Minnesota is known for its snowy winters. Duluth is ranked #4 in the Daily Beast's 2010 list of "Snowiest Cities". If the 1 ºC rise in TMIN has an observable impact in Minnesota's climate, then perhaps it will be reflected in changes of the average snow depth.

Analysis – Snow Depth

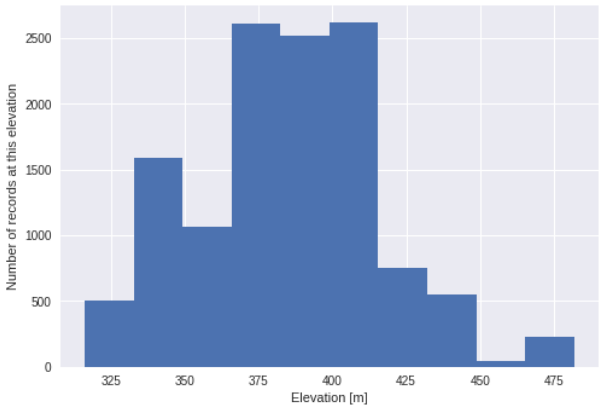

Figure 9: Elevation of the monitoring stations

Elevation is an important factor in annual snowfall. Higher elevations typically have more snow earlier and keep more snow later in the year. Fortunately, this region in Northern Minnesota/Southern Ontario is low and fairly flat (Figure 9). The mean elevation is 384 meters with a standard deviation of about 32 meters (a third of a football field). Therefore, we don't expect to see much influence from elevation in our SNWD results. For comparison, the highest elevation in Minnesota is Eagle Mountain at 701 meters. The lowest elevation is Lake Superior at 183 meters. The southeast section of our geographical area includes part of Lake Superior.

Unfortunately, the snow depth (SNWD) measurements for the data don't start until 1949. According to Table A, the relative change in TMIN for that period was around 0.7 ºC. I compared the mean SNWD for the 10 year periods between 1949 and 2009 (Figure 10). The least amount of snowfall occurred in the decade from 1999-2009. Nevertheless, snowfall in the decade prior to that (1989-1999) was similar to the 1949-1959 period. Therefore, there is no clear result in total SNWD.

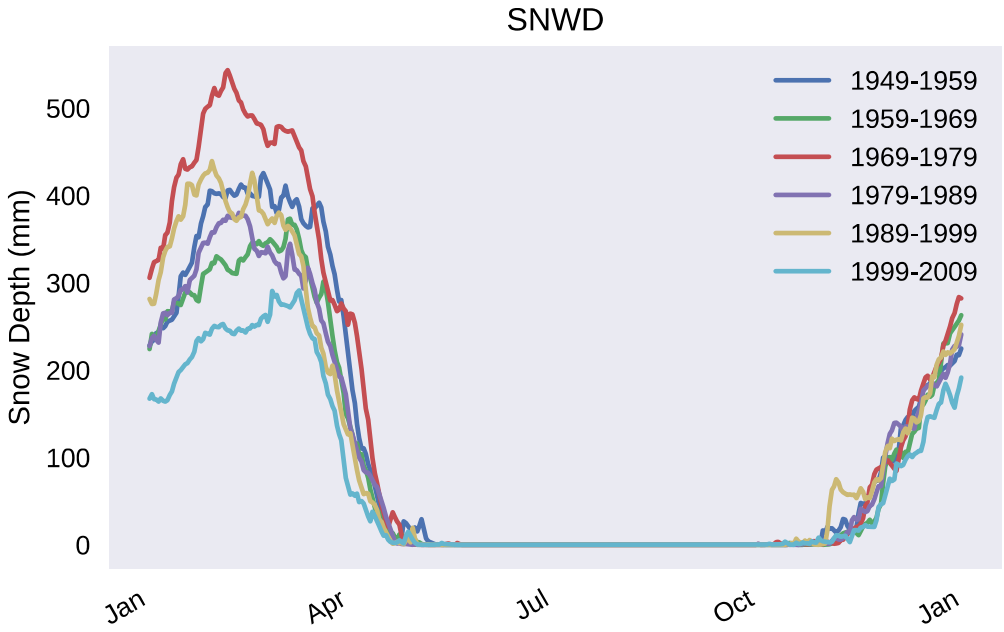

Figure 10: Average snow depth over the decades since 1949.

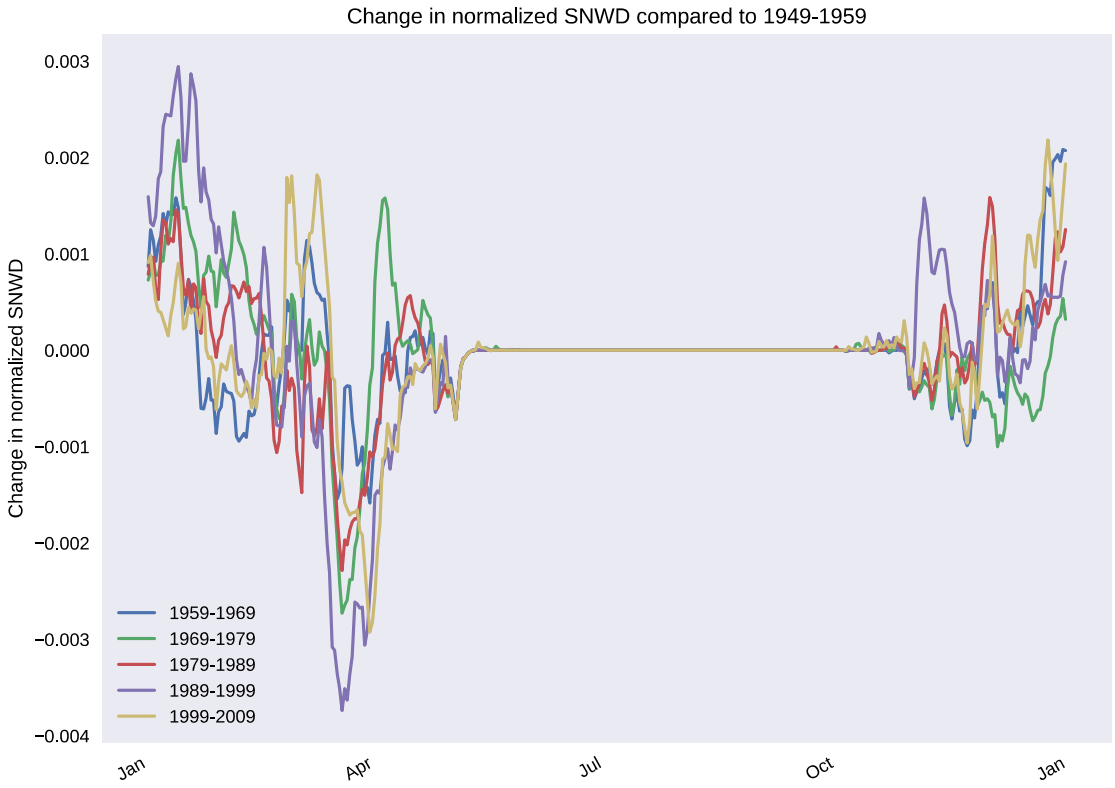

Figure 11: An earlier spring?

I normalized SNWD over the six decades by scaling the daily snowfall measure with the total snowfall for that decade (area under the curve). Then, I used the 1949-1959 SNWD data as a baseline and found the residual SNWD curves for the five successive decades (Figure 11). There is a clear decrease in SNWD between the baseline 1949-1959 decade and the successive decades. The months of March, April, and May have less snow on the ground. I believe this is a direct effect of the increase in TMIN. In the months when the snow pack is at its shallowest, the increase in nighttime temperature would speed up melting.

Conclusion

The average daily temperature of the Northern Minnesota/Southern Ontario region has increased over 1 ºC over the last century. This result has been previously reported in numerous studies and is a generally accepted observation of climate change at work.

Most notably, the average maximum daily temperature appears to have remained the same while the average minimum daily temperature has had the greatest increase. This implies that climate change in the region is not an overall "warming" of the area, but more appropriately described as a "prevention of cooling" of the area.

Nevertheless, the current evidence is not very conclusive on snow depth changes. Both total and maximal snow depths have varied widely over the last 70 years with no apparent trend. However, relative springtime snow depth declined in every decade since 1949-1959. Wagner reports that snow depth and snow cover actually cause lower temperatures (Wagner, A. J. "The Influence of Average Snow Depth On Monthly Mean Temperature Anomaly", Monthly Weather Review, 101(8):624-626, Aug. 1973). Therefore, it is possible that the analysis is not as strong because the snow depth is influencing the changes in temperature rather than vice versa.