SPATIOTEMPORAL SNOWFALL TRENDS IN CENTRAL NEW YORK

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Abstract

Central New York State, located at the intersection of the Northeastern United States and the Great Lakes basin, is impacted by snowfall produced by lake-effect and non-lake-effect snowstorms. The purpose of this study is to determine the spatiotemporal patterns of snowfall in Central New York, and their possible underlying causes. 93 Cooperative Observer Program stations are used in this study. Spatiotemporal patterns are analyzed using simple linear regressions, Pearson correlations, principal component analysis to identify regional clustering, and spatial snowfall distribution maps in ArcGIS. There are three key findings. First, when the long-term snowfall trend (1931/32-2011/12) is divided into two halves, a strong increase is present during the first half (1931/32-1971/72), followed by a lesser decrease in the second half (1972-2012). This suggests that snowfall trends behave non-linearly over the period of record. Second, Central New York spatial snowfall patterns are similar to those for the whole Great Lakes basin. For example, for five distinct regions identified within Central New York, regions closer to and leeward of Lake Ontario experience higher snowfall trends than regions farther away and not leeward of the lake. Finally, compared with multiple climate indices, only the Atlantic Multidecadal Oscillation, with no lag, had the greatest significant ($\rho < 0.05$) correlation (-0.41) with seasonal snowfall totals in Central New York. Findings from this study are valuable as they provide a basis for understanding snowfall patterns in a region affected by both non-lake-effect and lake-effect snowstorms.

1. Introduction

Natural forces have always shaped the earth's climate, but recently the IPCC (2013) has noted a positive correlation between global air temperatures and carbon dioxide from anthropogenic sources. This finding has considerable implications on the regional climate of an area, especially in the snow-dominated latitudes of the United States. Snowfall is dependent on air temperatures at or below freezing. Most of the observed warming in the last century has been in the high latitudes, where increased temperatures raise mean winter temperatures closer to the freezing threshold. This causes more precipitation to fall as rain rather than snow (Knowles et al. 2006), which is especially apparent during the spring (Groisman et al. 2004).

Central New York is one region negatively impacted by a transition from snow to rain. The region has grown accustomed to seasonal snowfall totals regularly exceeding 250 cm, which has created a societal dependency on snowfall for winter recreation, spring snowmelt, and insolation of plant biomass from freezing temperatures (Schmidlin 1993; Kunkel et al. 2002). Central New York is unique compared to other regions in the Great Lakes basin because it is located at the intersection of the Northeastern United States and the Great Lakes basin. As a result, snowfall in Central New York regularly occurs from both lake-effect and non-lake-effect snowstorms. Lake-effect snowstorms are those that result from the advection of a cold air mass (generally a polar or Arctic air mass) over a relatively warm lake (Peace and Sykes 1966; Kunkel et al. 2000). The moisture, lift, and instability that generate the snowfall are thus produced solely by the advection of cold air over warmer water. Non-lake effect snowstorms are those that result from all other mechanisms responsible for organizing moisture, lift, and instability into snowfall. These storms are generally associated with a transient low pressure system (i.e. mid-latitude cyclone or Nor'easter). Yet, several studies have found a large contrast between non-lake effect snowfall trends and lake-effect snowfall trends, as follows.

Braham and Dungey (1984), Norton and Bolsenga (1993), Burnett et al. (2003), Ellis and Johnson (2004), and Kunkel et al. (2009a) found a significant increase in snowfall for stations that experience lake-effect snowfall (those within the extent of the Great Lakes basin) since the early-20^{th} century. Using observations from over 1200 weather stations from 1951-1981, Norton and Bolsenga (1993) found that lake-effect snow in the Great Lakes basin increased, while there was little to no appreciable increase in snowfall outside of the basin. Burnett et al. (2003) corroborated an increase in lake-effect snow, as the authors noted an approximate 1.5 cm yr^{-1} increase from 1931-2001. However, Kunkel et al. (2009a) noted that due to inhomogeneities within the dataset of Burnett et al. (2003), the snowfall increase was overestimated by approximately 0.9 cm yr^{-1}. Kunkel et al. (2009a) suggests that this difference is attributed to the use of filtered Cooperative Observer Program (COOP) data, which removes biases in the data and reduces an overestimation of snowfall trends by Burnett et al. (2003).

The previously discussed studies all framed snowfall trends as a long-term increase. In contrast, a subsequent study by Bard and Kristovich (2012) proposed the presence of a trend reversal. The authors noted that the long-term snowfall trend actually experienced a reversal in the late-1970s, suggesting that since the 1970s, snowfall has decreased for the Lake Michigan basin. Even though the authors focused on the Lake Michigan basin, seasonal snowfall totals in the Lake Michigan basin behave similarly to that of the Lake Ontario basin due to the influence of lake-effect snow (Liu and Moore 2004). Notable differences between the two basins do exist, such as the orientation of the two lakes, the influence of coastal low pressure systems (i.e. Nor'Easters), and the water properties (i.e. depth, temperature, surface area, ice onset and breakup) of the two lakes (Wang et al. 2012). Therefore, it is important to expand upon the findings of Bard and Kristovich (2012) to determine if a trend reversal is also present for the snowfall in a second Great Lakes basin, and more importantly, quantify how significant it may be.

The presence of a trend reversal may suggest a cyclical pattern in snowfall trends, which could be driven by teleconnection patterns (Moses et al. 2006). Studies have found a climatic influence on weather patterns in the Northeastern United States and Great Lakes basin from three particular oscillations: the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Atlantic Multidecadal Oscillation (AMO). Grimaldi (2008) discovered that during the El Niño (warm) phase of ENSO, early winter months in Syracuse, New York are generally warmer with anomalously low snowfall totals. This pattern then reverses during later winter months. Also during El Niño years, major snow events are five times more likely to occur in Syracuse. Along with ENSO, Kocin and Uccellini (2004) found that the NAO has an impact on North American seasonal snowfall totals. The authors noted that the NAO is negatively correlated (-0.64) with increased seasonal snowfall in the eastern United States. The AMO, a 65-70 year variation in Atlantic sea surface temperatures (SSTs), has not been as widely studied as ENSO or the NAO (Schlesinger and Ramankutty 1994), although studies have begun to focus on the AMO's impacts on the North American climate. For example, Zhao et al. (2010) suggested that changes in the AMO result in shifts in the magnitude and location of the jet stream. Also, Fortin and Lamoureux (2009) linked changes in the AMO with northeastern United States' snowfall, as warmer than average North Atlantic sea surface temperatures favor moister conditions and increased snowfall in boreal and arctic regions.

Previous studies have observed snowfall trends for the entire Great Lakes basin. However, it is also important to understand the spatial and interseasonal snowfall changes at a local level. Therefore, an objective of this study is to determine if snowfall trends in Central New York, located in the Lake Ontario basin, behave in a similar manner to trends outlined by Norton and Bolsenga (1993), Burnett et al. (2003), Kunkel et al. (2009a) and Bard and Kristovich (2012). A major finding of previous studies was that snowfall significantly increased throughout the 20th century for lake-effect stations in contrast with stations distant from the lakes. However, the spatial variability of snowfall trends for the Great Lakes basin has not been examined. Thus, this study also determines if changes in seasonal snowfall totals are spatially homogenous throughout Central New York. Finally, the influence of air temperature, precipitation, and teleconnection patterns on seasonal snowfall totals within Central New York is examined.

The goal of this paper is to analyze the spatiotemporal patterns of snowfall in Central New York. Section 2 ("Methods") describes the datasets and the procedures used to analyze the data. Section 3 ("Results") discusses long-term (1931/32-2011/12) and shorter-term snowfall trends both temporally and spatially, and describes potential influences on snowfall patterns in Central New York, from mean air temperature and precipitation totals to teleconnection patterns. Section 4 ("Conclusion") provides a concise synopsis of the results.

2. Methods

a. Study area

With a population of over 1 million people, Central New York is defined by twelve counties (Figure 1). Due to its location, snow associated with transient low pressure systems and lake-effect snow regularly impact the region, making the city of Syracuse the snowiest metropolitan area in the United States (Kunkel et al. 2000; NOAA 2011). Lake Ontario is the primary source of moisture and warmth for lake-effect precipitation development. Even though it is the smallest of the Great Lakes in surface area, it rarely freezes over during the winter (Niziol 1987; Wang et al. 2012). Due to its east-west orientation and leeward position relative to Lake Ontario, macro-scale wind patterns favor the development of lake-effect precipitation over Central New York (Niziol et al. 1995).

There are five main topographic features in Central New York (Figure 2), which provide a setting conducive for the development of lake-effect snow. The Southern Hills and the Tug Hill Plateau are two of the most prominent snowfall regions in Central New York. Elevations in the Southern Hills quickly rise 500 m within 32 km of the lake shore, with irregular hills and valleys providing additional topographic features for low-level air convergence and orographic lifting (Clowes 1919). The Tug Hill, the region most known for snowfall in New York State, is also conducive for high snowfall totals due to its eastward position relative to Lake Ontario and its steep elevation gradients.

b. Data

Seasonal snowfall totals, defined here as the total snowfall from 1 July to 30 June, were examined from 1931-2012 for 93 National Weather Service COOP stations located in the twelve Central New York counties (Table 1). Data were accessed through the National Climate Data Center's (NCDC) online Monthly Summary Observations (digital database TD3220) and included precipitation totals, average monthly air temperatures, and monthly snowfall.

The reporting consistency for each COOP site varied, therefore stations were only used if observations were recorded for at least 5 consecutive years from 1931-2012, with at least 85% of the winter (November-April) monthly snowfall record reported during that time. A slightly lower threshold was used in this study compared to that of Kunkel et al. (2009a), who used 90% reporting frequency, in order to increase usable snowfall observations. If monthly snowfall data were missing for a station, daily COOP snowfall records were acquired for the missing month(s) from NCDC's Global Historical Climatology Network. If at least 85% of the days within an unreported month were observed, then the monthly snowfall total was used. Therefore, an assumption here is, if daily snowfall totals are recorded for at least 85% of a month, then the station accurately represents monthly snowfall totals for that month. However, after examining daily snowfall totals, if observations were missing for two or more snowfall months (November-April), then the annual snowfall total was not reported. If only one winter month was not reported, a 4-point weighted bilinear interpolation was used to estimate the missing monthly snowfall total (Accadia et al. 2003). Once interpolated, monthly snowfall totals were summed from November-April and reported as a seasonal snowfall total.

Since lake-effect snowfall is positively correlated with elevation (Clowes 1919), each station was scrutinized for inhomogeneities outlined in Kunkel et al. (2007), with a particular emphasis on elevation changes greater than 10 meters, and changes in latitude/longitude greater than 0.15º. Many reported relocation changes were actually updated geographic coordinates. Therefore, beyond these thresholds, it was judged that a change was likely due to a relocation instead of updated coordinates. A station was also deemed inhomogeneous if the time series for the station was less than 5 years. The determination of homogeneity for a station was used to compare snowfall trends for stations deemed homogenous and those deemed inhomogeneous.

Air temperature and precipitation data were retained for typical snowfall months (November-April). Air temperature was only available for 27 of the 93 COOP stations in Table

1, and was averaged together to calculate the mean monthly temperature for all of Central New York. It should be noted that even though air temperatures were averaged, the temperature variation across Central New York is minimal (1.58ºC average standard deviation). For consistency, monthly precipitation was obtained for the same 27 stations that reported air temperature.

Data for the Southern Oscillation Index (SOI), NAO, and AMO indices were obtained from National Center for Atmospheric Research's climate data guide server (NCAR 2012). Monthly values were obtained for each teleconnection, and seasonal values were calculated from 1931-2012 by averaging data from November-April. Oscillation data was based on the standardized Tahiti/Darwin dataset for the SOI, Hurrell (1995) for the NAO, and unsmoothed Kaplan SST V2 data calculated by NOAA/ESRL/PSD1 for the AMO.

3. Results

Multiple quantitative analyses were employed to assess the temporal and spatial patterns of snowfall in Central New York. Analyses included simple linear regressions, Pearson correlations, lag-correlations, principal component analyses, and GIS mapping. Results of these analyses were divided into three categories: temporal snowfall patterns, intraregional snowfall variability, and potential factors responsible for snowfall variability.

a. Temporal Snowfall Patterns

Temporal snowfall trends at a 5% significance were calculated using simple linear regressions (Figure 3). Autocorrelation tests were performed on each time series to investigate periodicities in the dataset, yet no significant (> 0.3) correlations existed within the dataset.

Snowfall trends were calculated for the entire region by averaging snowfall totals for all available stations for each snowfall season. To detect non-linearity in the trendline, trends were calculated for the entire time series (1931-2012), at two 41-year increments (1931-1972 and 1971-2012), and by computing a 21-year trend with a 1-year moving window.

The long-term (1931/32-2011/12) seasonal snowfall trend (Figure 3a) for Central New York was 1.16 ± 0.31 cm yr^{-1} ($\rho = 0.05$), comparable to the 1.5 cm yr^{-1} snowfall increase reported by Burnett et al. (2003). After filtering for inhomogeneities within the dataset, the recalculated long-term snowfall trend reduced to approximately 0.59 ± 0.30 cm yr^{-1} ($\rho = 0.05$). This supports Kunkel et al. (2009a) who noted the snowfall increase found by Burnett et al. (2003) reduced from approximately 1.5 to 0.6 cm yr^{-1} after filtering for inhomogeneities. However, it should be noted that for the long-term record, only nine stations were deemed homogenous in Central New York, with nearly half (four stations) located in Onondaga County. Therefore, the decrease from 1.16 to 0.59 cm yr^{-1} may be a result of regional clustering instead of inaccuracies in nonhomogeneous data.

If the trend is considered as two distinct time periods (Figure 3b), the first half of the record exhibits a strong increase in snowfall, 3.27 ± 0.67 cm yr^{-1} ($\rho = 0.05$), while the second half demonstrates a non-significant ($\rho = 0.05$) change in snowfall. Long-term snowfall trends calculated by previous studies (Norton and Bolsenga 1993; Burnett et al. 2003; Kunkel et al. 2009a) may not best represent changes in the data up to the present time, as also suggested by Bard and Kristovich (2012) for the Lake Michigan Basin. This may particularly hold true for the trends in the later studies done by Burnett et al. (2003) and Kunkel et al. (2009a), as both studies' time series included the lower snowfall totals in the early-21st century, in contrast to the higher snowfall totals in the latter 20th century (1970s and 1990s). Thus, similar to the findings of Bard and Kristovich (2012), snowfall patterns in the Great Lakes may not be best portrayed using a long-term trend, as there is a noticeable trend reversal within the data. This trend reversal is possibly driven by teleconnection patterns, as described later in this study.

Variations in snowfall trends are best demonstrated by the 21-year snowfall trends calculated each winter from 1942/43 to 2000/01 (Figure 4). Twenty-one year snowfall trends during this time period were highly variable, ranging from approximately -7.6 to 7.6 cm yr^{-1}. The greatest change in snowfall trends occurred from 1966-1980, in which snowfall trends rapidly decreased ($\bar{x}$= -1.04 cm yr^{-1}, σ = 4.35 cm yr^{-1}). Snowfall trends during the earlier (1940-1959), and later (1990-2000) part of the record were less variable ($\bar{x}$= 2.41 cm yr^{-1}, σ = 2.13 cm yr^{-1} and $\bar{x}$= 1.85 cm yr^{-1}, σ = 1.37 cm yr^{-1} respectively). From the mid-1970s through the late-1980s, 21-year snowfall trends were less than zero. This supports the finding that longer-term snowfall trends experienced a reversal after the 1970s, which may be influenced by cyclical oscillation patterns. Caution should be taken when inferring the presence of a cyclical oscillation in the data, but if this signal is real, then the slight decrease starting in the late 1990s may be signs of another reversal.

b. Intraregional Snowfall Variability

In order to group stations by region within Central New York, principal component analyses (PCA) were used to extract hidden temporal and spatial correlations in seasonal snowfall totals. Two PCAs were conducted, first when missing seasonal snowfall values were excluded (PCA-a) and a second when missing values were replaced with the mean (PCA-b). Using the two PCAs, five distinct modes, further referred to as regions, were identified within Central New York (Figure 5). Each station was grouped into a single region based on the absolute value correlation (≥ 0.30) with each of the five modes, and mapped using the ArcGIS polygon feature. It is important to note that the borders between the five regions are loose, and crossing regions does not suggest a vast difference between seasonal snowfall totals. Instead snowfall patterns for stations within the same region behave more similar than stations between regions. It should also be noted that all of the regions are generally concentrated to a subsection of Central New York, except for Region 4 which extends over a narrow and elongated area.

Seasonal snowfall totals for stations in each region were averaged together, and autocorrelation tests (≥ 0.30) were used to test for nonlinearity in the dataset. Snowfall trends for the entire record and two 41-year records were then calculated at the 5% significance level using simple linear regressions for each individual region (Figure 5). Similar to the findings for the entire Central New York basin, snowfall trends exhibited a strong trend reversal, as snowfall trends for all regions were considerably higher for the first half of the record (1931/32-1971/72) than the latter half (1971/72-2011/12). There were also strong regional variations in the snowfall trends. During the long-term and first half of the record, Regions 4 and 5 experienced the largest positive snowfall trends. Both regions are in areas conducive for lake-effect snow development due to their position to the east of Lake Ontario, and due to their inclusion of the Tug Hill Plateau and Adirondack Mountains. Therefore, a larger increase in snowfall totals in these regions suggests an increase in lake-effect snow rather than non-lake-effect snow. A diminished snowfall increase for locations further from the lake is supported by snowfall changes in Region 2. Compared to the other five regions, Region 2 experienced the smallest snowfall increase, likely because Region 2 is farthest from Lake Ontario and is southwest of the lake. Thus, it is assumed that lake-effect snowfall is less common for this region, with the majority of the region's snowfall coming from non-lake-effect snowstorms. A lower snowfall increase over the period of record for non-typical lake-effect regions in Central New York is consistent with previous studies (Norton and Bolsenga 1993; Burnett et al. 2003; Kunkel et al. 2009a) which noted that stations distant from the lake experienced little to no appreciable increase in snowfall throughout the 20th and early part of the 21st century.

The 1971/72-2011/12 snowfall trend for Region 3 should be noted, as it is the only region to experience a minimal decrease in the snowfall trend from the first half to the second half of the 1931/32-2011/12 period. Among the regions, Region 3 experienced the largest positive snowfall trend over 1971/72-2011/12 (Figure 5). The cause of this relatively higher positive trend is not readily apparent. Region 3 is located inland and slightly southeast of Lake Ontario, which suggests lake-effect snow is not typical in the region. Increased non-lake-effect snow events (e.g., Nor'easters) are unlikely to account for the difference in trend between Region 3 and the other regions. If non-lake-effect snow events had increased snowfall, it would be expected that all of the regions, especially Region 2, would exhibit a trend similar to that of Region 3. The relatively higher positive trend in snowfall in Region 3 could be related to anomalously low snowfall totals (-43.9 cm) during the 1980s, compared to the 1971/72-2011/12 average. Snowfall deviations during the 1980s for the other regions ranged from -20.2 cm (Region 1) to -30.9 cm (Region 5). Thus, the magnitude of the snowfall anomaly in the 1980s for Region 3 was greater than that of all other regions. The presence of this comparatively more negative snowfall anomaly early in the 1971/72-2011/12 time series may have contributed to the larger positive snowfall trend observed for Region 3 over 1971/72-2011/12. The cause of the anomalously low snowfall in Region 3 is beyond the scope of this paper.

Spatial representations of snowfall changes were constructed using ArcGIS 10.1 and consisted of a 41-year snowfall difference map. The 41-year snowfall difference map was calculated by subtracting average snowfall totals for available stations during the latter period (1971/1972-2011/12) by average snowfall totals of the earlier period (1931/32-1971/72). Recall that 1971/1972 represents the break point of the trend reversal. In order to represent snowfall totals throughout Central New York, 10-point interpolations were performed using the inverse distance weighting function (Chen and Liu 2012).

The snowfall difference map (Figure 6) supports the idea of an overall increase in snowfall for Central New York, but the increase is not spatially homogenous. The northern reaches of Central New York, within the Tug Hill Plateau (See Figures 1 and 2), experienced the greatest increase (over 75 cm) in average seasonal snowfall totals. An appreciable increase in snowfall totals was also noticed for eastern Oswego County (45-55 cm increase) and for a north-south transect in central Central New York, extending from northern Lewis County to southern Cortland County (≥ 15 cm increase). A few areas experienced a decrease in annual snowfall, most notably northwestern Onondaga, southern Chenango, western Oswego, and northern Herkimer counties. All of these regions, except for northwestern Onondaga and western Oswego Counties, are not commonly associated with lake-effect snow due to their orientation to, and distance from, Lake Ontario. This further supports the notion that snowfall increases in Central New York are not evenly distributed and instead are highest in typical lake-effect snow locations and lowest near the edges, or in non-typical lake-effect locations of the Lake Ontario snow basin.

c. Potential Factors of Snowfall Variability

Possible factors influencing snowfall changes in Central New York were also examined. In order to compare annual snowfall, winter air temperatures, and winter precipitation, each field was normalized by subtracting the mean long-term value from the seasonal mean for each year, then dividing by the standard deviation of the long-term record. Results were then plotted using a 1.5-year Gaussian filter and Pearson correlations were computed on the unfiltered datasets to determine the correlation between the three different variables.

Snowfall totals are highly dependent on air temperatures at or below 0ºC and substantial moisture content in the air. Figure 7 shows that winters in Central New York have experienced greater variance in snowfall ($\bar{x}$= 0.59, σ = 0.15) and winter precipitation ($\bar{x}$= 0.60, σ = 0.10) than winter air temperature ($\bar{x}$= 0.85, σ = 0.06). Deviations from the mean precipitation peaked in the 1950s, while mean snowfall deviations were at a maximum during the 1970s and 1980s. During the early 1950s, seasonal snowfall means were below average, while precipitation and air temperatures were anomalously high. Interestingly, two peaks exist in the snowfall record from 1965-1980, at the years of 1970 and 1976. During the two peaks, air temperatures were lower (< -0.5), while during the snowfall minimum (1973) air temperatures peaked (> 0). Similar relationships were apparent during the early-mid 1990s and early-mid 2000s. Correlations between snowfall, air temperature, and precipitation validated this relationship, as snowfall had a greater significant (ρ = 0.05) correlation with air temperature (-0.56) than precipitation (0.02). Also, temperature and precipitation were significantly (ρ = 0.05) positively correlated (0.23), suggesting that increased temperatures increase moisture within the air, resulting in more precipitation. However, due to warmer temperatures the precipitation falls predominately as rain. This supports the findings of previous studies (Norton and Bolsenga 1993; Burnett et al. 2003; Kunkel et al. 2009a; Bard and Kristovich 2012), which noticed that winter air temperatures, rather than winter precipitation totals, are the controlling factor in seasonal snowfall totals in lake-effect dominated regions. Since precipitation is not increasing in step with snowfall, it can be assumed that the snow-to-liquid ratio (SLR) is increasing. This increase in SLR is associated with an increase in lake-effect snow, which is typically a low-density snow (Burnett et al. 2003; Baxter et al. 2005). In contrast to Burnett et al. (2003), it was found that increased air temperatures are associated with a decrease in total snowfall. However, this difference may be explained by changes in the thermal characteristics of Lake Ontario. Burnett et al. (2003) noted that thermal changes in the lake do not appear to be strongly influenced by winter air temperatures and instead are strongly influenced by spring, summer, and fall air temperatures. The present study did not observe air temperatures outside of November-April; therefore, an increase in spring, summer, and fall temperatures may have a larger role in increasing winter lake surface temperatures resulting in increased lake-effect snow.

The majority of the long-term time series experienced mean winter air temperatures below 0ºC, with the lowest average temperatures (under -2.8ºC) occurring during the 1930s and 1990s (Figure 8). However, the frequency of mean winter air temperatures above the freezing threshold increased, especially after the 1983/84 season. The 2011/12 season was the warmest for the time series, with mean air temperatures exceeding 1.6ºC. Average winter air temperatures above the freezing threshold favors rain over snow, decreasing seasonal snowfall totals (Knowles et al. 2006). The IPCC (2013) suggests that anthropogenic forcing is the underlying cause of air temperature change; however, teleconnections have significant impact as well (Serreze et al. 1998; Livezey and Smith 1999; Kocin and Uccellini 2004; and Kunkel et al. 2009b). Observing Figure 8, there appears to be a slight periodic variation that exists within winter air temperatures, as mean temperatures were at a minimum during the early 1930s, again during the latter 1960s, and finally during the early 1990s. Therefore, the possible 30-year periodic variation in air temperatures may be linked to an established climate-scale oscillation, further motivating the investigation of teleconnection influences on snowfall in Central New York.

The correlations of the SOI, NAO, and AMO with seasonal snowfall totals in Central New York were calculated. Each teleconnections' time series was normalized between -1 and 1 and plotted at 0-3 year lags, along with the average seasonal snowfall totals for Central New York. Pearson correlations were then performed between snowfall and each teleconnection lag to determine if annual snowfall totals in Central New York are correlated with the teleconnection indices.

Contrary to previous studies (Grimaldi 2008; Kocin and Uccellini 2004), no significant correlations were apparent between snowfall totals and the SOI, possibly because Grimaldi (2008) observed a shorter time period and Kocin and Uccellini (2004) focused on the Northeast United States. There is a slight significant ($\rho = 0.05$) correlation with the NAO at a 2-year lag. However, of the three observed teleconnections (SOI, NAO, and AMO), the AMO demonstrated the largest significant ($\rho = 0.01$) correlation with snowfall (Figure 9). The greatest correlation with the AMO was negative and at no lag. This anti-correlation is most noticeable during the 1970s and 1990s, when the AMO is below normal and snowfall totals are well above normal.

The AMO is a long-term oscillation in sea surface temperatures in the North Atlantic (0-87.5°N). Compared to the SOI ($\bar{x}$= 2.274, σ = 1.508) and NAO ($\bar{x}$= 0.556, σ = 0.746), from 1931/32-2011/12 the AMO experienced a smaller variance ($\bar{x}$= 0.008, σ = 0.178). From 1931-2012, the AMO experienced a warm phase from 1930-1960 peaking in 1944, a strong cool phase from 1970-1990 peaking in 1975, and transitioned back into a warm phase during the mid-1990s peaking in 1993 (Gray et al. 2004). This 20-30 year variation in the AMO coincides with changes in snowfall, as well as air temperatures, due to the negative correlation between air temperatures and snowfall (Figure 7; Figure 8). For example, during the 1970s snowfall is at a maximum, while air temperatures and the AMO index are below normal. Similarly, the AMO is higher during the early decades (1930s and 1940s), while air temperatures are slightly above normal, and snowfall totals are diminished. The inverse relationship between snowfall and the AMO is inconsistent with the finding of Fortin and Lamoureux (2009) who noted a snowfall increase in northeast North America during the positive AMO phase, which may be due to the restriction to a predominately lake-effect snowfall area.

Findings from the present study suggest that the AMO possibly influences snowfall changes in Central New York. Since the AMO varies at such a low frequency and snowfall measurements only date back to the 1930s, caution should be taken when analyzing the data and making predictions. However, if the signal is real and periodic and dominates over other influences, snowfall might peak again around 2030 in Central New York. Unfortunately, due to little information on past phases of the AMO, prediction capabilities are sub-par (Gray et al. 2004). It should also be noted that even though there is a significant correlation with the AMO, the correlation value is not large, and further study would need to be undertaken to evaluate how the AMO phase physically relates to lake-effect snowfall changes.

4. Conclusion

Several studies (Norton and Bolsenga 1993; Burnett et al. 2003; Kunkel et al. 2009a) have noted an increase in snowfall for lake-effect stations in the Laurentian Great Lakes since the early 20th century. Bard and Kristovich (2012) were the first to recognize a trend reversal within the time series for snowfall in the Laurentian Great Lakes, focusing on Lake Michigan. Due to numerous physical and climatic differences between Lake Michigan and Lake Ontario, this study examined snowfall trends for Central New York – located in the heart of the Lake Ontario snow basin.

There are three key findings of this study. The first finding was the recognition that Central New York snowfall trends are not linear, and instead experienced a trend reversal during the 1960s-1970s. Norton and Bolsenga (1993), Burnett et al. (2003) and Kunkel et al. (2009a) all noted a long-term increase in snowfall for lake-effect stations compared to non-lake-effect stations. This finding was corroborated by the long-term snowfall trend (1.16 ± 0.31 cm/yr^{-1}) for Central New York, but further analysis demonstrated a reversal in the trend. It was found, similar to Bard and Kristovich (2012), that above average snowfall during the 1970s and 1990s likely increased long-term snowfall trends, especially during the latter half of the time series (1971-2012). Annual 21-year snowfall trends continually decreased from the mid-1970s through the mid-1980s, further suggesting that Central New York snowfall trends behave non-linearly over the period of record.

Second, snowfall patterns in Central New York are not spatially homogenous. It is common for a study to overgeneralize a region, for example the Lake Erie basin, the Lake Ontario basin, or even the Great Lakes basin. However, there are important microclimatic variations that should be accounted for. Therefore, one goal of this study was to spatially represent snowfall trends in Central New York. It was found that Central New York can be divided into five distinct regions, with the regions closer to and leeward of Lake Ontario experiencing higher snowfall trends than regions farther away and not leeward of the lake. Since 1931, the Tug Hill experienced the largest increase in snowfall for Central New York. The Tug Hill is commonly known for the vast amounts of lake-effect snow that it receives over a snowfall season. Therefore, it is suggested that even though Central New York is a lake-effect snow dominated region, there are spatial differences in which areas typically associated with lake-effect snow (the Tug Hill, the Southern Hills, and Oswego County) experienced a higher snowfall trend than areas not characteristically associated with lake-effect snow (northeastern and southern Central New York).

Finally, winter air temperatures and the AMO have the greatest correlation with seasonal snowfall totals in Central New York. Winter air temperatures are significantly ($\rho = 0.05$) inversely correlated to seasonal snowfall totals (-0.56), suggesting that colder (warmer) winter temperatures promote increased (decreased) seasonal snowfall totals. This relationship was notably stronger than that between snowfall and precipitation, suggesting that winter air temperatures have a greater influence on seasonal snowfall totals than winter precipitation totals. It was found that for the teleconnection patterns observed, the AMO, with no lag, had the greatest significant ($\rho < 0.01$) correlation (-0.41) with seasonal snowfall totals in Central New York. The driving forces of the AMO's influences are not determined in this study, but it is recognized that there is a 30-year snowfall pattern in seasonal snowfall totals, likely connected to the AMO.

Due to the relative abundance of snowfall throughout the winter season, snowfall is an important resource in Central New York. Stable seasonal snowfall totals are vital for the region's habitats and economy, as agriculture, water resources, winter recreation, wildlife, and the Department of Transportation depend on stable snowfall totals. Therefore, the results from this study will help understand Central New York snowfall trends and aid in forecasting seasonal snowfall totals. Enhanced forecast predictions will allow better preparation for and adaption to future seasonal snowfall totals.

The most significant limitation during this study was the consistency of COOP observations. Records for each of the 93 stations were not consistent, with varying time series, reporting frequencies, missing data, and spatial homogeneity. This consistency is a significant limitation in COOP data, and possibly biased trend calculations; however, it should be emphasized that COOP data are the only data available to do this type of study. A second limitation was presented during the analysis of temperature and precipitation data. Due to the limited availability of air temperature data, temperature records were averaged throughout Central New York; assuming that the average air temperature is representative of the whole region.

Finally, future work should expand the analysis of driving factors of snowfall patterns in Central New York. For example, lake-effect snow is largely dependent on the air-lake temperature contrast; therefore, it would be beneficial to examine yearly air and lake surface temperatures to determine their influence on seasonal lake-effect snow totals. Further analysis should also be done to explore the influence of the AMO on seasonal snowfall totals in Central New York, specifically examining the AMO's influence on other factors such as changes to lake ice (Wang et al. 2012), the lake-air temperature difference (Peace and Sykes 1966), and the tracks of low pressure systems (Liu and Moore 2004).

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Figure 7. Normalized annual snowfall totals, winter air temperature, and winter precipitation data run through a 1.5-year Gaussian filter.

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Table 1. COOP Stations by Central New York County.

County	No. of Stations	Start Year	End Year	Length of Record (yrs.)
Cayuga	4	1897	2012	115
Chenango	6	1931	2012	81
Cortland	4	1892	2010	118
Herkimer	13	1931	2012	81
Jefferson	8	1920	2012	92
Lewis	12	1920	2012	92
Madison	4	1920	2012	92
Oneida	14	1931	2012	81
Onondaga	6	1893	2012	119
Oswego	9	1920	2012	92
Otsego	9	1931	2012	81
Tompkins	4	1918	2012	94

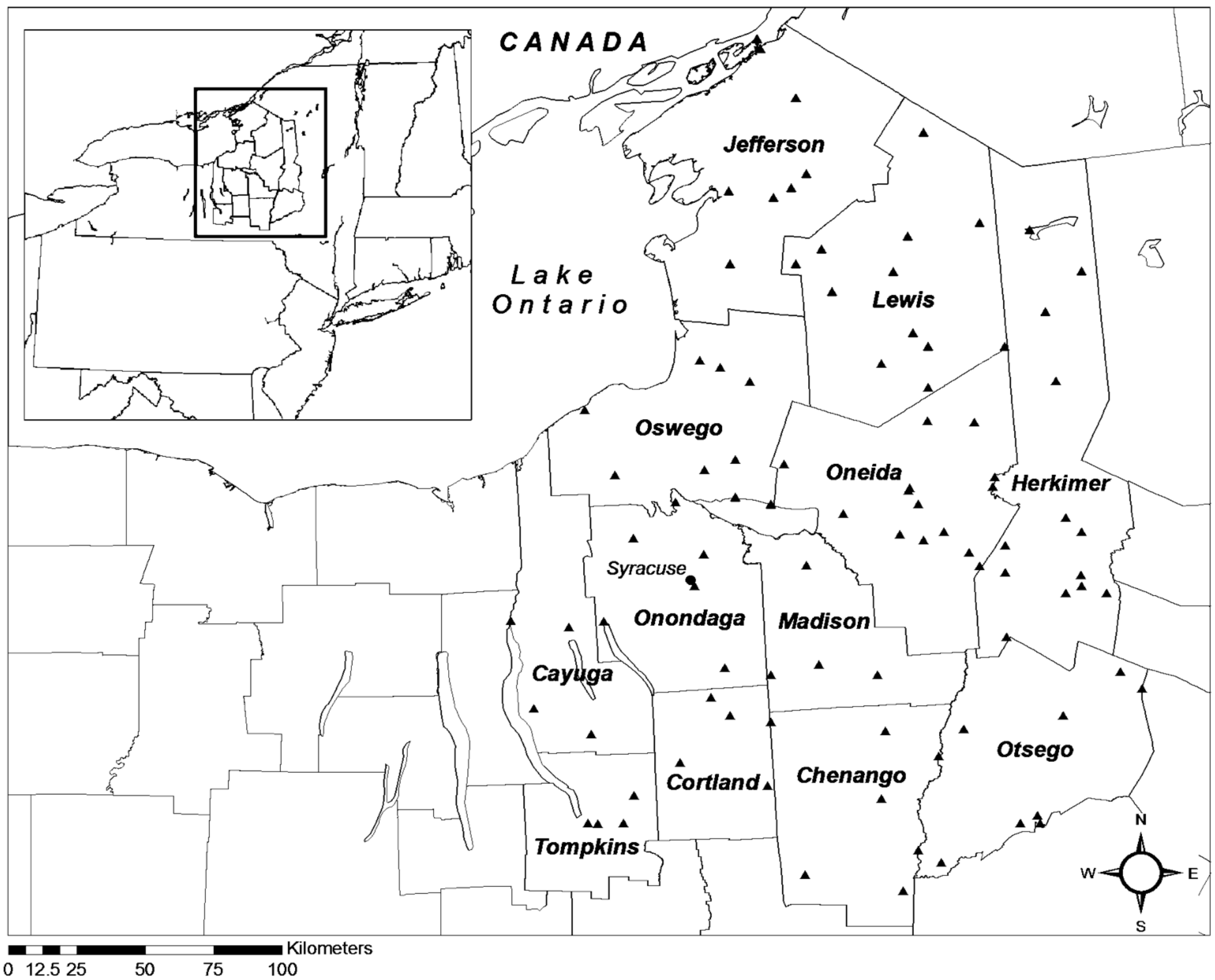


Figure 1. Study area. The labeled counties are the twelve counties that make up Central New York. Points symbolized with a triangle represent the 93 COOP stations in the study area.

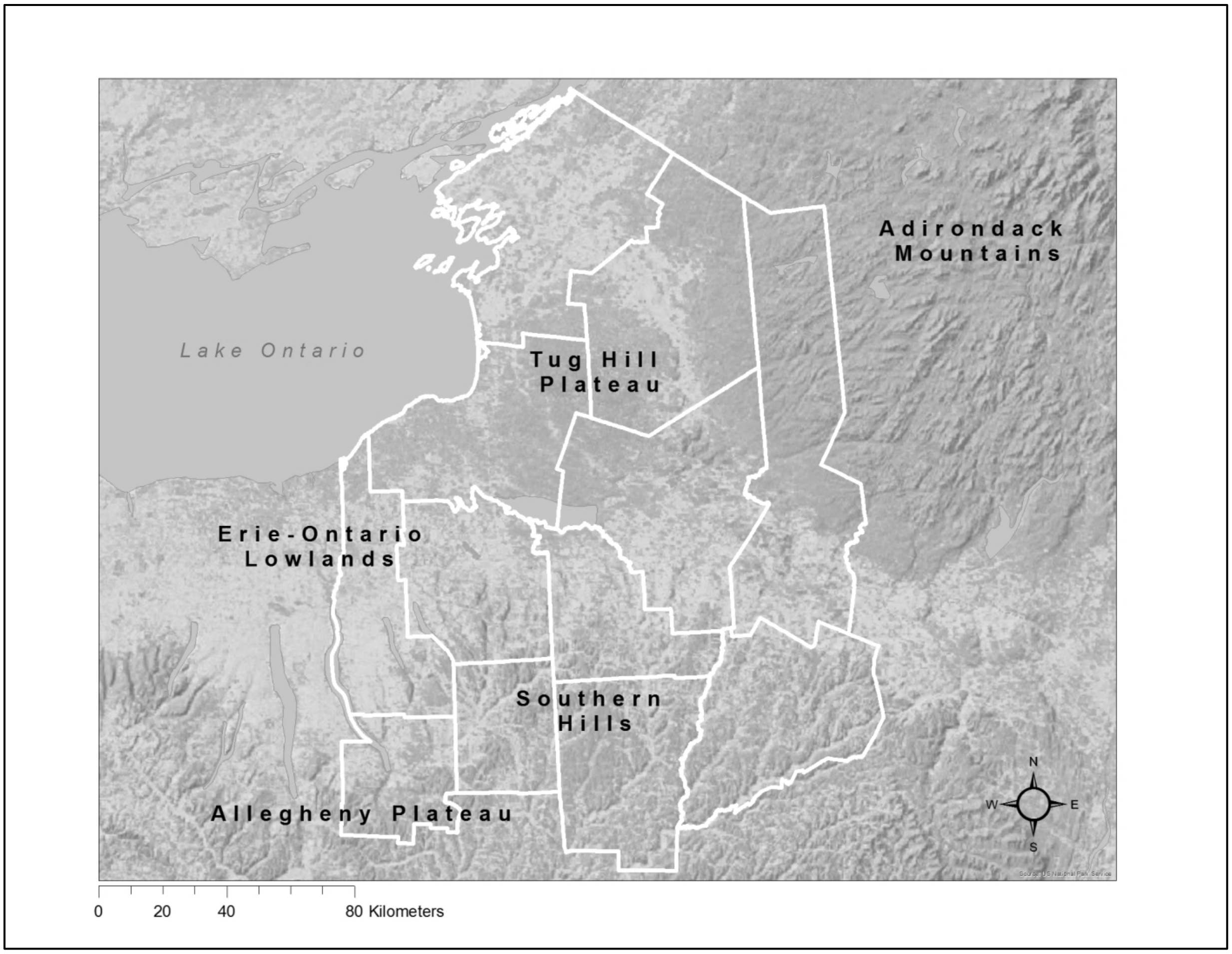


Figure 2. Topographic features of central New York State.

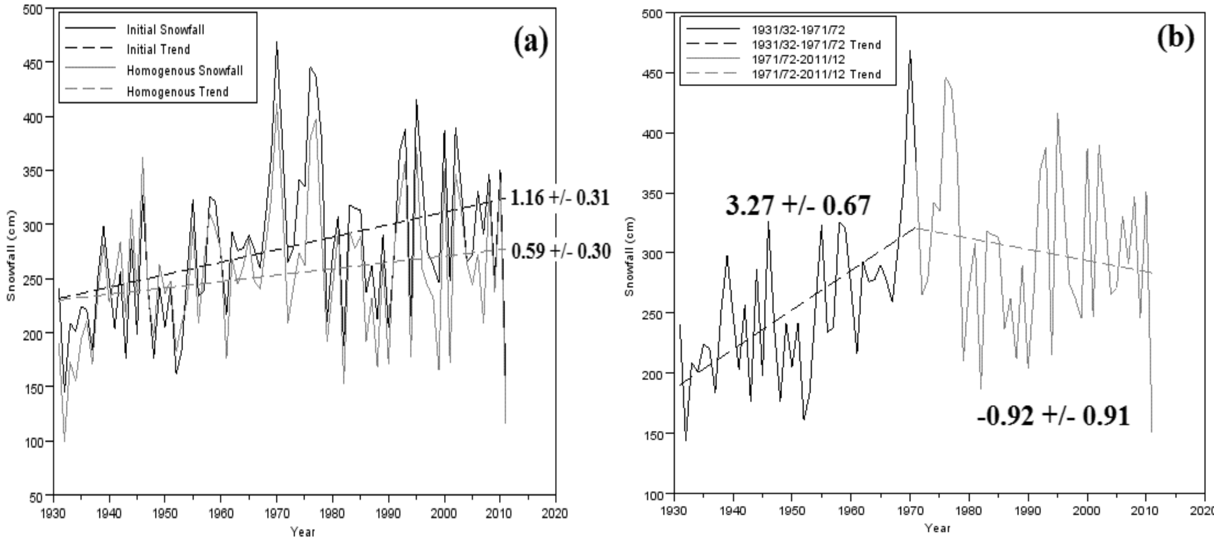


Figure 3. Initial and homogenous snowfall trends for multiple time intervals. Trends are reported at the 5% significance level. Figure 3a represents the long-term trends, while Figure 3b represents two 41-year trends using initial COOP stations.

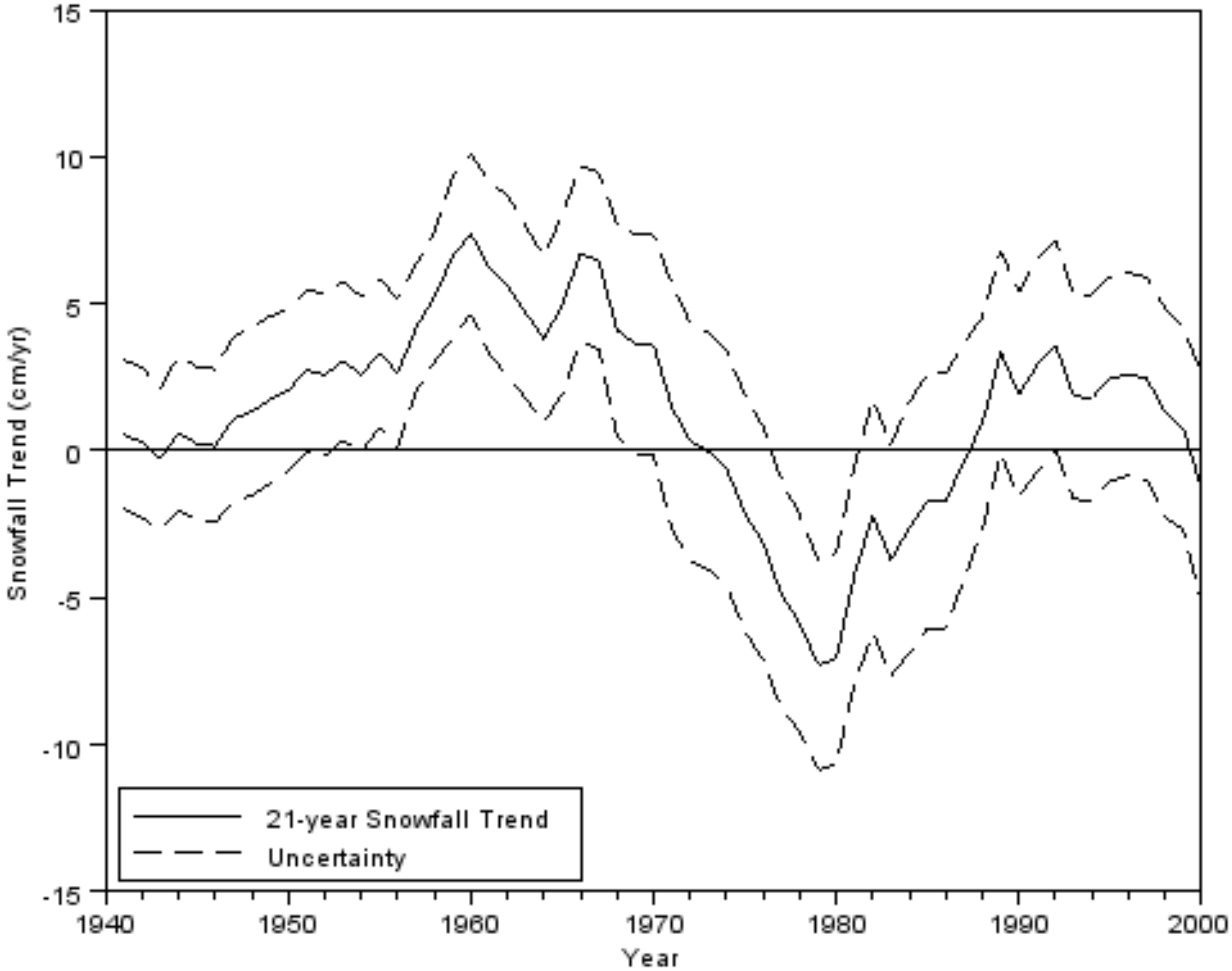


Figure 4. 21-year CNY snowfall trends at 1-year time-step intervals. The solid line represents the 21-year snowfall trend for each year from 1942-2000, while the dashed lines are the associated uncertainty of the trends at a 5% significance.

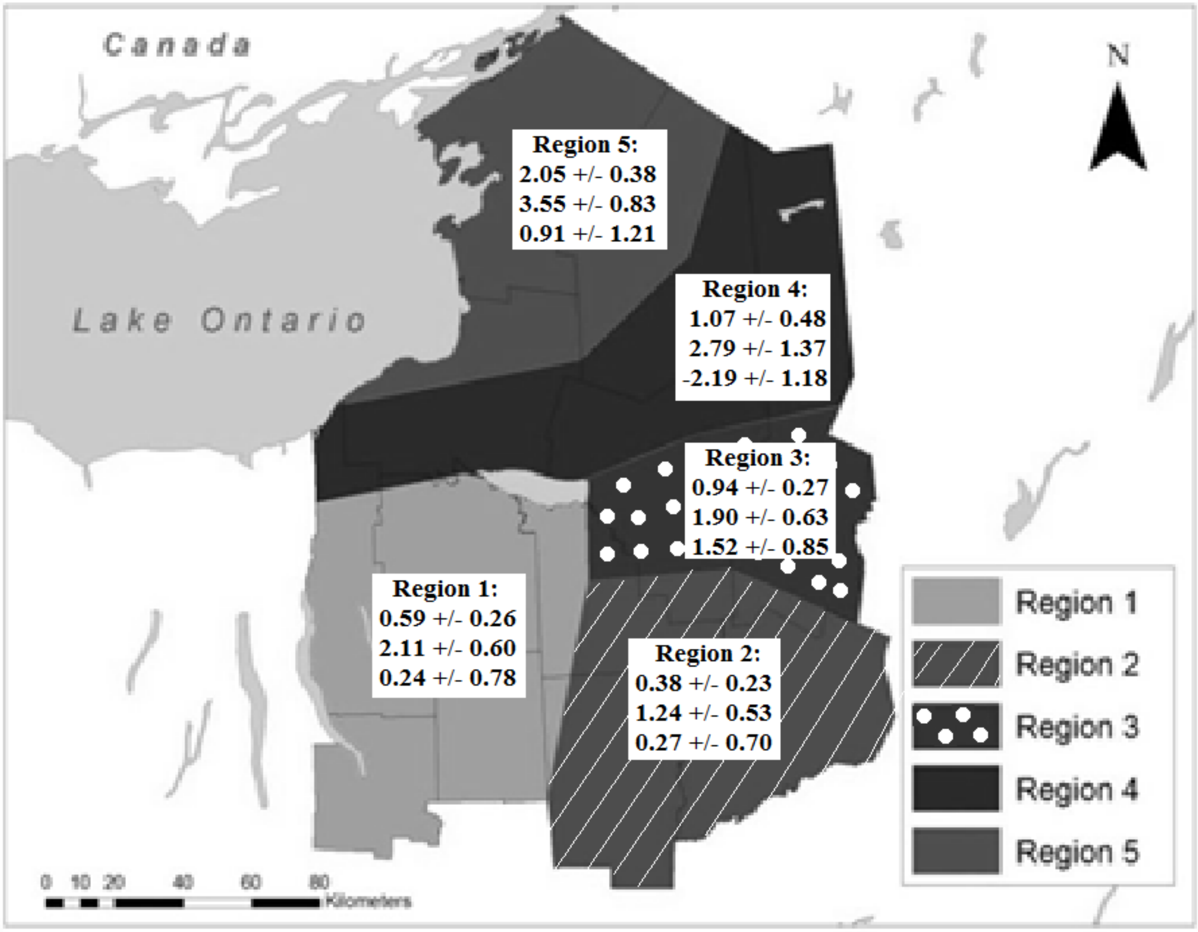
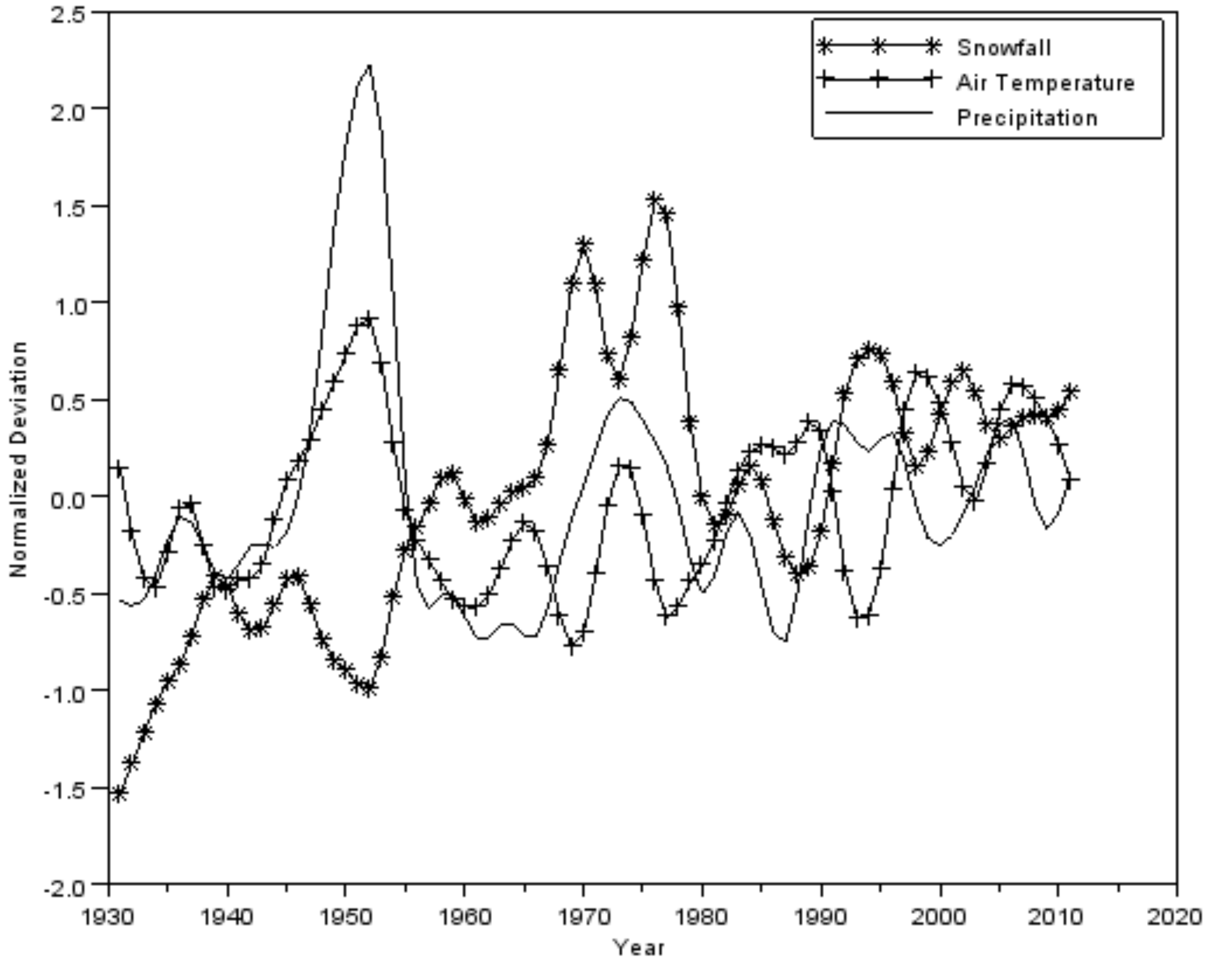


Figure 5. Regional snowfall trends classified by PCA-a and PCA-b. Trends and uncertainties are reported in cm yr^{-1} and are significant at the 5% level. The trends are ordered from top to bottom: first trend is the long-term trend (1931/32-2011/12), the second trend is from 1931/32-1971/72, and the third trend is from 1971/72-2011/12.

Figure 6. Difference in mean annual snowfall totals between 1971/72 – 2011/12 and 1931/32 – 1971/72.



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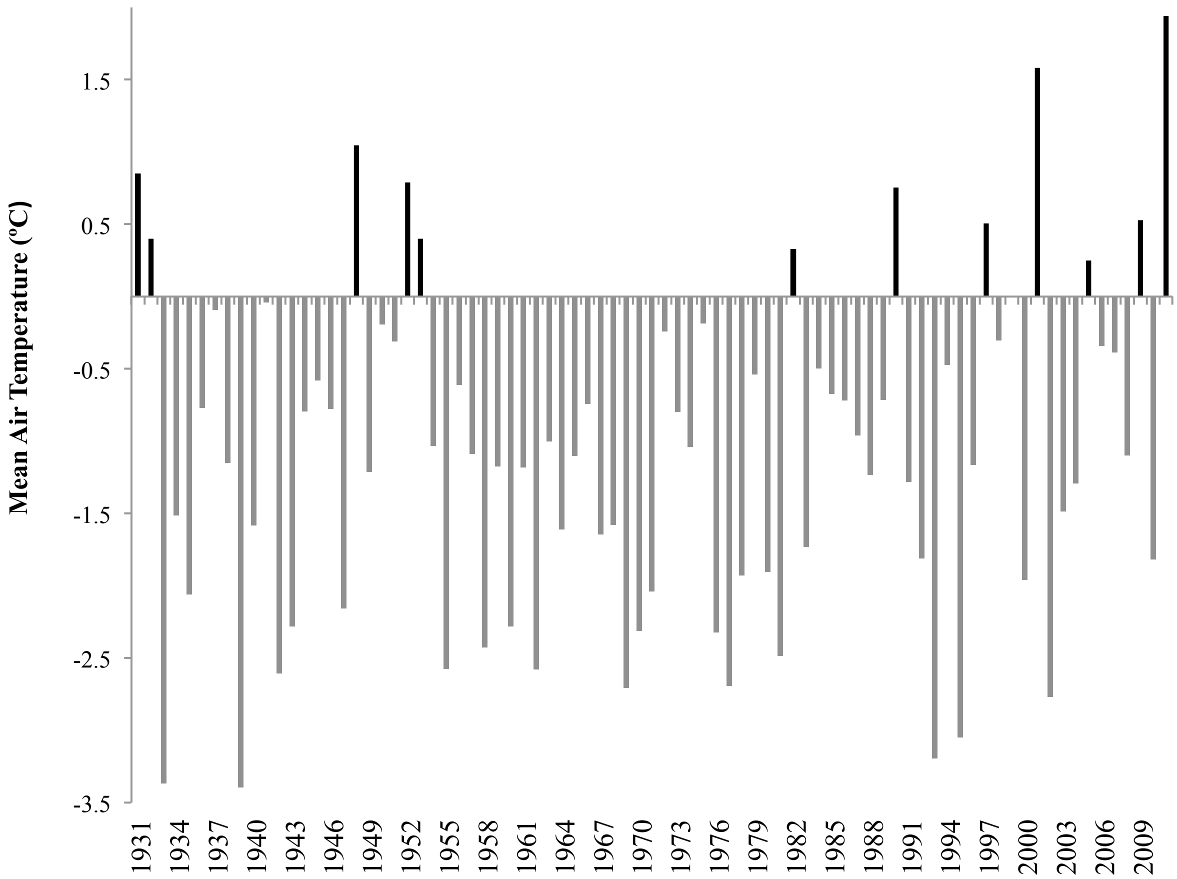

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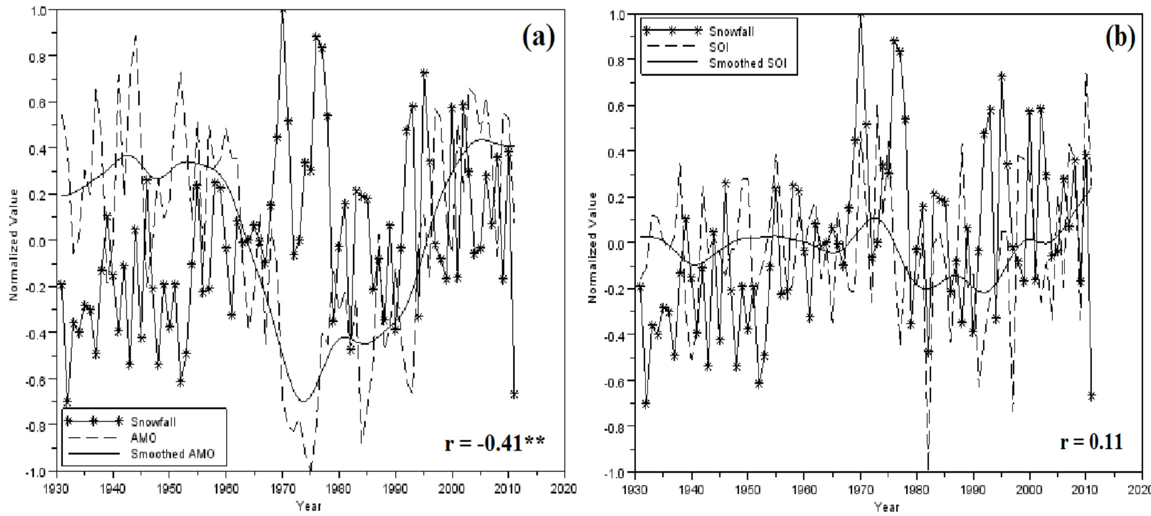

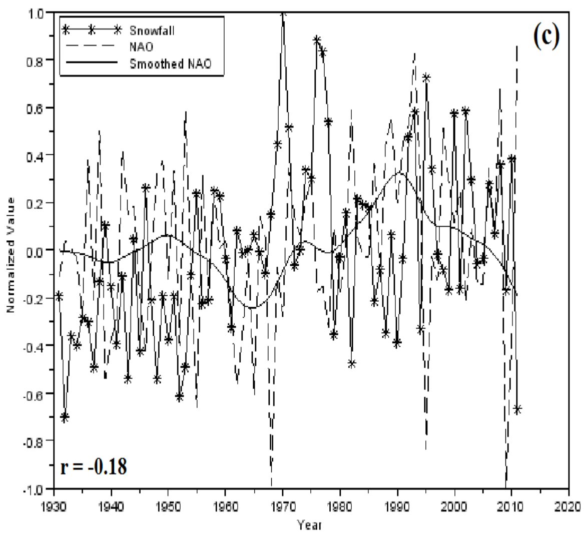

	No Lag	1 yr.	2 yrs.	3 yrs.
AMO	-0.41**	-0.32**	-0.28*	-0.26*
SOI	0.11	-0.07	0.07	0.02
NAO	-0.18	-0.06	0.25*	-0.01

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